High Efficiency CCM Bridgeless Totem Pole PFC Design using GaN E-HEMT

Reference Design

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Table of Contents

1. Introduction

This reference design highlights the motivation, operating principle and design considerations of Bridgeless Totem Pole PFC (BTPPFC) using GaN enhancement mode HEMT (E-HEMT). A 3-kW BTPPFC design example using GaN Systems 650-V GaN E-HEMT is presented in detail.

2. Why GaN-based bridgeless PFC?

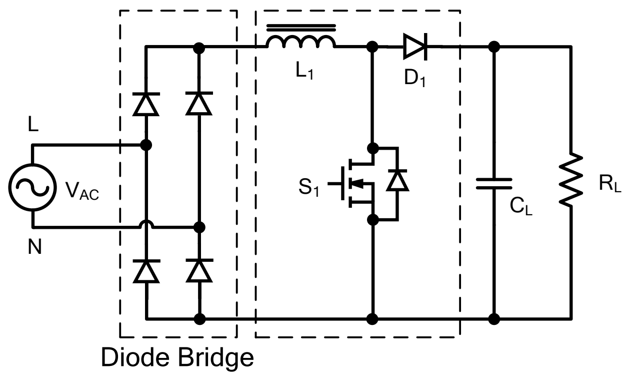


Figure 2.1. Conventional boost PFC circuit

A conventional PFC circuit is shown in Figure 2.1. It consists of a full bridge rectifier and a boost pre-regulator. The boost stage can be CCM, or DCM/critical conduction mode (CrCM) with zero/valley voltage switching for improved efficiency.

However, large portion of system loss are in the **diode bridge** and cannot be avoided even with zero voltage switching on the Boost stage. This inherently limits the peak efficiency of the conventional PFC stage. A rectifier diode has typical 1-V forward voltage drop and there are 2 diodes in the current path, which could account for 2% of total efficiency loss. A well-designed PFC stage can probably achieve efficiency about 97 to even 98%, but efficiency higher than 98% becomes very challenging for standard PFC due to the fixed diode bridge loss.

For example, the 80PLUS Titanium efficiency standard demands half load efficiency of 94% at low line and 96% at high line. Considering the typical DC/DC stage efficiency is about 97.5%, in order to meet the 80PLUS Titanium standard, the PFC stage efficiency needs to be >98.5% [1].

In a bridgeless PFC, the diode losses can be eliminated so efficiencies of 99% or higher are made possible to meet highest efficiency standards. Various bridgeless PFC topologies have been proposed to overcome the high diode bridge losses [2]. Among all the bridgeless PFC topologies, the popular 2-phase bridgeless PFC and BTPPFC will be illustrated and compared.

2.1. Two phase bridgeless PFC

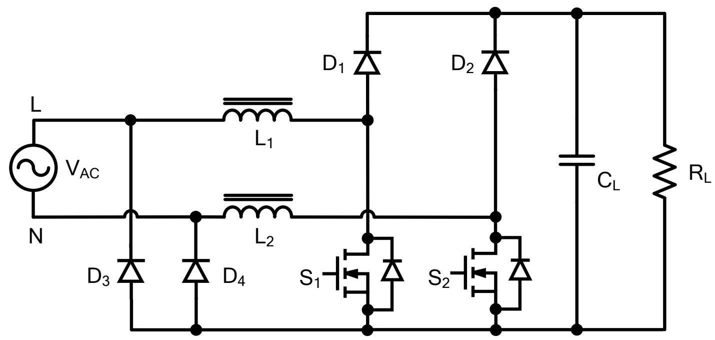
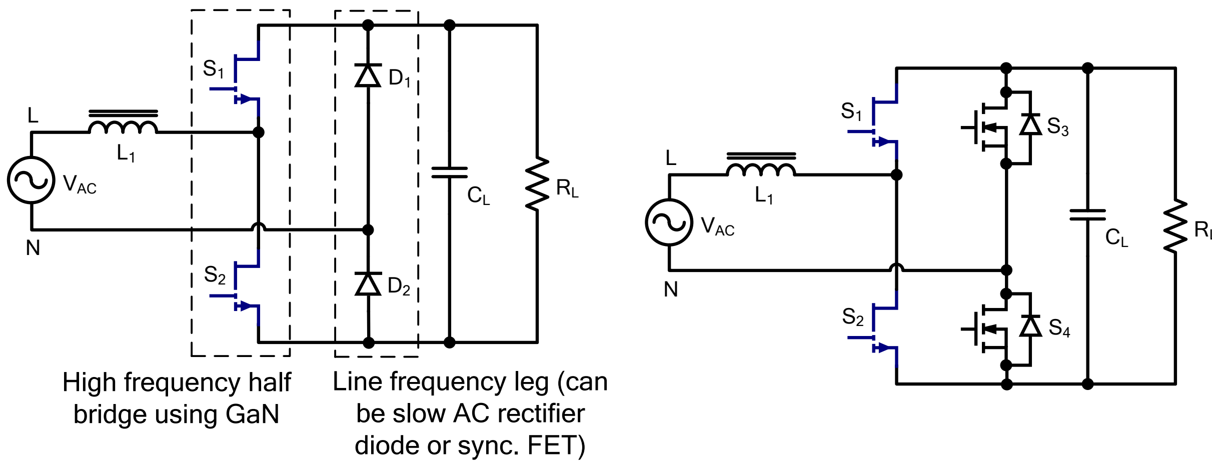


Figure 2.2. 2-phase bridgeless PFC

The topology of the 2-phase bridgeless PFC is shown in Figure 2.2. This topology is essentially two boost legs with each one taking control during each half of the AC cycle. S_1/S_2 are typically superjunction MOSFETs and D_1/D_2 can be diodes, or for higher efficiency, SiC diodes. It has, in the past years, been the popular bridgeless PFC topology on the market because it is easy to implement using conventional Si MOSFETs with control similar to a standard PFC circuit, and efficiency is improved as it eliminates one diode from the current path. However, it comes with following drawbacks:

- **Low power density and component utilization:** it doubles the part counts and each one of the boost stages only works during one half cycle, which reduces the power density and adds to the BOM cost.
- **Additional return diodes:** for EMI purpose, diodes D_3/D_4 are needed to provide a return current path and reference DC link ground to *N* to reduce the common mode noise [2].
- **D_1/D_2 needs to be fast SiC diodes:** higher V_F (conduction loss) and relatively higher cost than AC rectifier diodes.
- **Complicated current sensing circuit:** S_1/S_2 body diodes and D_3/D_4 share the return current.
- **No bidirectional capability:** This PFC topology cannot be utilized in applications that require bidirectional power flow between AC and DC ends. Due to the aforementioned high reverse recovery loss D_1/D_2, cannot be replaced by MOSFETs.

2.2. Bridgeless Totem-Pole PFC



(a) BTPPFC circuit (b) Replace D_1/D_2 with synchronous MOSFETs

Figure 2.3. BTPPFC circuit using GaN

Figure 2.3 shows the topologies of a BTPPFC. It can be considered as a conventional boost PFC in which one half of the diode bridge is replaced by active switches S_1 and S_2 in a half bridge configuration, hence the name "totem pole". The diode D_1/D_2 forms the slow 50/60Hz line frequency leg which can either be slow AC rectifier diodes or can be replaced by low-$R_{DS(on)}$ synchronous MOSFETs for improved efficiency, as shown in Figure 2.3(b).

The BTPPFC overcomes many issues which existed in the previous 2-phase bridgeless PFC and has the following advantages:

- **Improved efficiency:** main current only flows through two switches at a time. S_1/S_2 are driven synchronously with complimentary PWM signals and the S_3/S_4 on the slow line frequency legs can be low $R_{DS(on)}$ Si MOSFETs to further reduce the conduction loss.

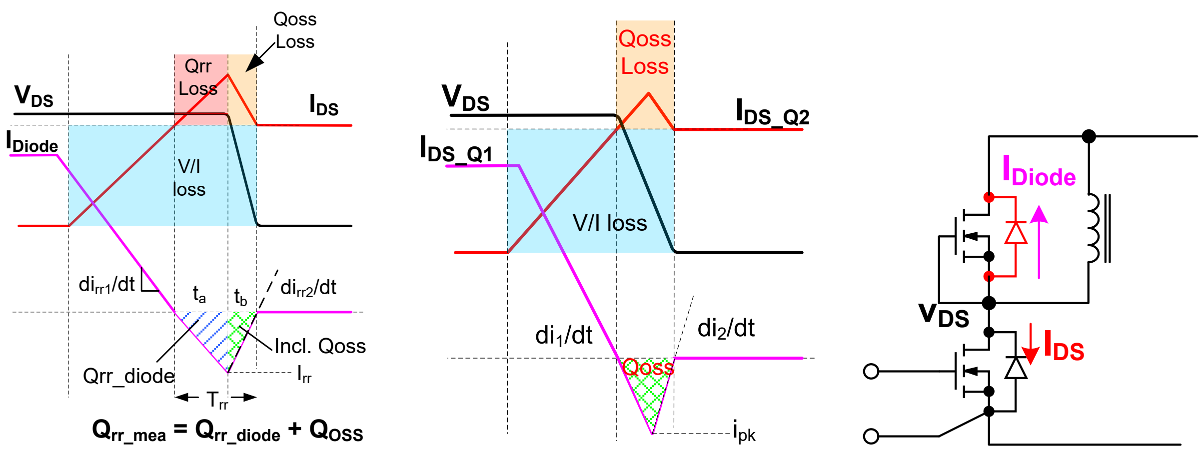
- **Lower part counts, higher power density and lower BOM cost.** It uses fewer parts and has a simpler circuit: It needs only one inductor and neither SiC diodes nor AC return diodes are required.

- **Bidirectional power flow.** BTPPFC is inherently capable of bidirectional operation, which is ideal applications which may require power flow in both directions, such as Energy Storage System (ESS) and on-board bidirectional battery chargers (OBBC).

2.3. Zero Q_{rr} GaN for CCM BTPPFC

BTPPFC has been proposed before but its application has been very limited until recently. The major challenge is the poor reverse recovery performance of conventional silicon MOSFETs in the half bridge configuration, which makes CCM operation impractical due to the excess Q_{rr} loss at turn-on. To avoid body diode conduction, BTPPFC with silicon MOSFETs must work in CrCM/DCM modes, which only fits for lower power and has more complicated control. Usually, multi-phase interleaved configuration is used to get higher power level and improve current ripple, which again adds extra cost and complexity.

The absence of a body diode (zero Q_{rr}) and the fast switching nature of GaN make a GaN HEMT a good fit for CCM hard switching half bridge power stage. As can be seen in Figure 2.4 (a), Q_{rr} measured using standard test methods include both Q_{rr} of the high side body diode and Q_{oss} of the MOSFET, though Q_{rr} usually dominates for Si MOSFETs. By contrast, GaN exhibits significantly lower hard turn-on loss as there is only Q_{oss} loss – the loss induced at hard switching device during turn-on due to the output capacitance charging current of free-wheeling switch.



(a) MOSFET – Q_{rr} loss (b) GaN – Q_{oss} loss only (c) Q_{rr} test circuit

Figure 2.4. Hard turn-on loss breakdown (MOSFET vs GaN)

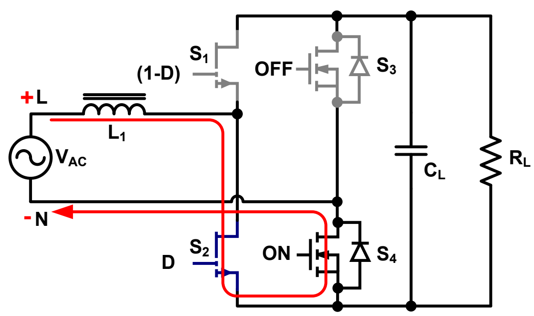
Table 2.1 compares the switch-on loss caused by Q_{rr} (or Q_{oss} for GaN) between a silicon MOSFET and a GaN E-HEMT device from GaN Systems. GaN has zero Q_{rr} and its output capacitance charge can be more than an order of magnitude smaller than 650 V silicon MOSFETs. Even compared to CoolMOS CFD with an ultra-fast body diode, GaN shows much superior reverse recovery performance. Assuming a CCM BTPPFC operating at 50 kHz, GaN dissipates 0.75 W switching loss due to the Q_{oss} loss at turn-on, while a similar CoolMOS CFD2 has about 20 W at switch-on because of the Q_{rr} alone! This excellent hard switching performance makes GaN HEMT the perfect candidate for CCM BTPPFC design.

Table 2.1. Q_{rr}/Q_{oss} Loss Comparison (650 V GaN HEMT vs Si CoolMOS)

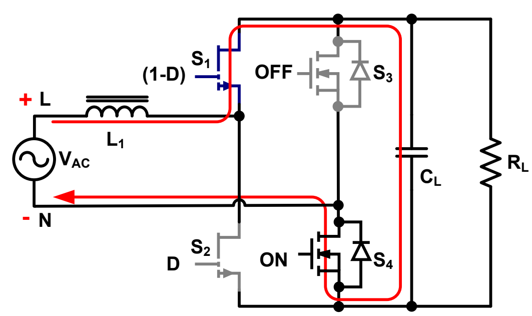
	Si CoolMOS CFD2 w/ Fast Body Diode	GaN HEMT	
	IPW65R080CFD	**GS66508B**	Unit
$R_{DS(ON)}$	**80**	**50**	mΩ
Q_{rr}	**1000**	**0**	nC
Q_{OSS} @ V_{DS}=400V	**318**	**57**	nC
Turn-on loss due to Q_{RR}/Q_{OSS}@F_{SW}=50kHz	**20**	**0.75**	W

2.4. Basic operating principle

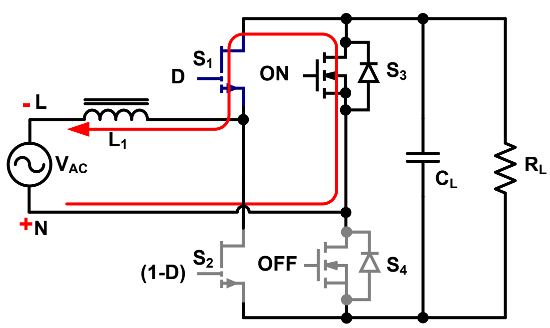
The BTPPFC operates in two modes depending on the polarity of input AC voltage as shown in the Figure 2.5.



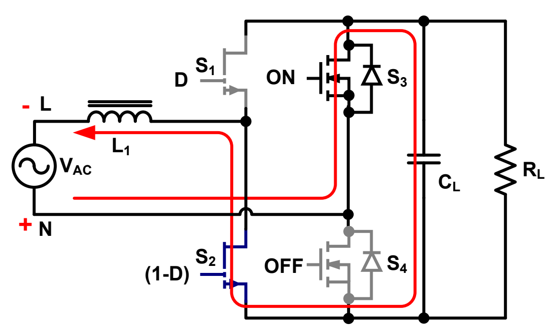
(a) Positive AC half cycle: $t = D$



(b) Positive AC half cycle: t = (1-D)



(c) Negative AC half cycle: $t = D$



(d) Negative AC half cycle: t = (1-D)

Figure 2.5. Current flows in TPPFC during positive and negative AC half cycles

1. During positive half cycle (line > neutral): S_2 is the main switch and S_1 is driven with a complementary PWM signal. S_1/S_2 and L_1 form the boost DC/DC stage. During this positive half cycle, half bridge leg S_4 is turned on and S_3 is always inactive. During the time when the main switch S_2 is turned on, current flows from L_1->S_2->S_4 and back to N. During the

period of (1-D) when S_2 is turned off, S_1 is turned on and current flows through S_1 and back to *N* via S_4. The DC bus ground VDC- is tied to *N* potential as S_4 is conducting all the time.

2. During negative half cycle (neutral > line): the operation in the negative half cycle is similar except the role of top and bottom switches are swapped. Now S_1 becomes the main switch and S_2 is free-wheeling, and S_3 is turned on and S_4 is inactive.

3. Design example

A 3-kW CCM BTPPFC has been built to demonstrate the performance of GaN HEMTs as shown in Figure 3.1. The detailed design specification is shown in Table 3.1.

Table 3.1. 3-kW BTPPFC design specification

Parameter	Value
Input Voltage(V_{in})	**176-264 V_{rms}**
Output Voltage(V_{out})	**400 V**
Maximum Output Power	**3 kW**
Switching Frequency	**65 kHz**
Line Frequency	**50/60 Hz**
Output voltage ripple	**≤5%**
Inductor current ripple	**≤20%**

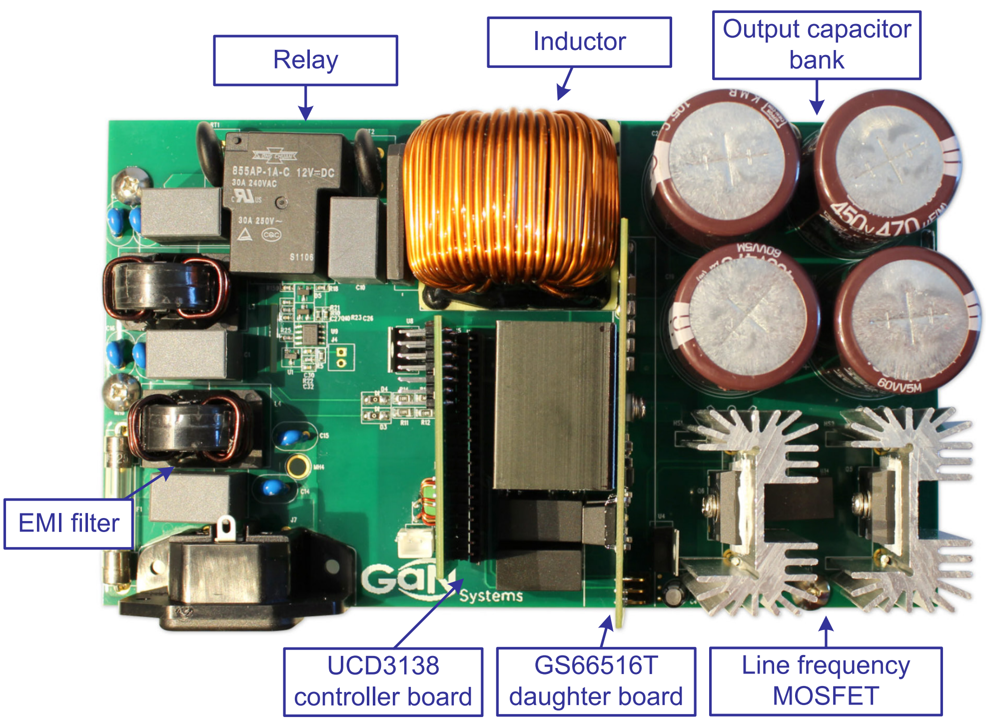


Figure 3.1. 3-kW CCM BTPPFC evaluation board

3.1. System Block Diagram

The designed PFC evaluation board consists of three major parts. They are the PFC controller daughter board, GS66516T half-bridge daughter board, and the mother board. The PFC control chip is the UCD3138 IC chip from Texas Instruments. The GS66516T devices from GaN Systems are chosen for the fast GaN E-HEMT [3]. The IXFH80N65X2 is chosen for the Si MOSFET switches. The system block diagram is shown in Figure 3.2.

The mother board consists of EMI filter, start up circuit, line frequency Si MOSFETs and their gate drive circuits, and voltage and current sensing circuits.

The PFC controller daughter board requires 3.3-V input and it includes current, input line voltage and output voltage sampling pins as inputs. The outputs are 4 PWM pins, in which 2 of them are applied to the GaN half bridge and the other 2 are applied to the line frequency Si MOSFETs.

The GS66516T daughter board needs 5-V input from the mother board. The detailed information for this daughter board can be found in [4].

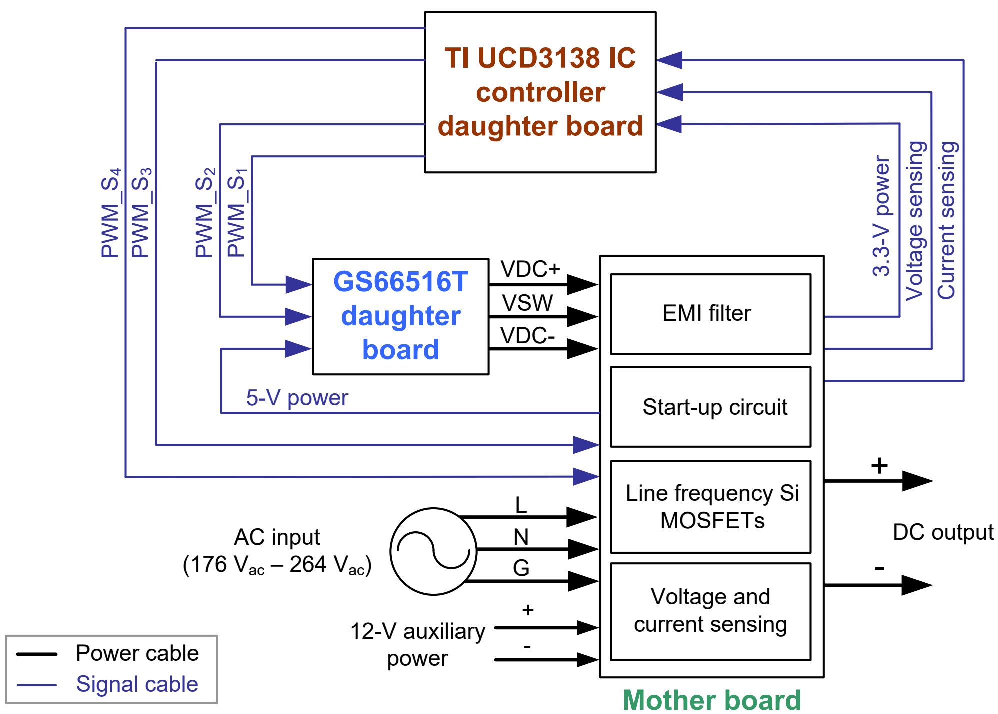


Figure 3.2. System interconnection block diagram

3.2 Control scheme

The average current control is selected. The voltage and current loop control are similar to conventional boost PFC converter. The measured signals are DC output voltage V_{dc}, inductor current i_L, and input voltage V_{acL} and V_{acN}. The inductor current is measured by a shunt resistor. The overall control block diagram is shown in Figure 3.3. A relay is applied to achieve the soft-start function. The AC polarity detection is achieved by measuring the voltage V_{acL} and V_{acN}. The power reference is generated from the output voltage V_{dc} loop. The input current reference can be obtained by multiplying the power reference with the rectified AC input voltage, and divided by the square of input AC RMS voltage. The output from the current loop drives the PWM modulator to generate the gate signals. Therefore, the line current can be tracked to the input voltage waveform as shown in Figure 3.4.

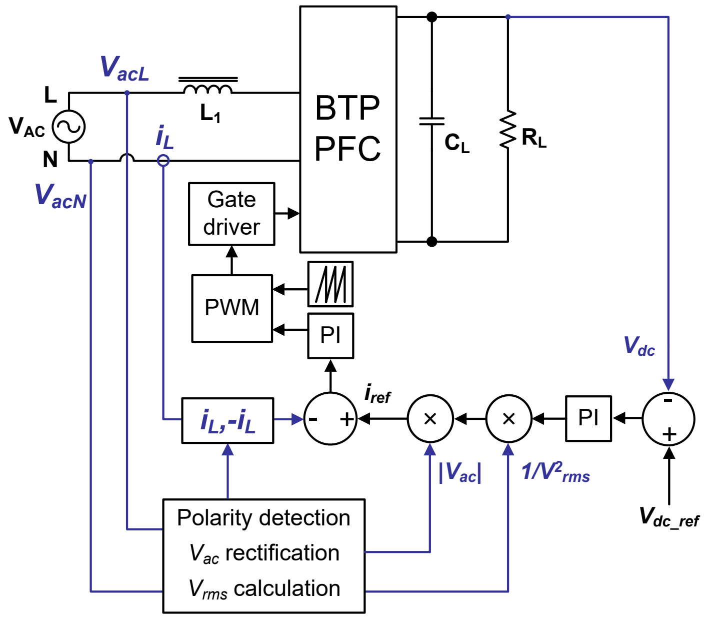


Figure 3.3. Overall control block diagram

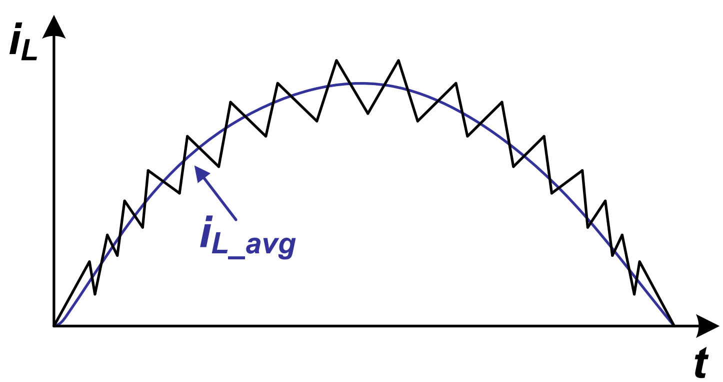


Figure 3.4. Average current mode control scheme

4. Test Setup

4.1 Test equipment

Figure 4.1 shows the basic test setup Gan Systems used to evaluate the GS66516T-based BTPPFC.

The AC input source shall be capable of supplying between 176 V_{ac} and 264 V_{ac} with a line frequency 50-60Hz. A 12-V power supply is needed to supply all the low voltage auxiliary power. The programmable electronic load can be set to either constant current or constant resistance mode. A fan should be used to maintain component temperatures within safe operating ranges at all times during operation. Position the fan so as to blow the heatsink as shown in Figure 4.1.

Note: The GS66516 half-bridge daughter board must be connected tightly with mother board.

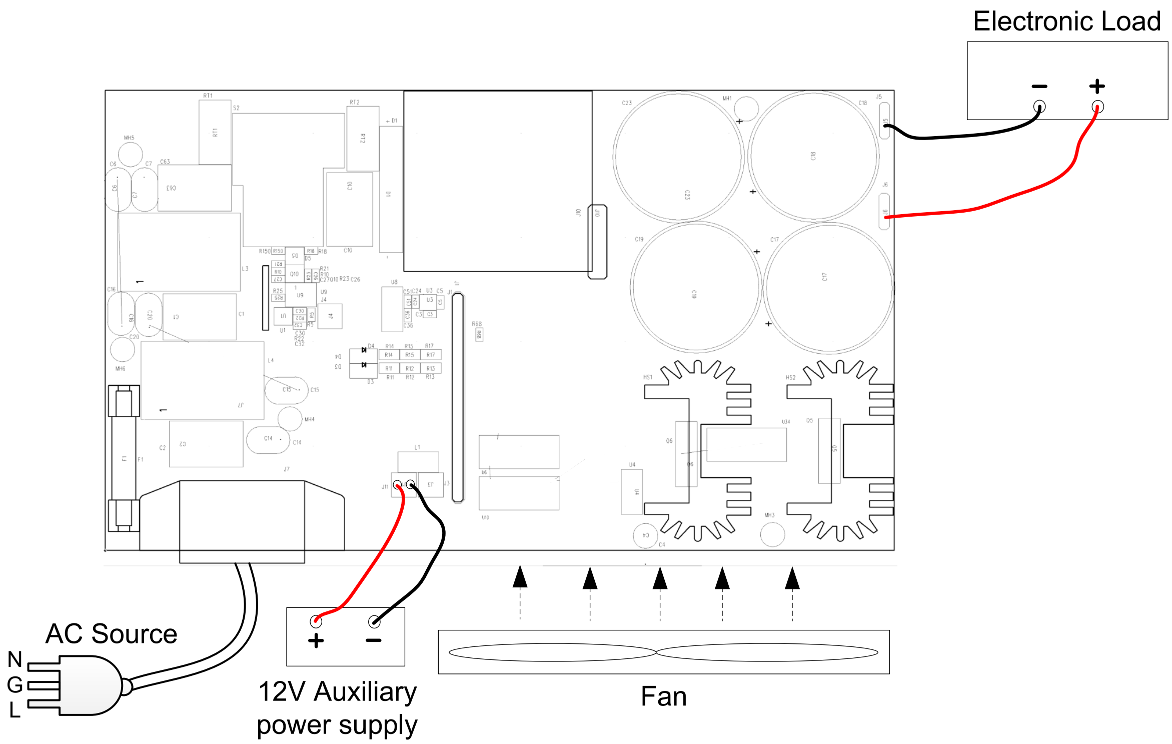


Figure 4.1. Recommended test set up

4.2 Power-up/Power-down Procedure

The following test procedure was used primarily for power up and shutting down the test setup. The module should never be handled while power is applied to it or the output voltage is greater than 50 V_{dc}.

Power-up procedure:

(1) Connect the equipment as shown in Figure 4.1.
(2) Turn on the electronic load.
(3) Turn on the fan.
(4) Turn on the 12-V power supply.
(5) Turn on the AC power input (176 V_{ac} to 264 V_{ac}).

The ***power-down procedure*** is in reverse order of the above procedure,

(1) Turn off the AC power input.
(2) Turn off the 12-V power supply.
(3) Turn off the fan.
(4) Turn off the electronic load.

Note: Once the AC power input is shut down, the 12-V power supply needs to be turned off so that the program in the controller can be restarted fully for the next operation. Otherwise, huge inrush current might be occurred due to the programming disruption at the beginning of the next operation.

5. Test Results

5.1 Efficiency

The measured efficiency curve is shown in Figure 5.1. The peak efficiency reaches 99.1% around 1.4 kW, at 230 V_{ac}, 50 Hz.

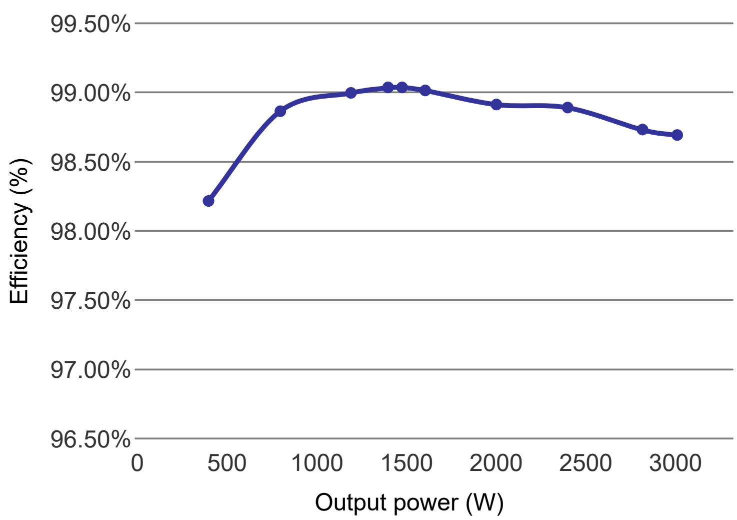


Figure. 5.1. Evaluation board Efficiency at 230 V_{ac}, 50 Hz

5.2 Power factor

The power factor curve is shown in Figure 5.2.

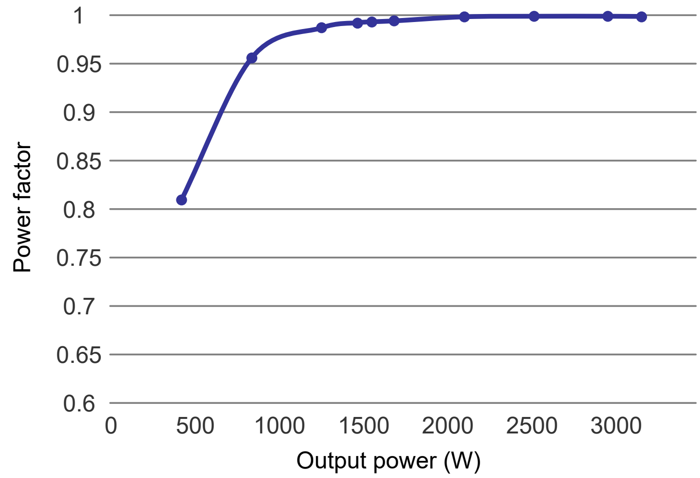
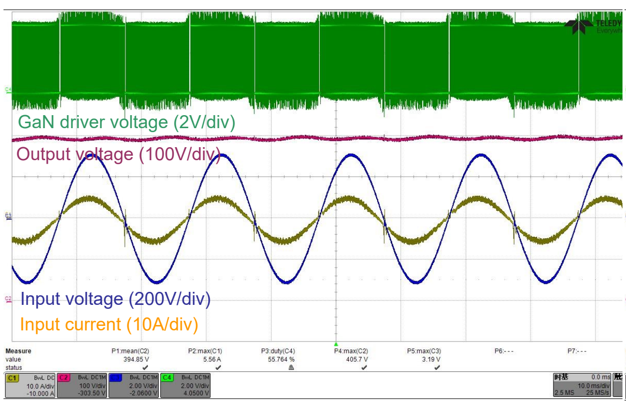
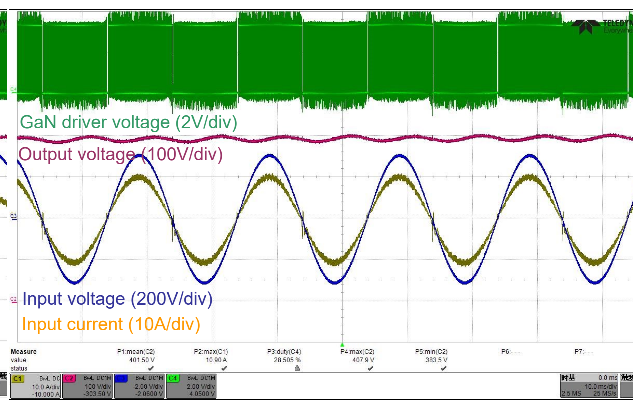


Figure 5.2. Evaluation board power factor at 230 V_{ac}, 50 Hz

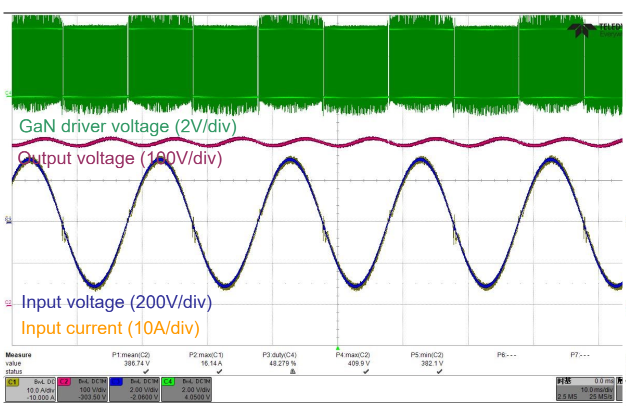
5.3 Waveforms



(a)



(b)



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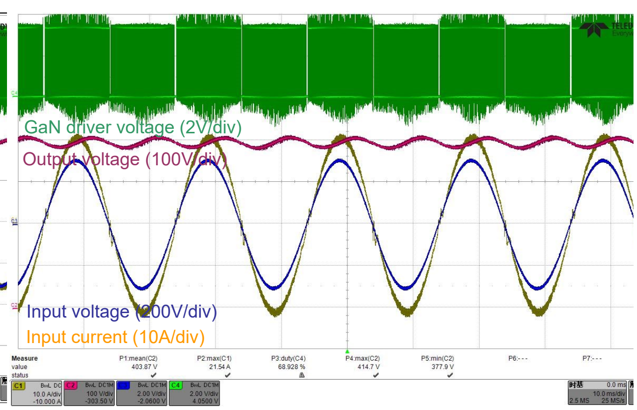


(d)

Figure. 5.3. Evaluation board testing waveforms (a) at 230 V_{ac}, 400 V_{dc} and 2 A_{dc}, (b) at 230 V_{ac}, 400 V_{dc} and 4 A_{dc}, (c) at 230 V_{ac}, 400 V_{dc} and 6 A_{dc}, (d) at 230 V_{ac}, 400 V_{dc} and 7.5 A_{dc}.

The designed evaluation board is able to start up to full load condition as shown in Figure 5.4. In the steady-state, the output voltage and current are 400 V and 7.5 A, respectively.

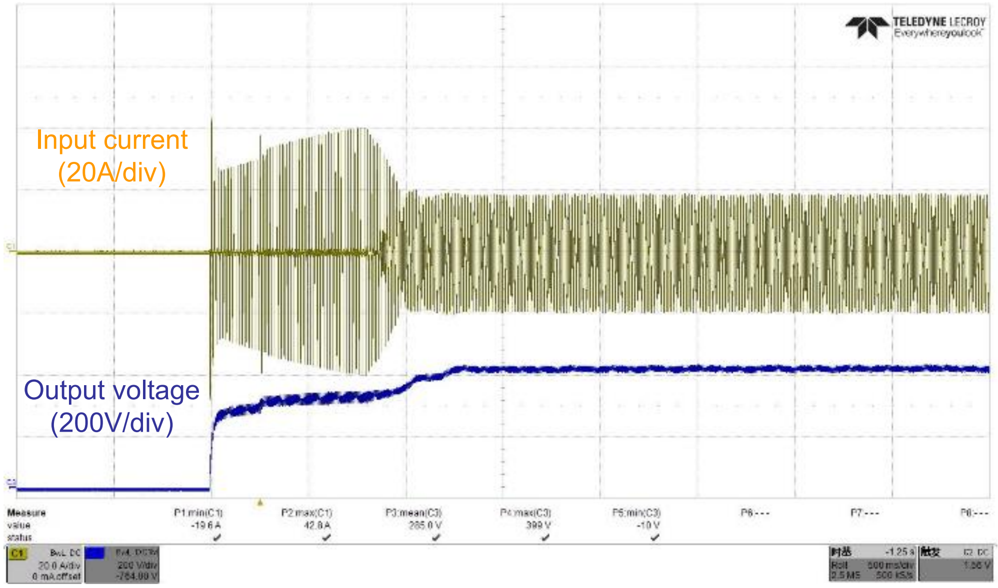
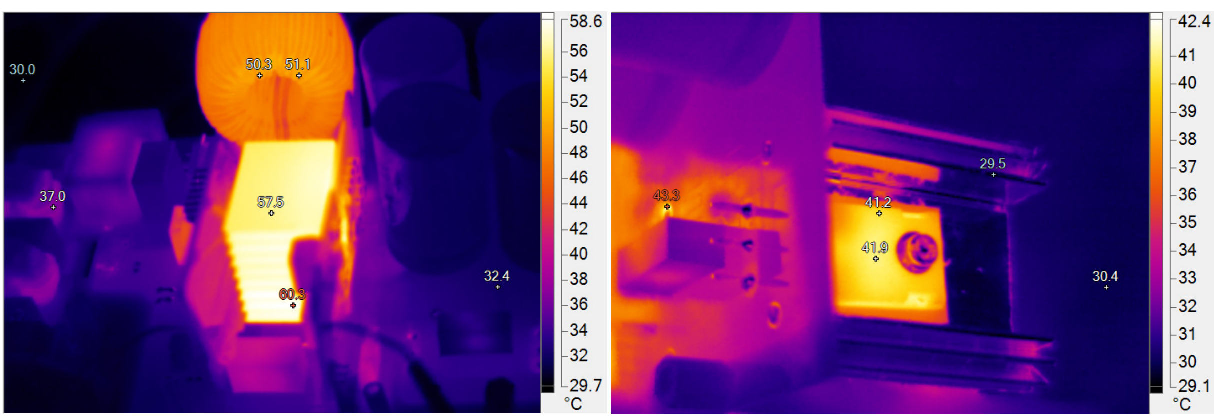


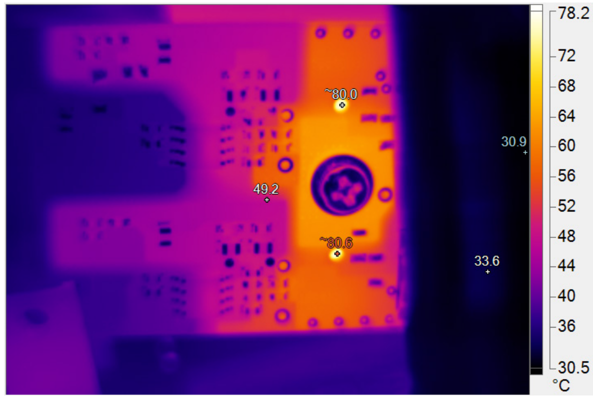
Figure. 5.4. Start up to full load

5.4 Thermal measurement

Thermal testing was performed at 230 V_{ac}, 400 V_{dc} and 7.5 A_{dc} with fan. The ambient temperature was 25 °C. The thermal testing results are shown in Figure 5.5. The inductor temperature is 51.1 °C. The temperatures on the MOSFET and GaN E-HEMT are 41.9 °C and 80.6 °C, respectively.



(a) (b)



(c)

Figure. 5.5. Thermal testing results, (a) Inductor temperature, (b) MOSFET temperature, (c) GaN E-HEMT temperature.

6. Applications

The application scope of this 3-kW GaN E-HEMT-based BTPPFC includes, but is not limited to following,

1. Unidirectional or bidirectional onboard battery charger in electrified vehicle application. The BTPPFC is a promising bidirectional PFC candidate to achieve the bidirectional power flow from grid to vehicle (G2V) and from vehicle to grid (V2G).

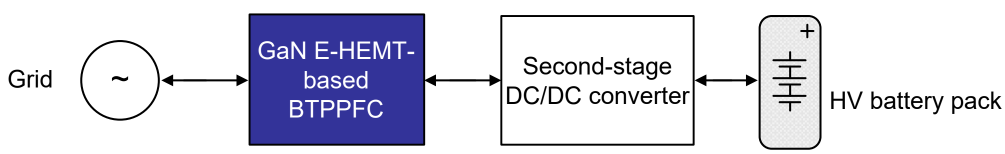


Figure 6.1. Electrified vehicle onboard bidirectional battery charger system

2. Energy storage systems. The BTPPFC can realize the bidirectional interconnection between the grid and an energy storage system to better utilize the harvested energy and optimize the overall system.

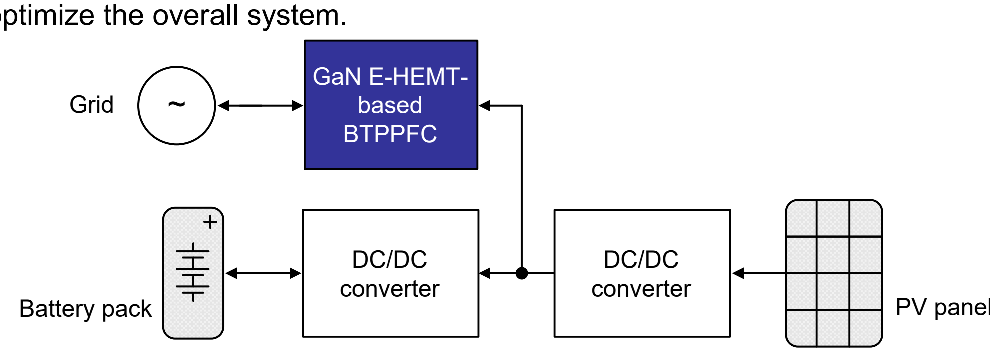


Figure 6.2. Energy storage system

3. Telecom applications. The BTPPFC can also be applied to the telecom applications to increase efficiency, reduce systems size and reduce system BOM cost.

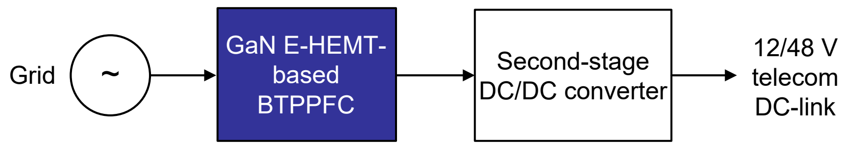


Figure 6.3. Telecom application

7. Conclusion

This application note presents the motivation, operating principle, design considerations of BTPPFC using GaN enhancement mode HEMT (E-HEMT). A 3-kW BTPPFC design example using GaN Systems 650-V GaN E-HEMT is given. The testing results as well as the thermal performance are presented. It is clear that the GaN Systems transistors have certain advantages in the CCM BTPPFC design in terms of power density, efficiency and performance. Several possible application examples based on this BTPPFC are also given.

8. Appendix

8.1 Evaluation board schematics

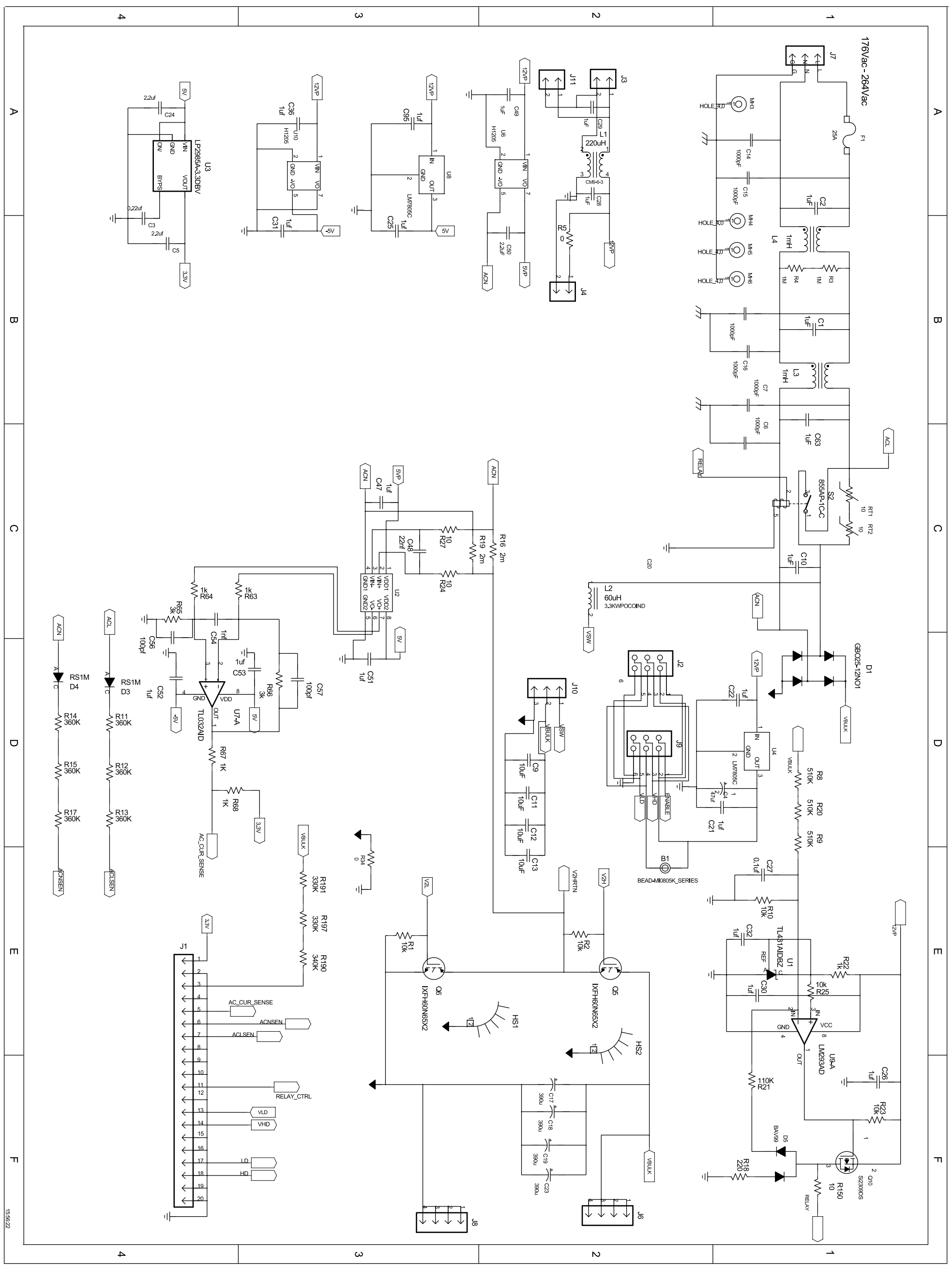


Figure. 8.1. Mother board schematic

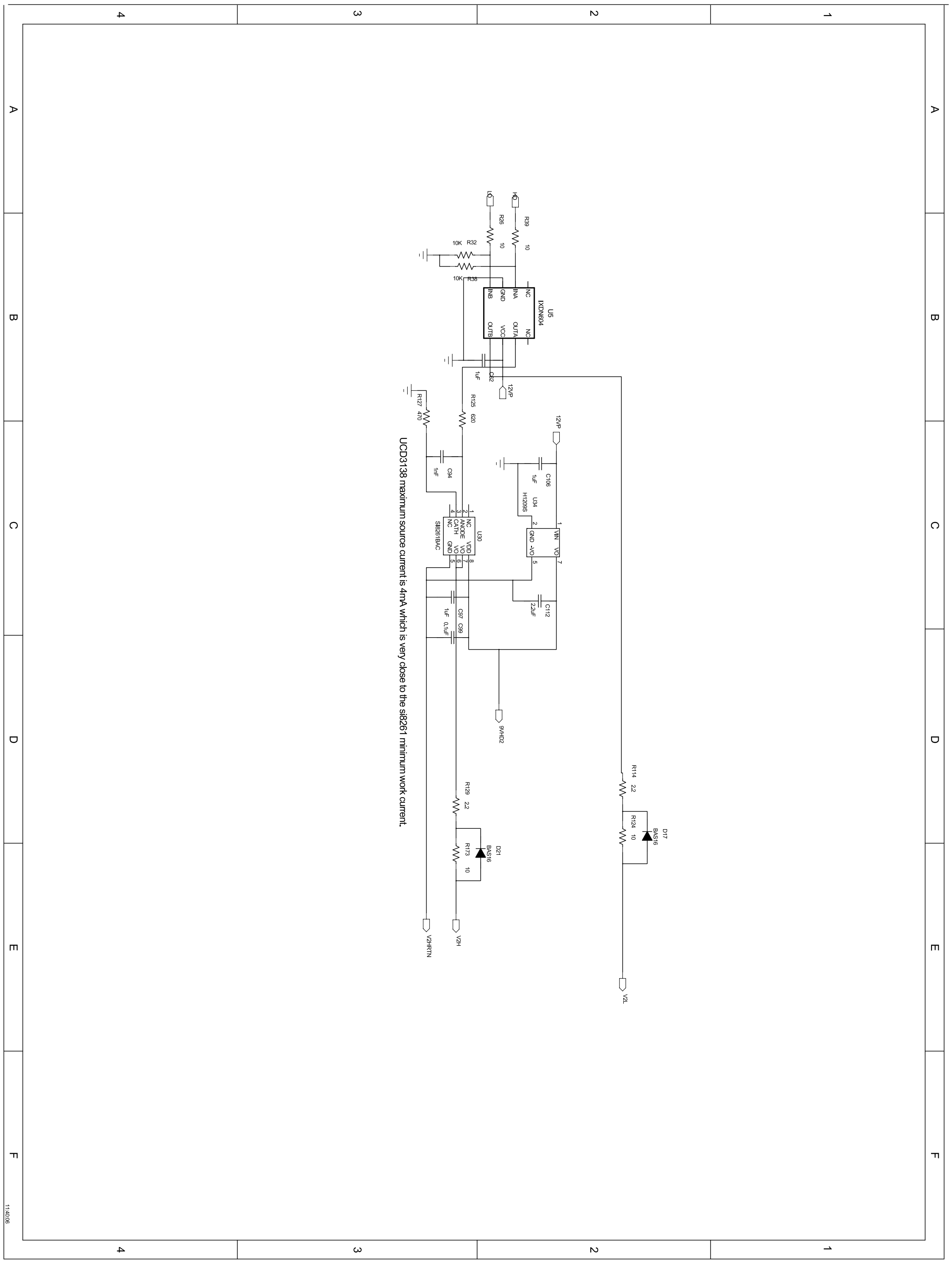


Figure. 8.1. Mother board schematic (Continued)

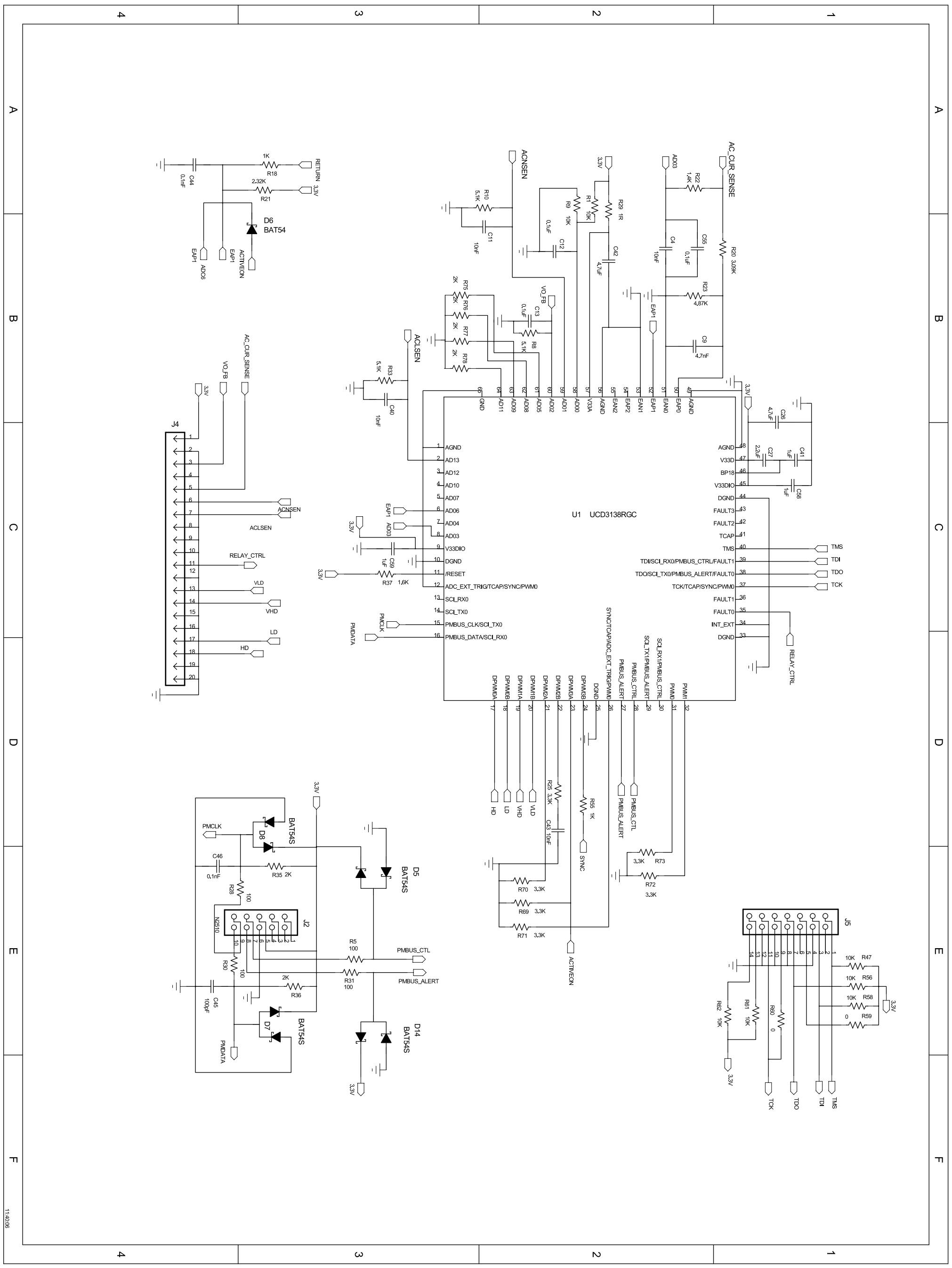
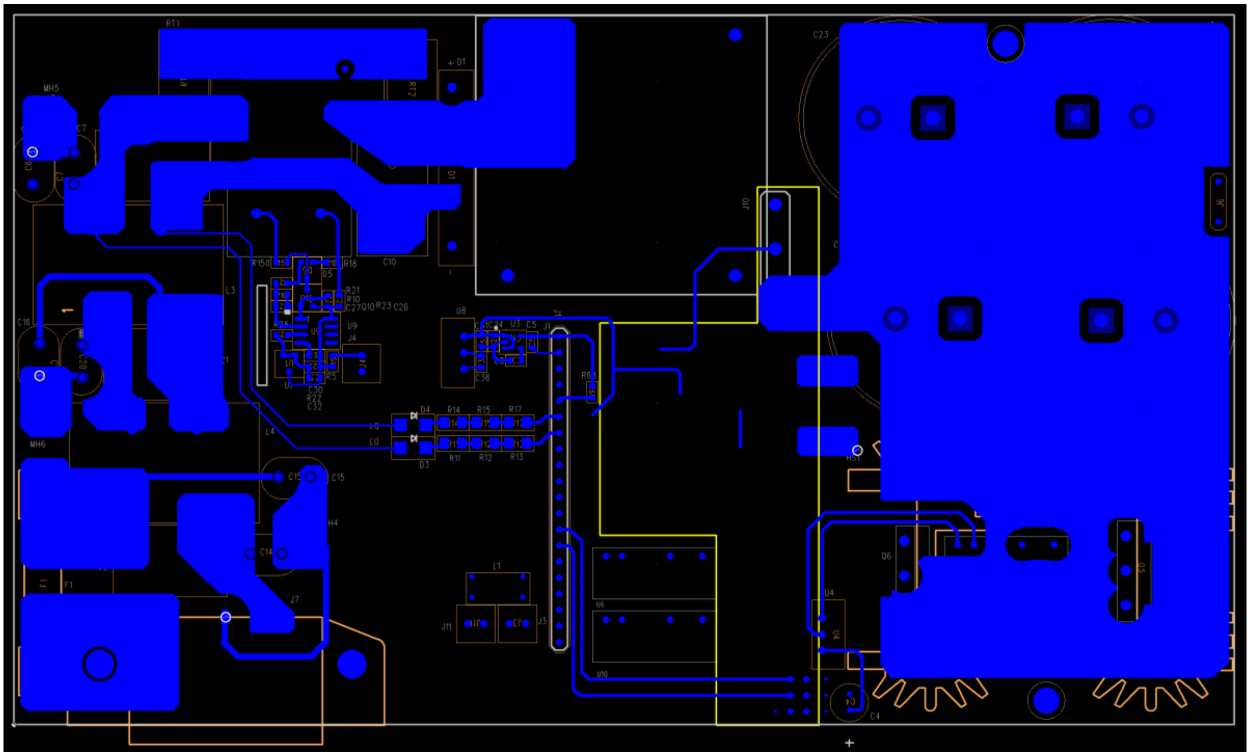


Figure. 8.2. UCD3138 daughter board schematic

8.2 PCB layout



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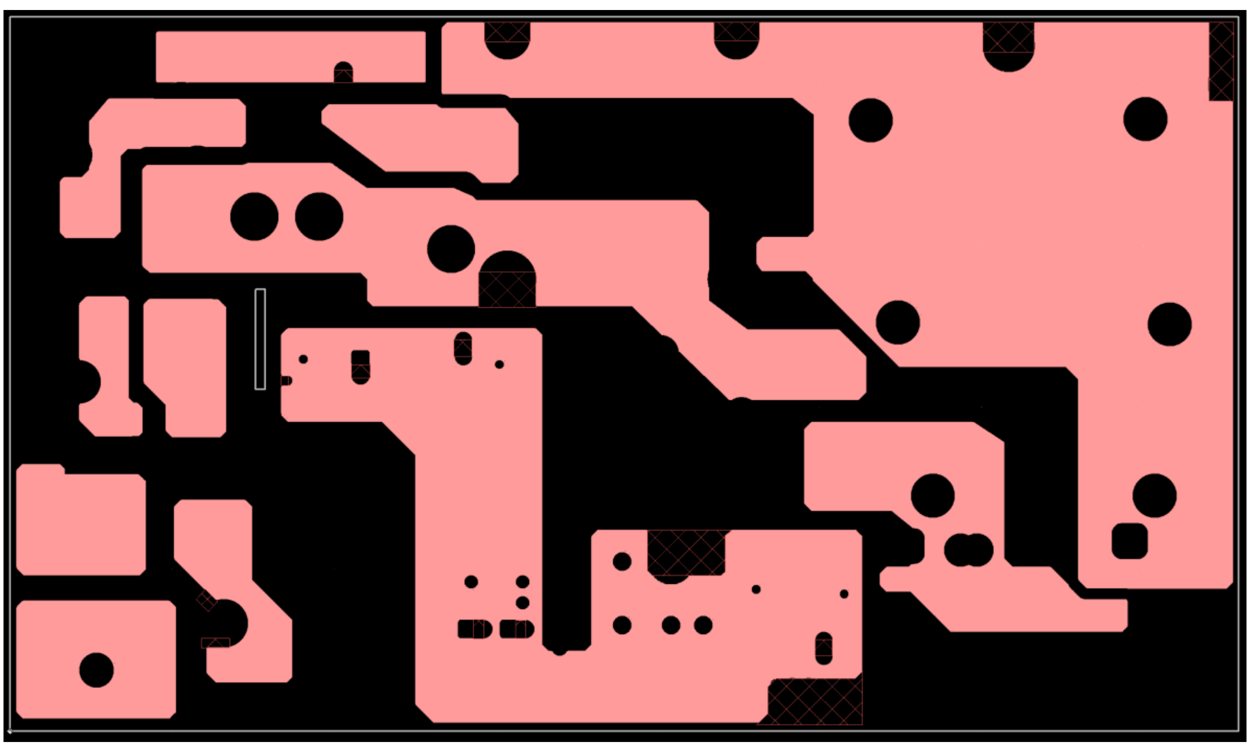

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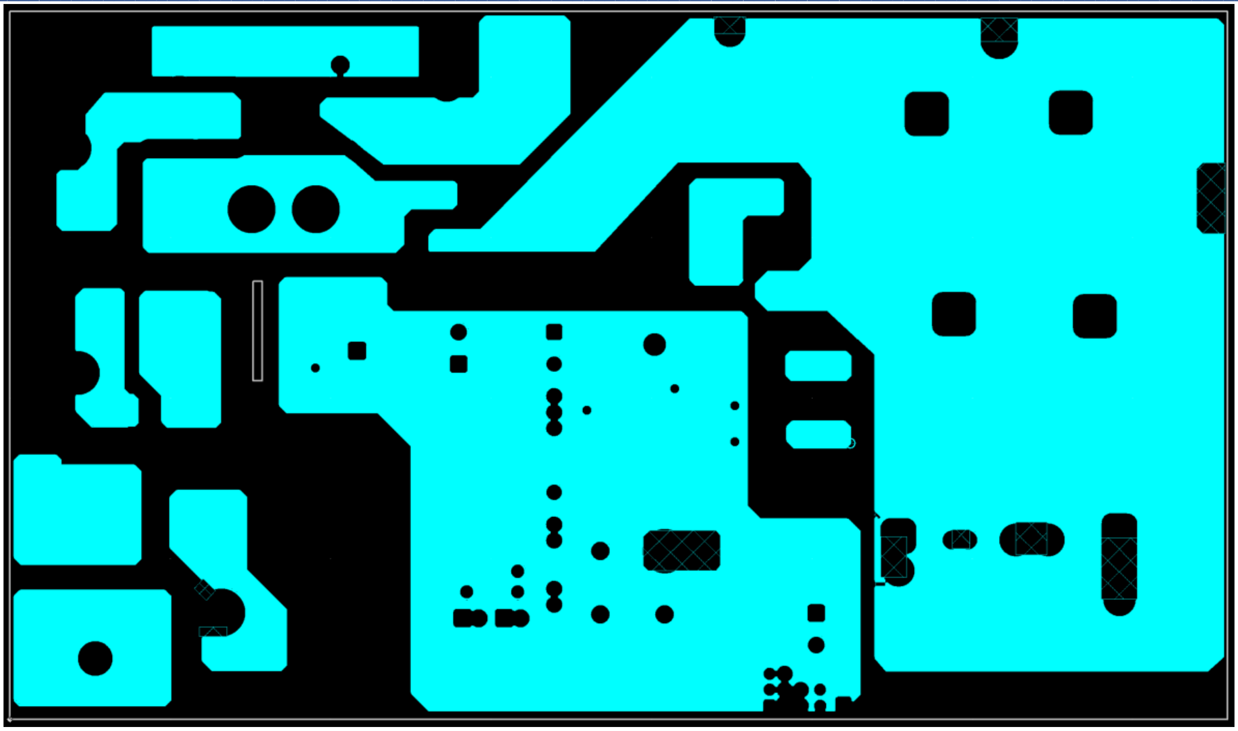

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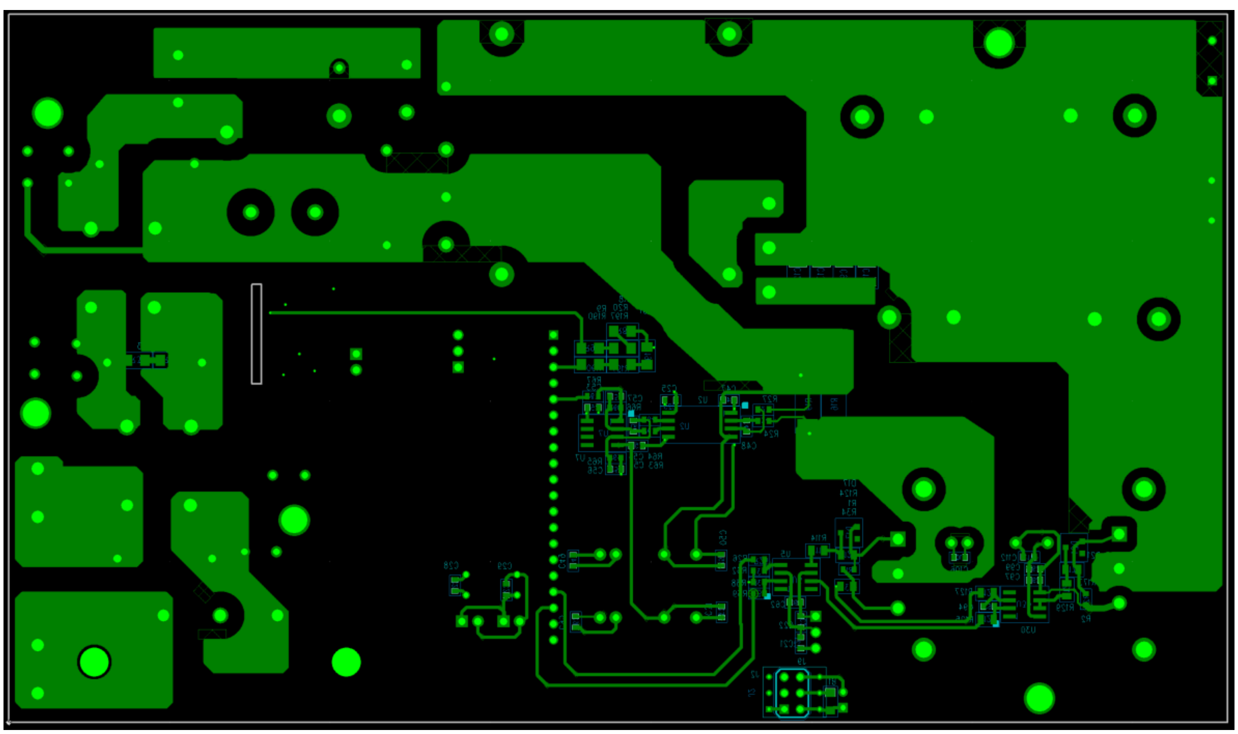
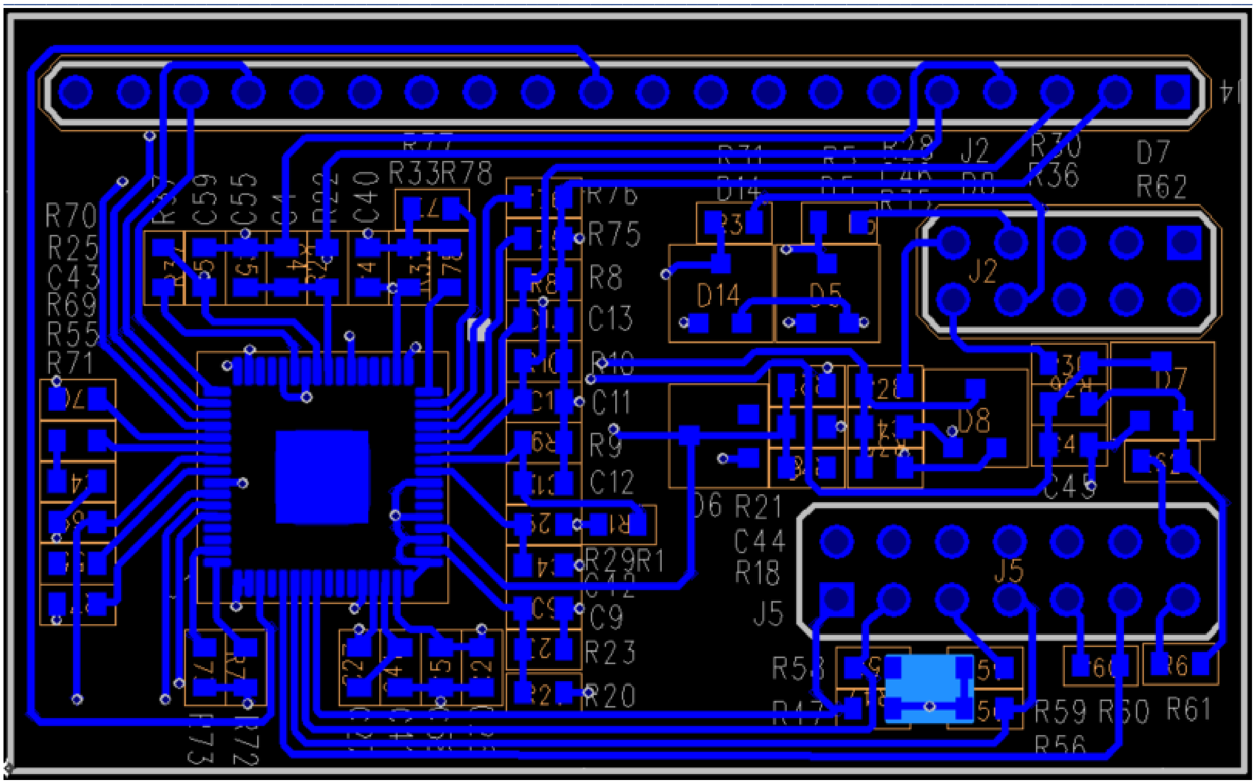


(d)

Figure. 8.3. Mother board PCB layout, (a) top layer, (b) mid layer 1, (c) mid layer 2, (d) bottom layer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R25
C43
R69
R55
R71
R33R78
R75
R8
C13
C11
R9
C12
R29R1
C9
R23
R20
D14
D5
D8
J2
D7
R62
R36
D6 R21
C44
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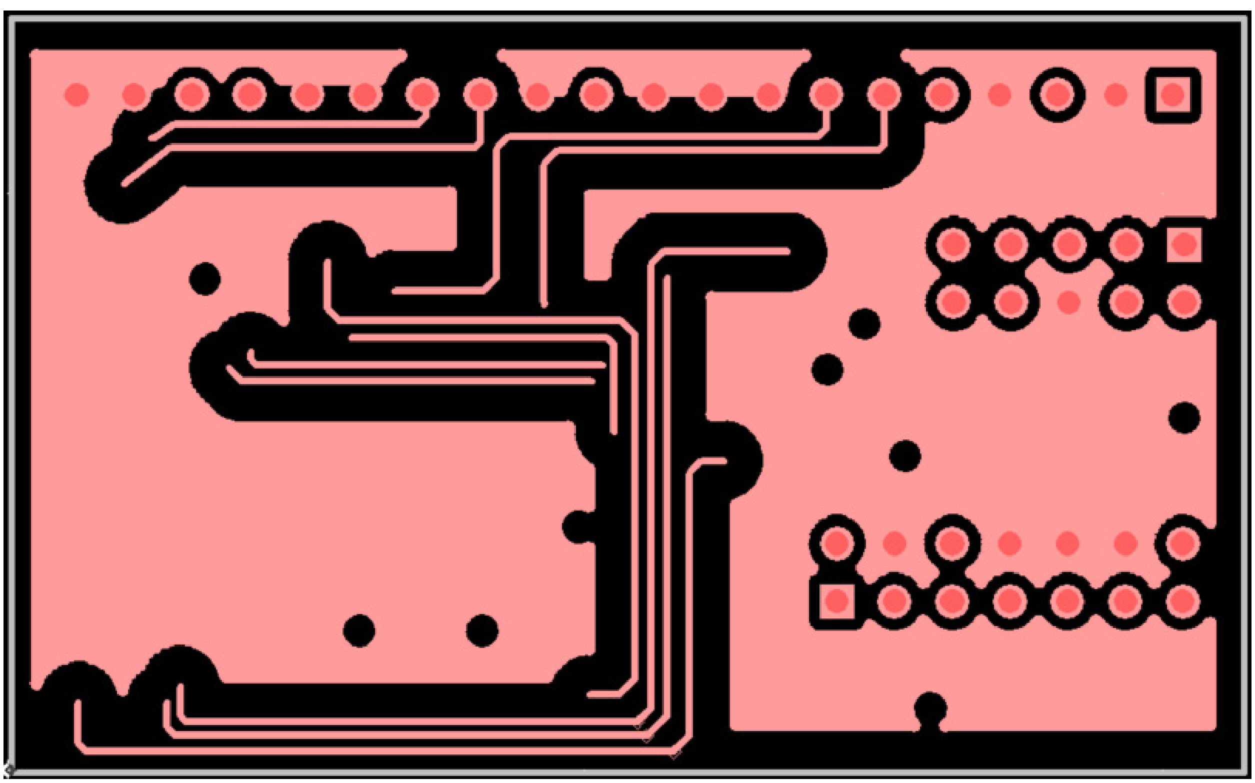
C49
R59
R61
R56

(a)



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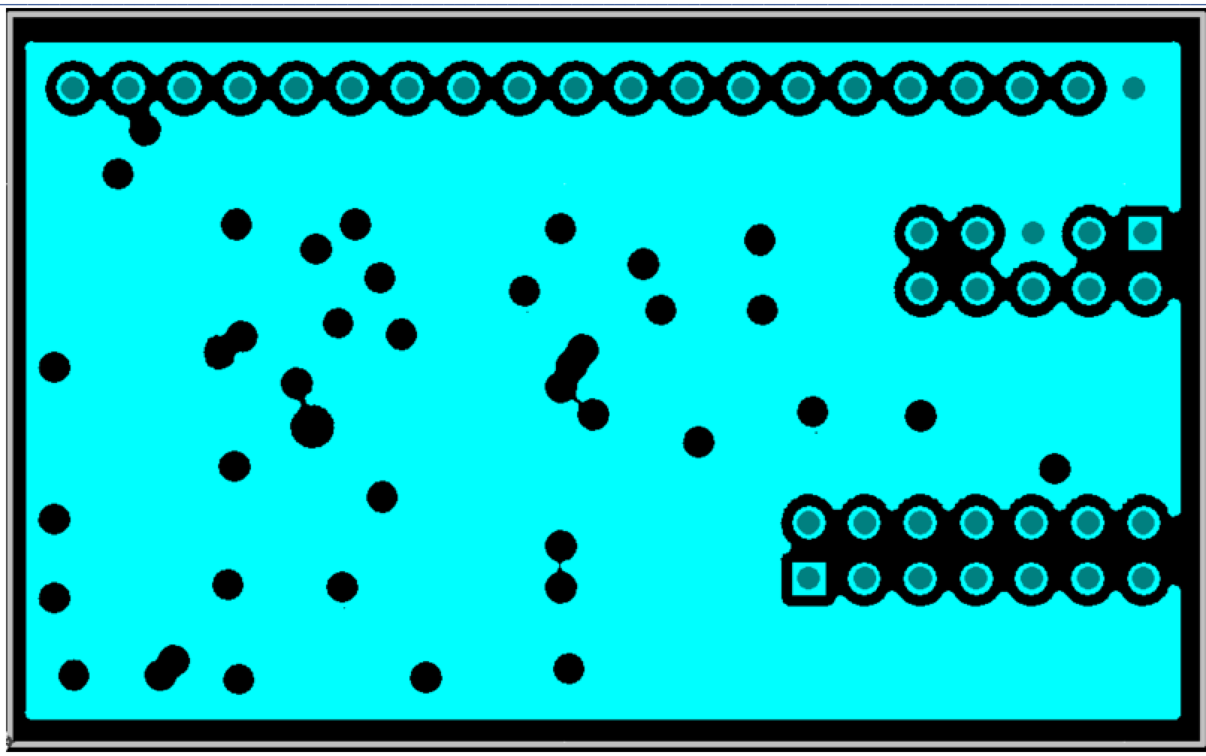

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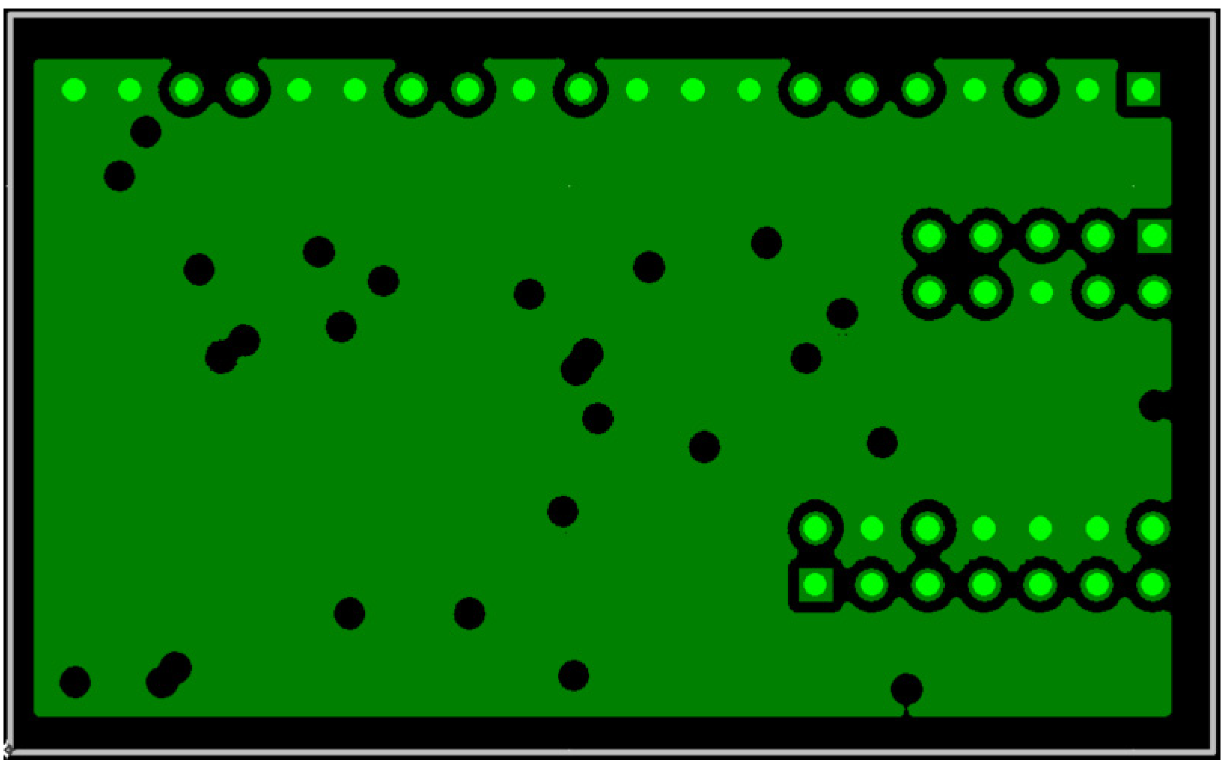

(d)

Figure. 8.4. UCD3138 daughter board PCB layout, (a) top layer, (b) mid layer 1, (c) mid layer 2, (d) bottom layer

8.3 List of materials

Table 8.1. Mother board list of materials

QTY	Ref-Des	Part Number	Description	Manufacturer
2	L3-4	744 804 2001	Inductor, CM Choke	Wurth
1	L2	PI160694V1/MC-35-51	Power Inductor,400uH	POCO/Magtec
1	U2	ACPL-C790	GENERIC 8 PIN DUAL INLINE PACKAGE (DIP) .300 SPACING	Avago
1	B1	BLM21AG471SN1D	Bead, Ferrite, 100mA, 0805	Murata
2	C27,C99	General	Capacitor, Ceramic, 50V, 0.1uF, 0603, X7R, 20%	Std
1	C3	General	Capacitor, Ceramic, 50V, 0.22uF, 0603, X7R, 20%	Std
2	C56-57	General	Capacitor, Ceramic, 50V, 100pF, 0603, X7R, 20%	Std
2	C54,C94	General	Capacitor, Ceramic, 50V, 1nF, 0603, X7R, 20%	Std
19	C28-29,C21-22,C25-26,C30-32 C36,C47,C51-53,C95,C49,C62, C97,C106	General	Capacitor, Ceramic, 50V, 1uF, 0603, X7R, 20%	Std
4	C5,C24,C50,C112	General	Capacitor, Ceramic, 50V, 2.2uF, 0603, X7R, 20%	Std
1	C48	General	Capacitor, Ceramic, 50V, 22nF, 0603, X7R, 20%	Std
4	C9,C11-13	General	Capacitor, Ceramic, 630V, 0.1uF, 1210, X5R, 20%	Std
6	C6-7,C14-16,C20	ECKNVS102MB	Capacitor, Ceramic Disc, 250WV, 1000pF, Y5U	Vishay
4	C17-19,C23	EKMR451VSN471MR45S	Capacitor, 450V,105C 20%	United Chemi-Con
1	C4	UVR1E470MDD1TD	Capacitor, Electrolytic,47uF, 25 VDC	Samxon
1	L1	CM9-6-3,220uH, Minimum current 1A	Inductor, CM Choke Filter	
1	J7	CONN_AC_HP-TYPE,703W-00/54	Connector, AC Board mount, 9mm	Qualtek
2	D17,D21	BAS16	Diode, Switching, 150-mA, 75-V, 350mW	Panjit
1	D5	BAV99	DIODE SW DUAL 75V 350MW SOT23	Panjit
2	D3-4	RS1M	Diode, Rectifier, xx-mA, yy-V	Panjit
2	F1	0315025.HXP	Fuseholder, 1/4" fuses, board mount	Littelfuse Inc
1	D1	GBO25-12NO1	RECT BRIDGE 1PH 1200V SIP	HY
1	U34	H1209S	Power Module	MORNSUN
2	U6,U10	H1205	Power Module	MORNSUN
1	J10	3620-2-32-15-00-00-08-0	Multi-Purpose Terminal Pin	Mill-Max
1	J1	PEC20SBAN	Header, Male 20-pin, 100mil spacing,	Sullins Connector Solutions
2	J2,J9	PEC03DBAN	Header, Male 2x3-pin, 100mil spacing	Sullins Connector Solutions

Table 8.1. Mother board list of materials (Continued)

QTY	Ref-Des	Part Number	Description	Manufacturer
3	J3-4,J11	70543-0001	Header, Shrouded 2-pin, 100mil spacing	Molex
2	HS1-2	FL37-009	TO247 Heatsinker 40mm Height	Shenzhen Fengling Radiator Manufacturer
4	MH3-6	HOLE_4.0		
1	U5	IXDN604SIA	IC, 4A Dual Output Driver	IXYS
2	J6,J8	NA	Soldering Hole	
1	U9	LM293AD,LM293AD	IC, Dual Differential Comparators, 2-36 Vin	TI
2	U4,U8	LM7805C	5 VOLT, VOLTAGE REGULATOR	TI
1	U3	LP2985A-3.3DBV	IC, 150 mA Low-Noise LDO Regulator With Shutdown, vv V	TI
4	C1-2,C10,C63	890324026027CS	Capacitor, X2 Cap 275Vac 1uF	Wurth Electronics
1	S2	855AP-1A-C	Relay 30A	Songchuan
1	R5	General	Resistor, Chip, 0 ohm, 0603, 1/10-W, 1%	Std
3	R24,R27,R150	General	Resistor, Chip, 10 ohm, 0603, 1/10-W, 1%	Std
5	R1-2 R10 R23 R25	General	Resistor, Chip, 10k ohm, 0603, 1/10-W, 1%	Std
1	R21	General	Resistor, Chip, 110k ohm, 0603, 1/10-W, 1%	Std
5	R22,R63-64,R67-68	General	Resistor, Chip, 1k ohm, 0603, 1/10-W, 1%	Std
1	R18	General	Resistor, Chip, 220 ohm, 0603,1/10-W, 1%	Std
2	R65-66	General	Resistor, Chip, 3k ohm, 0603, 1/10-W, 1%	Std
1	R4	General	Resistor, Metal Film, 1M ohm, 1206, 1/4 watt, 1%	Std
2	R26,R39	General	Resistor, Chip, 10 ohm, 0603, 1/8W, 1%	Std
2	R32,R38	General	Resistor, Chip, 10k ohm, 0603, 1/8W, 1%	Std
1	R34	General	Resistor, Chip, 0 ohm, 0805, 1/8W, 1%	Std
2	R124,R173	General	Resistor, Chip, 10 ohm, 0805, 1/8W, 1%	Std
2	R114,R129	General	Resistor, Chip, 2.2 ohm, 0805, 1/8W, 1%	Std
1	R127	General	Resistor, Chip, 470 ohm, 0805, 1/8W, 1%	Std
1	R125	General	Resistor, Chip, 620 ohm, 0805, 1/8W, 1%	Std
2	R191,R197	General	Resistor, Metal Film, 330k ohm, 1206, 1/4 watt, 1%	Std
1	R190	General	Resistor, Metal Film, 340k ohm, 1206, 1/4 watt, 1%	Std
6	R11-15,R17	General	Resistor, Metal Film, 360k ohm, 1206, 1/4 watt, 1%	Std

Table 8.1. Mother board list of materials (Continued)

QTY	Ref-Des	Part Number	Description	Manufacturer
3	R8-9,R20	General	Resistor, Metal Film, 510k ohm, 1206, 1/4 watt, 1%	Std
1	R3	General	Resistor, Metal Film, 1M ohm, 1206, 1/4 watt, 5%	Std
2	R16,R19	General	Resistor, Chip, 2M ohm, 2512, 1W, 1%	Std
1	U30	SI8261BAC	Opto Isolate Driver	Avago
2	RT1-2	NTC 5D-20	Thermistor, NTC, 5 ohms, 7A	
1	U1	TL431AIDBZ	IC, Precision Adjustable Shunt Regulator	TI
1	U7	TLC272CD	IC, Dual Op Amp, Single Supply 5V	TI
2	Q5-6	IXFH80N65X2	Transistor, Nch Insulated Gate Mosfet, 80A, 650V	IXYS
1	Q10	TR-SI2301DS,Si2309DS	MOSFET, P-ch, -60V, -1.25A, 550 milliohms	NXP

Table 8.2. UCD3138 daughter board list of materials

QTY	Ref-Des	Part Number	Description
4	C4, C11,C40,C43	General	Capacitor, 10nF, 0603
1	C9	General	Capacitor, 4.7nF, 0603
3	C12-13,C55	General	Capacitor, 0.1uF, 0603
2	C26,C42	General	Capacitor, 4.7uF, 0603
1	C27	General	Capacitor, 2.2uF, 0603
3	C41,C58-59	General	Capacitor, 1uF, 0603
3	C44-46	General	Capacitor, 0.1nF, 0603
4	R5,R28,R30-31	General	Resistor, 100 ohm, 0603_1%
3	R8,R10,R33	General	Resistor, 5.1K ohm, 0603_1%
6	R1,R9,R47,R56,R58, R61-62	General	Resistor, 10K ohm, 0603_1%
2	R18,R55	General	Resistor, 1K ohm, 0603_1%
1	R20	General	Resistor, 3.09K ohm, 0603_1%
1	R21	General	Resistor, 2.32K ohm, 0603_1%
1	R22	General	Resistor, 1.4K ohm, 0603_1%
1	R23	General	Resistor, 4.87K ohm, 0603_1%
1	R25	General	Resistor, 3.3K ohm, 0603_1%
1	R29	General	Resistor, 1 ohm, 0603_1%
2	R35,R36	General	Resistor, 2K ohm, 0603_1%
1	R37	General	Resistor, 1.6K ohm, 0603_1%
2	R59-60	General	Resistor, 0 ohm, 0603_1%
5	R69-73	General	Resistor, 3.3K ohm, 0603_1%
4	R75-78	General	Resistor, 2K ohm, 0603_1%
1	U1	UCD3138RGC	UCD3138RGC
4	D5,D7,D8,D14	BAT54S	D-BAT54S
1	D6	BAT54	D-BAT54
1	J2	PEC05DAAN	HEADER_2X5
1	J4	PEC20SAAN	HEADER_1X20
1	J5	PEC07DAAN	HEADER_2X7
1	J2	PEC05DAAN	HEADER_2X5

Reference

[1] Z. Ye, A. Aguilar, Y. Bolurian, and B. Daugherty, "GaN FET-Based High CCM Totem-Pole Bridgeless PFC," 2014/2015 Texas Instruments Power Supply Design Seminar, [Online]. Available: http://edu.21ic.com/uploads/down/edu/2015/1447033762_2508.pdf

[2] L. Huber, Y. Jang, and M. M. Jovanovic, "Performance evaluation of bridgeless PFC boost rectifiers," *IEEE Transactions on Power Electronics*, vol. 23, no. 3, pp. 1381-1390, May 2008.

[3] GaN Systems, GS66516T top-side cooled 650 V E-mode GaN transistor datasheet, 2016, [Online].Available: http://www.gansystems.com/datasheets/GS66516T%20DS%20Rev%20161007.pdf

[4] GaN Systems, GS66508T/GS66516T-EVBDC 650V GaN E-HEMT Evaluation Board User's Guide, 2016, [Online]. Available: http://gansystems.com/evaluationboards/GS665xxT-EVBDB_UserGuide_rev_20161014.pdf.

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