3kW High-Efficiency CCM Bridgeless Totem Pole PFC Reference Design using GaN E-HEMTs

Reference Design
Technical Manual

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Table of Contents

3kW High-Efficiency CCM Bridgeless Totem Pole PFC Reference Design using GaN E-HEMTs.................1
1. Introduction 3
2. Why a GaN-based bridgeless PFC? 3
  2.1. 2 Phase Bridgeless PFC 4
  2.2. Bridgeless Totem Pole PFC 5
  2.3. Zero Q_{rr} GaN for CCM BTPPFC 6
  2.4. Basic operating principle 7
3. Design example 8
  3.1. System Block Diagram 9
  3.2. Control scheme 10
4. Test Results 11
 12
5. Applications 14
6. Conclusion 15
7. Appendix A – Schematics 16
  7.1. Motherboard Schematics 16
  7.2. PFC Controller Daughter Board Schematic 17
  7.3. GaN E-HEMT Driver Board schematic 18
  7.4. Auxiliary power Board schematic 19
8. Appendix B – Layout 20
  8.1. PCB Layout - Motherboard 20
  8.2. PCB layout – PCB Controller Daughter board 24
  8.3. PCB layout - GaN E-HEMT Driver Board 26
  8.4. PCB layout - Auxiliary Power Board 28
9. Appendix C – List of Materials 29
  9.1. List of materials - Motherboard 29
  9.2. List of Materials - PFC Controller Card 32
  9.3. List of Materials - GaN E-HEMT Driver Board 34
  9.4. List of Materials - Auxiliary Power Board 34

1. Introduction

This application note highlights the motivation, operating principle, and design considerations of Bridgeless Totem Pole PFC (BTPPFC) using GaN Enhancement-mode HEMTs (E-HEMTs). The design of a 3kW BTPPFC example using GaN Systems' 650V GaN E-HEMTs is presented in detail.

2. Why a GaN-based bridgeless PFC?

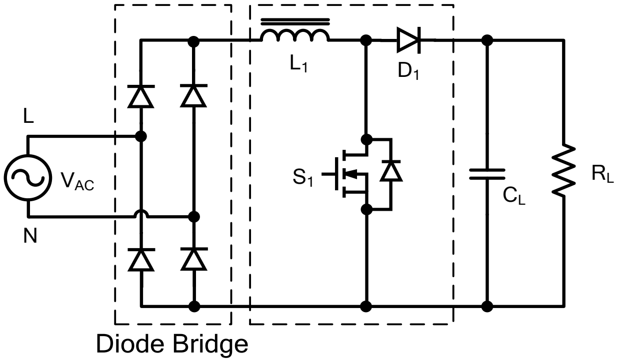


Figure 1. Conventional boost PFC circuit

A conventional PFC circuit is shown in Figure 1. It consists of a full bridge rectifier and a boost pre-regulator. The boost stage can be Continuous Conduction Mode (CCM) or Discontinuous Conduction Mode/Critical Conduction Mode (DCM/CrCM) with zero/valley voltage switching for improved efficiency.

However, a large portion of system loss is in the **diode bridge** and can not be avoided even with zero voltage switching on the Boost stage. This inherently limits the peak efficiency of the conventional PFC circuit. A rectifier diode has a typical 1V forward voltage drop, and there are two diodes in the current path, which could account for 2% of total efficiency loss. A well-designed PFC stage can achieve an efficiency of approximately 97 to 98%, but an 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 a half-load efficiency of 94% at low line and 96% at high line. Considering the typical DC/DC stage efficiency is about 97.5%, 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, allowing for efficiencies of 99% or higher to meet the 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. 2 Phase Bridgeless PFC

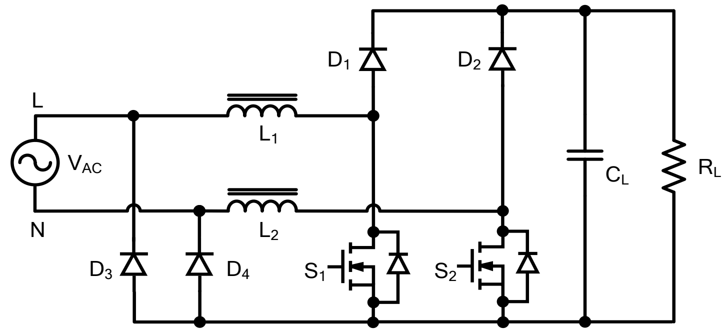


Figure 2. Two-phase bridgeless PFC

The topology of the 2-phase bridgeless PFC is shown in Figure 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 super junction 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 the following drawbacks:

- **Low power density and component utilization:** The part count is doubled, and each boost stage only works during a one-half cycle, which reduces the power density and adds to the BOM cost.

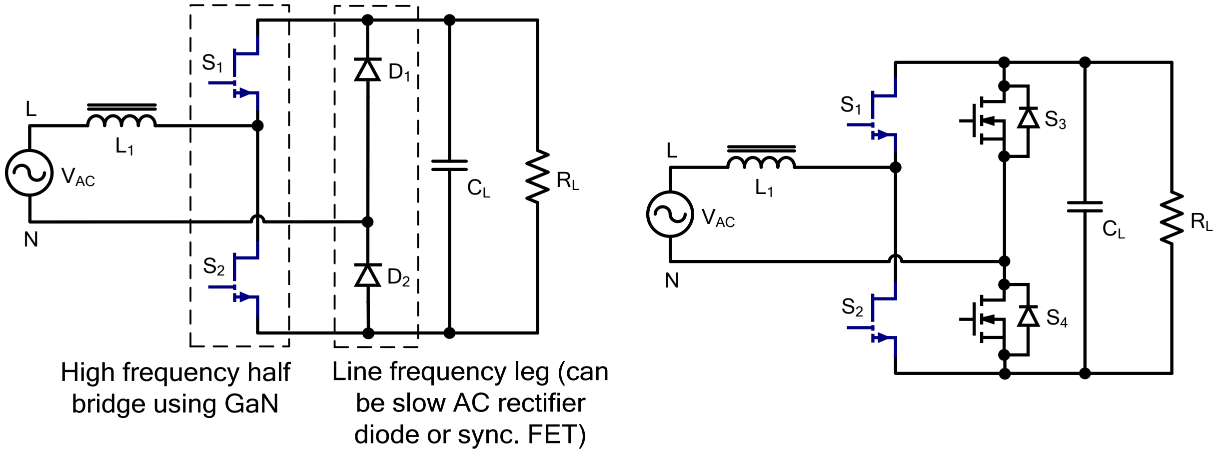
- **Additional return diodes:** for EMI purposes, diodes D_3/D_4 are needed to provide a current return path and reference DC-link ground to *N* to reduce the common-mode noise [2].

- **D_1/D_2 needs to be fast SiC diodes:** These SiC diodes have a 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, can not be replaced by MOSFETs.

2.2. Bridgeless Totem Pole PFC



(a) BTPPFC circuit

(b) Replace D_1/D_2 with synchronous MOSFETs

Figure 3. A BTPPFC circuit using GaN E-HEMTs

Figure 3. shows the topologies of a BTPPFC. It can be considered 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-Rds(on) synchronous MOSFETs for improved efficiency, as shown in Figure 3.(b).

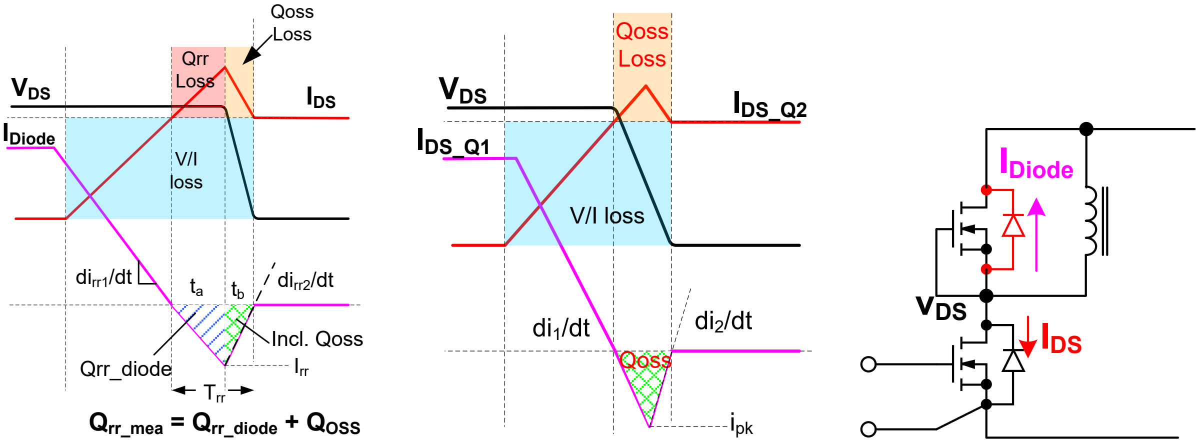
The BTPPFC overcomes many issues which existed in the previous two-phase bridgeless PFC, and has the following advantages:

- **Improved efficiency:** The main current only flows through two switches at a time. S_1/S_2 are driven synchronously with complementary PWM signals, and the S_3/S_4 on the slow line frequency legs can be low Rds(on) Si MOSFETs to further reduce the conduction loss.
- **Lower part counts, higher power density, and lower BOM cost.** It is a simpler circuit that uses fewer parts: It needs only one inductor, and neither SiC diodes nor AC return diodes are required.
- **Bidirectional power flow.** The BTPPFC is inherently capable of bidirectional operation. It is ideal for applications that require power flow in both directions, e.g., Energy Storage System (ESS) and onboard bidirectional battery chargers (OBBC).

2.3. Zero Q_{rr} GaN for CCM BTPPFC

The BTPPFC has been proposed before, but its application has been minimal until recently. The major challenge is the poor reverse recovery performance of conventional silicon MOSFETs in the half-bridge configuration. It 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 is only suitable for lower power and has more complicated control. Usually, a multi-phase interleaved configuration is used to achieve a higher power level and increases the current ripple, which again adds cost and complexity.

The absence of a body diode (zero Q_{rr}) and the fast switching speed of GaN make GaN E-HEMTs an ideal fit for CCM hard switching half-bridge power stage. As can be seen in Figure 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 E-EHMTs exhibit 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 the free-wheeling switch.



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

Figure 4. Hard turn-on loss breakdown (MOSFET vs. GaN)

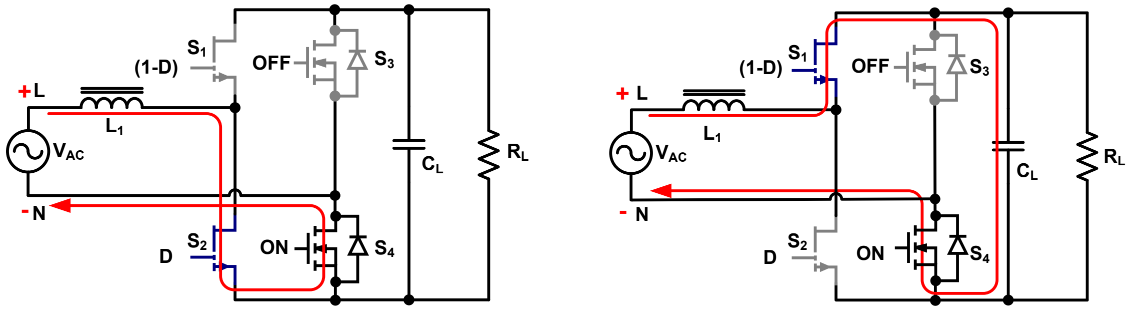
Table 1 compares the switch-on loss caused by Q_{rr} (or Q_{oss} for GaN) between a silicon MOSFET and a GaN E-HEMT from GaN Systems. GaN has zero Q_{rr}, and its output capacitance charge can be more than an order of magnitude smaller than 650 V silicon MOSFETs. Even compared to CoolMOS CFD with an ultra-fast body diode, GaN shows a 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[A1].

Table 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

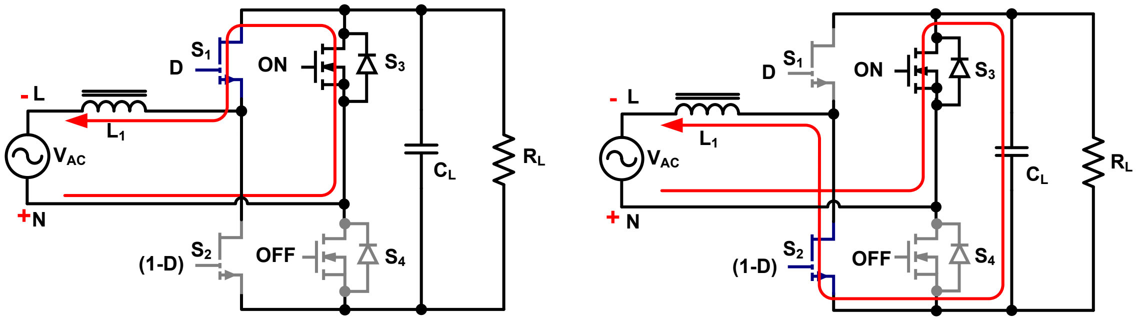
2.4. Basic operating principle

The BTPPFC operates in two modes depending on the polarity of input AC voltage, as shown in Figure 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 5. Current flows in TPPFC during positive and negative AC half-cycles

1. During the 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. 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 the 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 reference design is provided to demonstrate the performance of GaN HEMTs, as shown in Figure 6. The detailed design specifications are shown in Table 2

Table 2. 3 kW BTPPFC design specification

Parameter	Value
Input Voltage (V_{in})	**90-264 V_{rms}**
Output Voltage (V_{out})	**400 V**
Maximum Output Power	**3 kW (1.5kW for low line)**
Switching Frequency	**65 kHz**
Line Frequency	**50/60 Hz**
Output voltage ripple	**≤5%**
Inductor current ripple	**≤20%**

[A2]

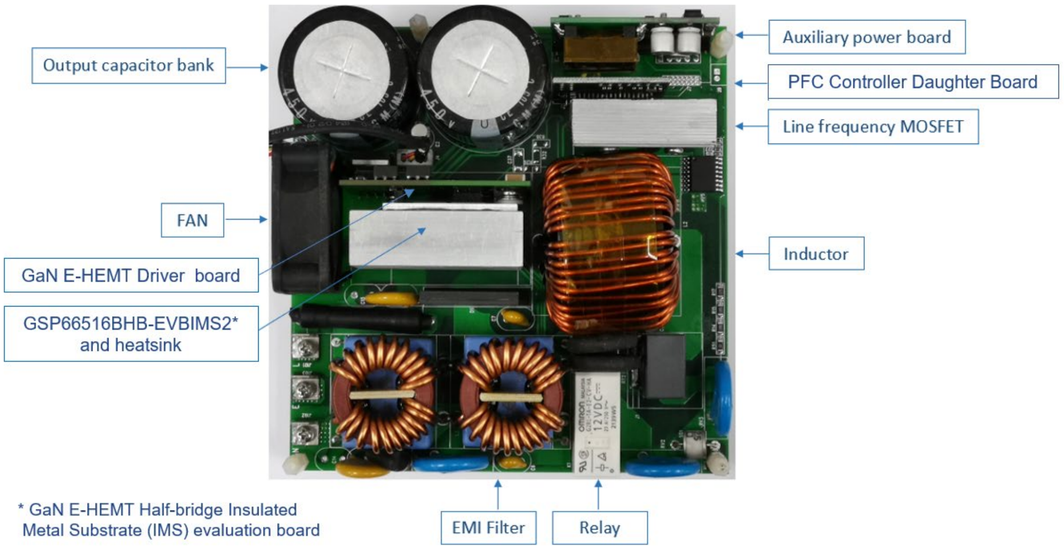


Figure 6. The 3 kW CCM BTPPFC reference design

3.1. System Block Diagram

The BTPPFC reference design block diagram is shown in Figure 7. The reference design consists of four sub-assemblies;

1) Motherboard: This board consists of an EMI filter, a start-up circuit, the line frequency Si MOSFETs and their gate drive circuits, and voltage and current sensing circuits. The IXFH80N65X2 devices from IXYS were chosen as the line-frequency switches.

2) PFC Controller Daughter Board: This control board uses the UCD3138 PFC control chip from Texas Instruments. The PFC controller Daughter Board includes current, input line voltage, and output voltage sampling pins as inputs. The outputs are 4 PWM pins, of which two are applied to the GaN E-HEMT driver board, and the other two are applied to the line frequency Si MOSFETs.

3) GaN E-HEMT Driver Board: This board uses the SiLabs SI8271 isolated gate drive IC to drive the GaN Half-bridge IMS board (GSP66516BHB-EVBIMS2).

4) GSP66516BHB-EVBIMS2 evaluation board from GaN Systems, which is a Half-Bridge Insulated Metal Substrate (IMS) board that uses high switching speed GS66516B GaN E-HEMT's [3]. The design details of this evaluation board can be found on the GaN Systems website at [4].

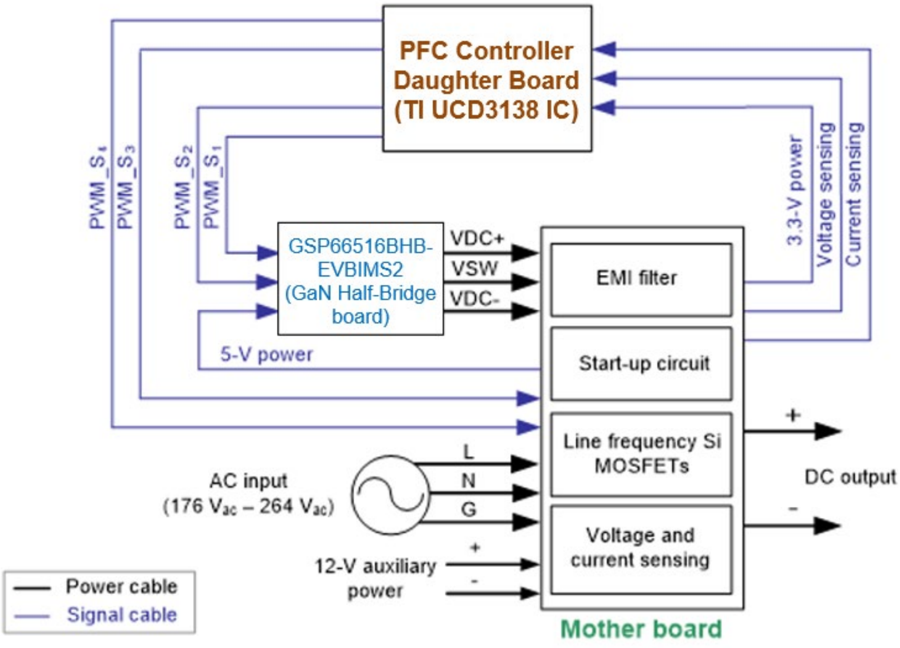


Figure 7. System block diagram

5) Auxillary power board: This board is a flyback dc-dc converter. It offers power for all control circuits, transistor driver and fan cooling. The board's input is 400V bus voltage, and output is 12V for fan and driver, 7V for the control circuit, and an isolated 9V for driving the high-side Si MOSFET.

3.2. Control scheme

The average current control is employed. 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 high bandwidth hall sensor IC. The overall control block diagram is shown in Figure 8. A relay is applied to achieve the soft-start function. The AC polarity detection is performed 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 9.

Overvoltage, Undervoltage, and overcurrent protection have been implemented for the input and output of the PFC converter. <10uS reacting time of grid overcurrent protection is enabled by the 1MHz bandwidth hall sensor.

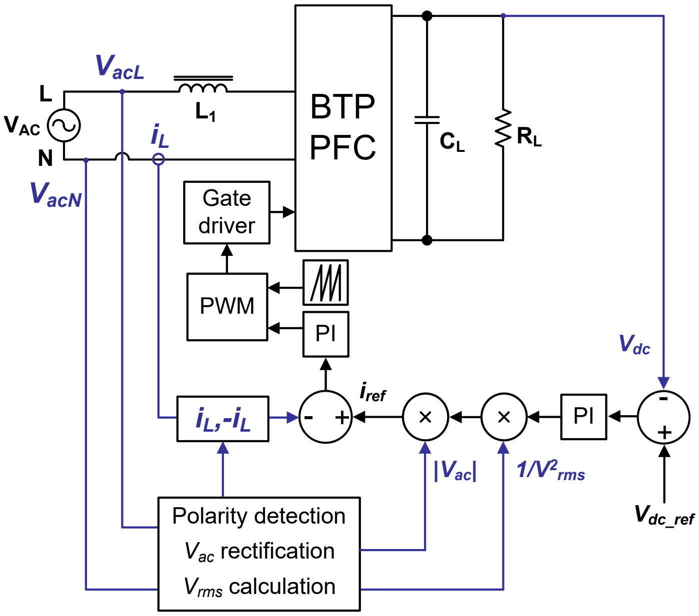


Figure 8. Control block diagram

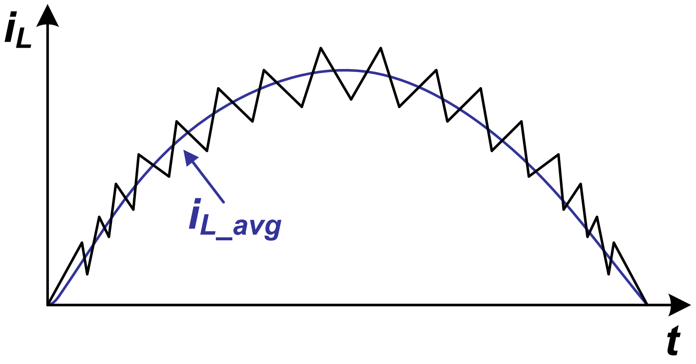


Figure 9. The average current mode control scheme

4. Test Results

The measured efficiency curve is shown in Figure 10. The peak efficiency reaches 99.05% at 1.5 kW, 230 V_{ac} (the aux loss includes the auxiliary power, and fan cooling loss). The power factor under different loads is shown in Figure 11. The converter input and output waveform under the full load is shown in Figure 12. The converter full-load start-up waveform is shown in Figure 13.

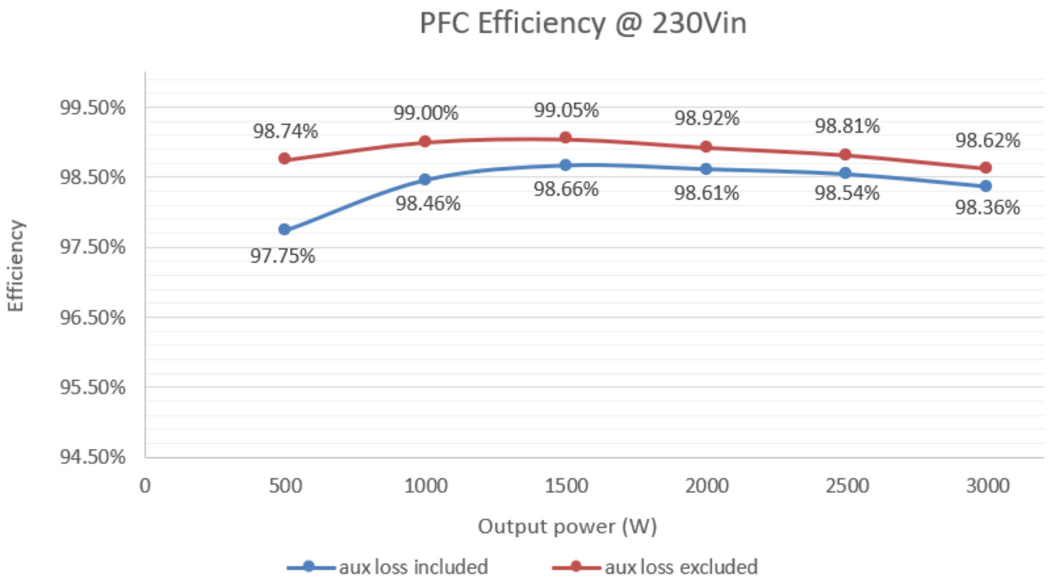


Figure. 10. Efficiency at 230 V_{ac}

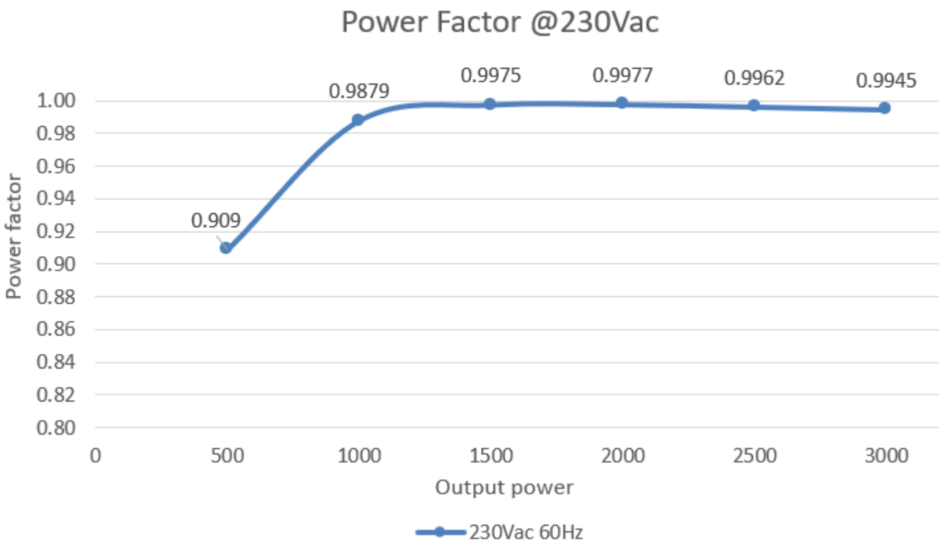
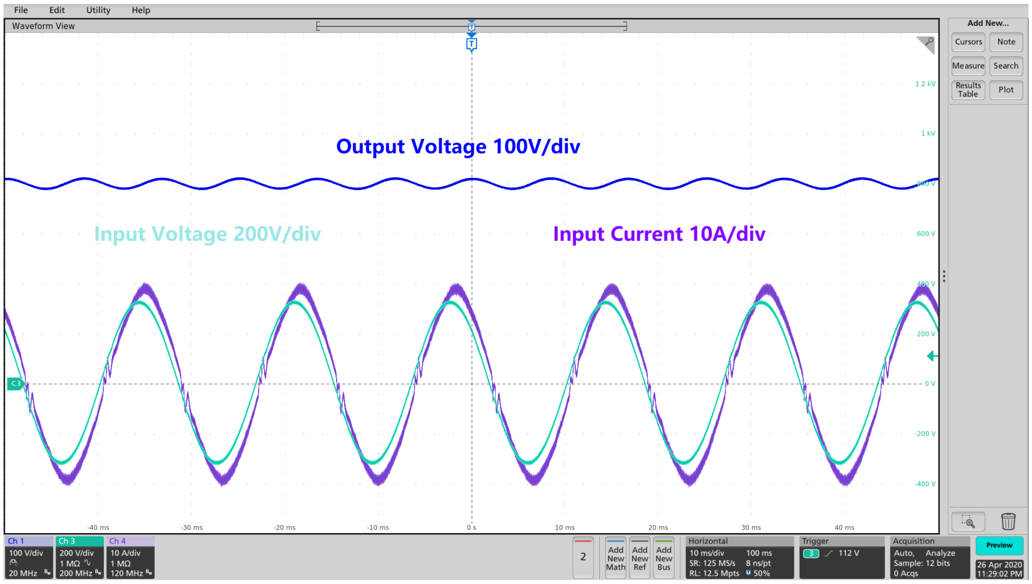


Figure 11. Power factor at 230 V_{ac}, 60 Hz



Ch 1: 100 V/div, 20 MHz
Ch 3: 200 V/div, 1 MΩ, 200 MHz
Ch 4: 10 A/div, 1 MΩ, 120 MHz
Horizontal: 10 ms/div, 100 ms, SR: 125 MS/s, 8 ns/pt, RL: 12.5 Mpts, 50%
Trigger: 3, 112 V
Acquisition: Auto, Analyze, Sample: 12 bits, 0 Acqs
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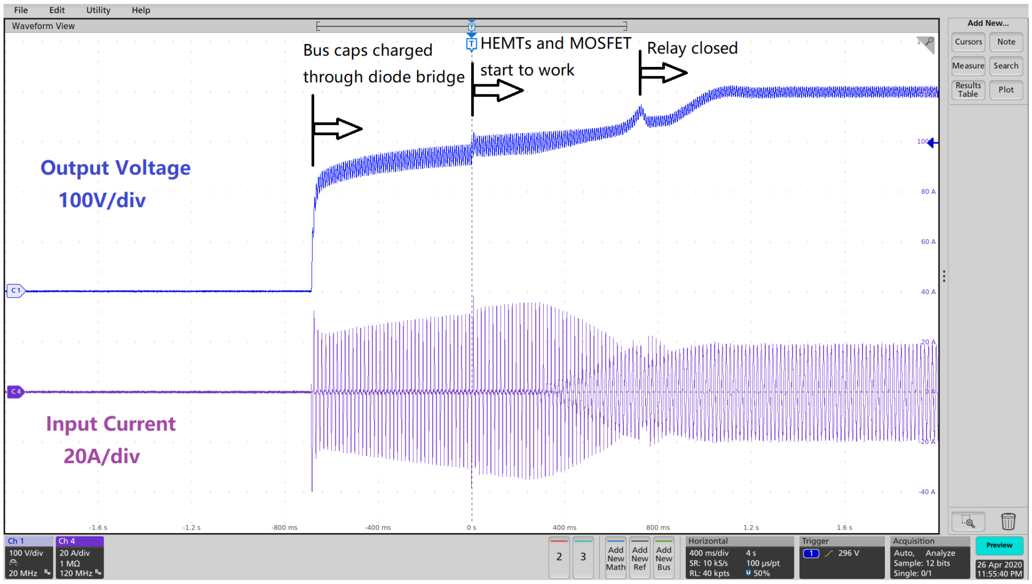
Figure. 12. Converter Input and output waveform at 230 V_{ac}, 400 V_{dc}, and 7.5 A_{dc}.



Ch 1
100 V/div
20 MHz

Ch 4
20 A/div
1 MΩ
120 MHz

Horizontal
400 ms/div 4 s
SR: 10 kS/s 100 µs/pt
RL: 40 kpts 50%

Trigger
1 296 V

Acquisition
Auto, Analyze
Sample: 12 bits
Single: 0/1

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Figure. 13. Converter 3kW full load start-up waveform

The thermal images was taken at 230 V_{ac}, 400 V_{dc}, and 7.5 A_{dc} with a fan, and the ambient temperature was 25 °C. As shown in Figure.14 and 15, the boost inductor temperature is 49.4 °C, the temperatures on the MOSFET, and GaN E-HEMT are 55.5 °C and 57.2 °C, respectively.

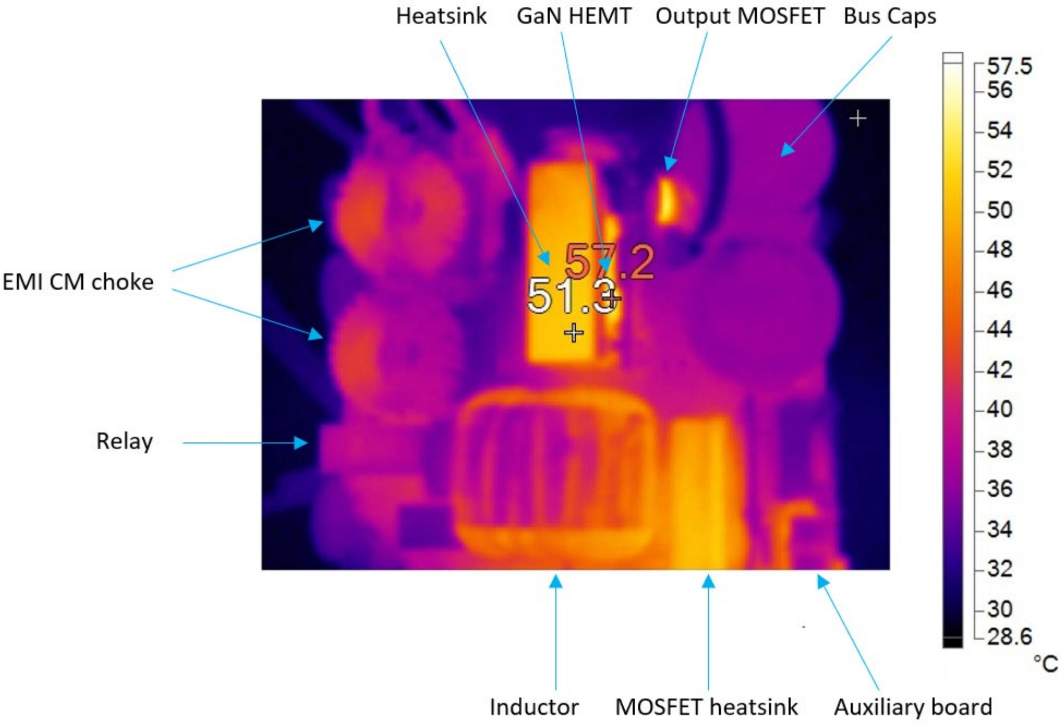


Figure 14. Temperature of GaN HEMTs and its heatsink

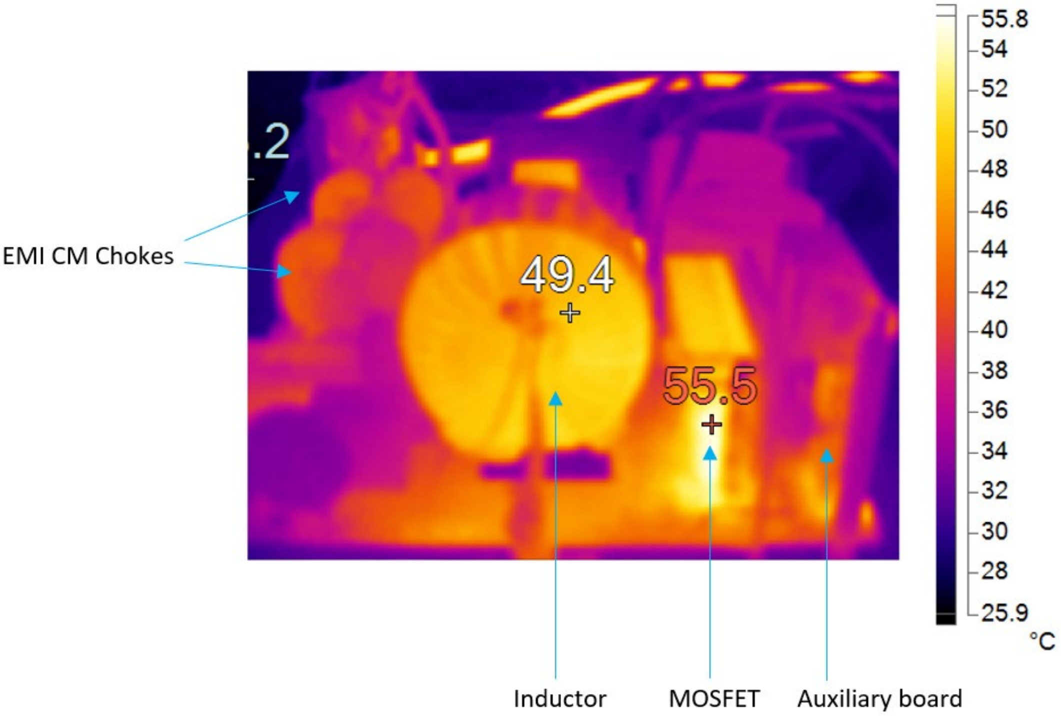


Figure 15. Temperature of the boost inductor and Si MOSFET

5. Applications

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

1. The unidirectional or bidirectional onboard battery charger in electrified vehicles. 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).

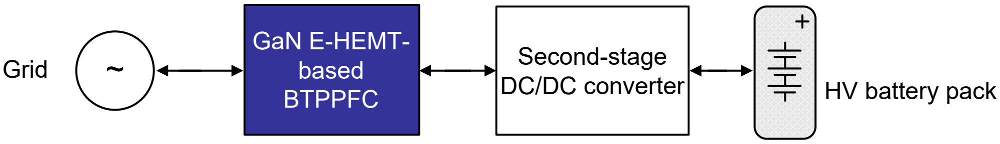


Figure 16. Electrified vehicle onboard bidirectional battery charger system

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 design.

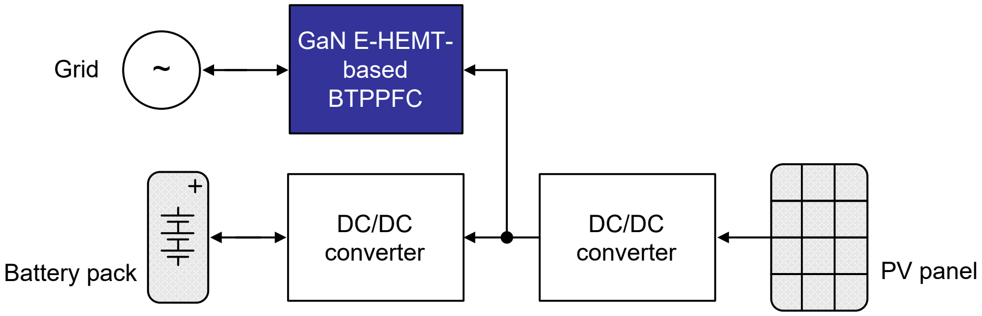


Figure 17. Energy storage system

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

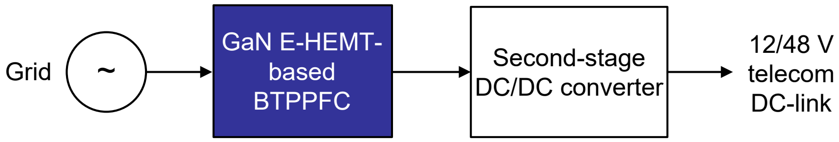


Figure 18. Telecom application

6. Conclusion

This technical maual presents the motivation, operating principle, and design considerations of a BTPPFC using GaN E-HEMTs. A 3 kW BTPPFC reference design using GaN Systems 650-V GaN E-HEMT is provided. The test results, as well as the thermal performance, are presented. GaN Systems' E-HEMTs have advantages in the CCM BTPPFC design in terms of power density, efficiency, and performance. Several possible application examples based on the BTPPFC are also given.

7. Appendix A – Schematics

7.1. Motherboard Schematics

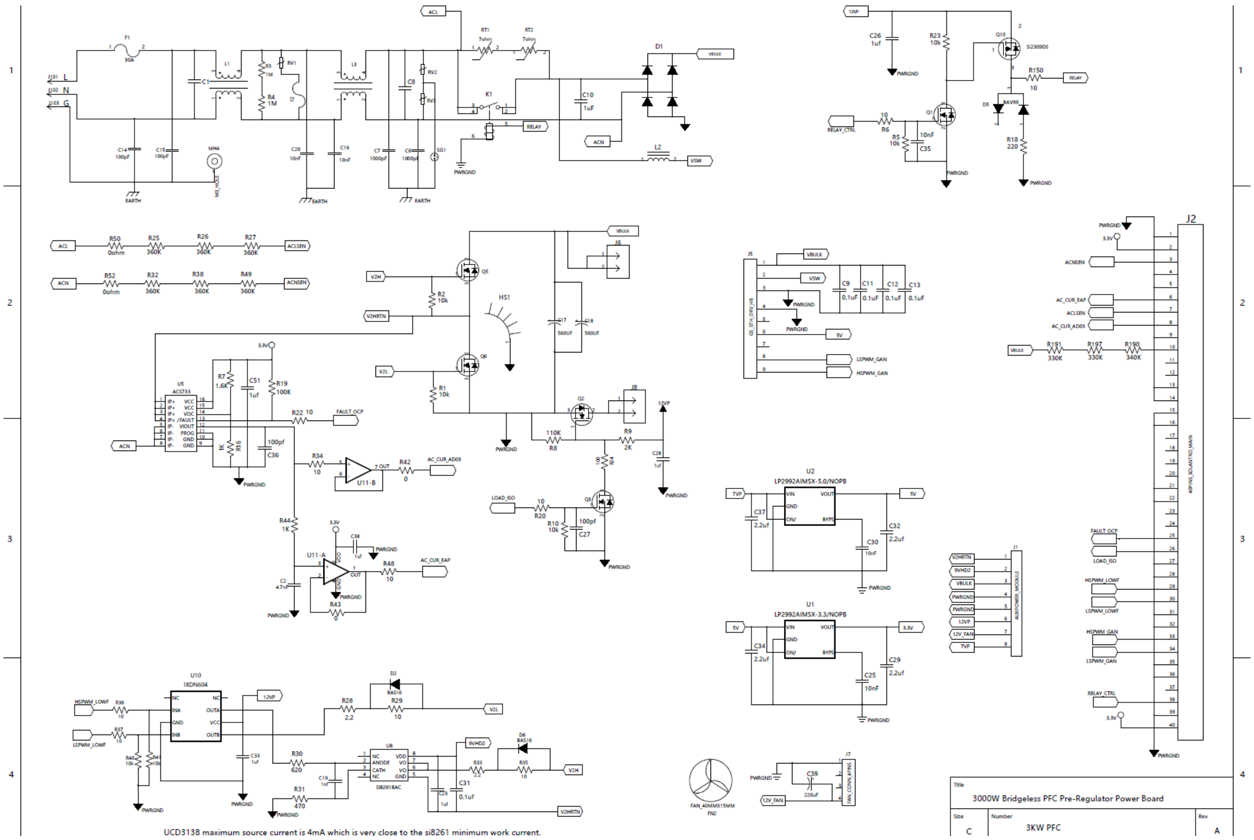


Figure. 19. Motherboard schematic page 1

7.2. PFC Controller Daughter Board Schematic

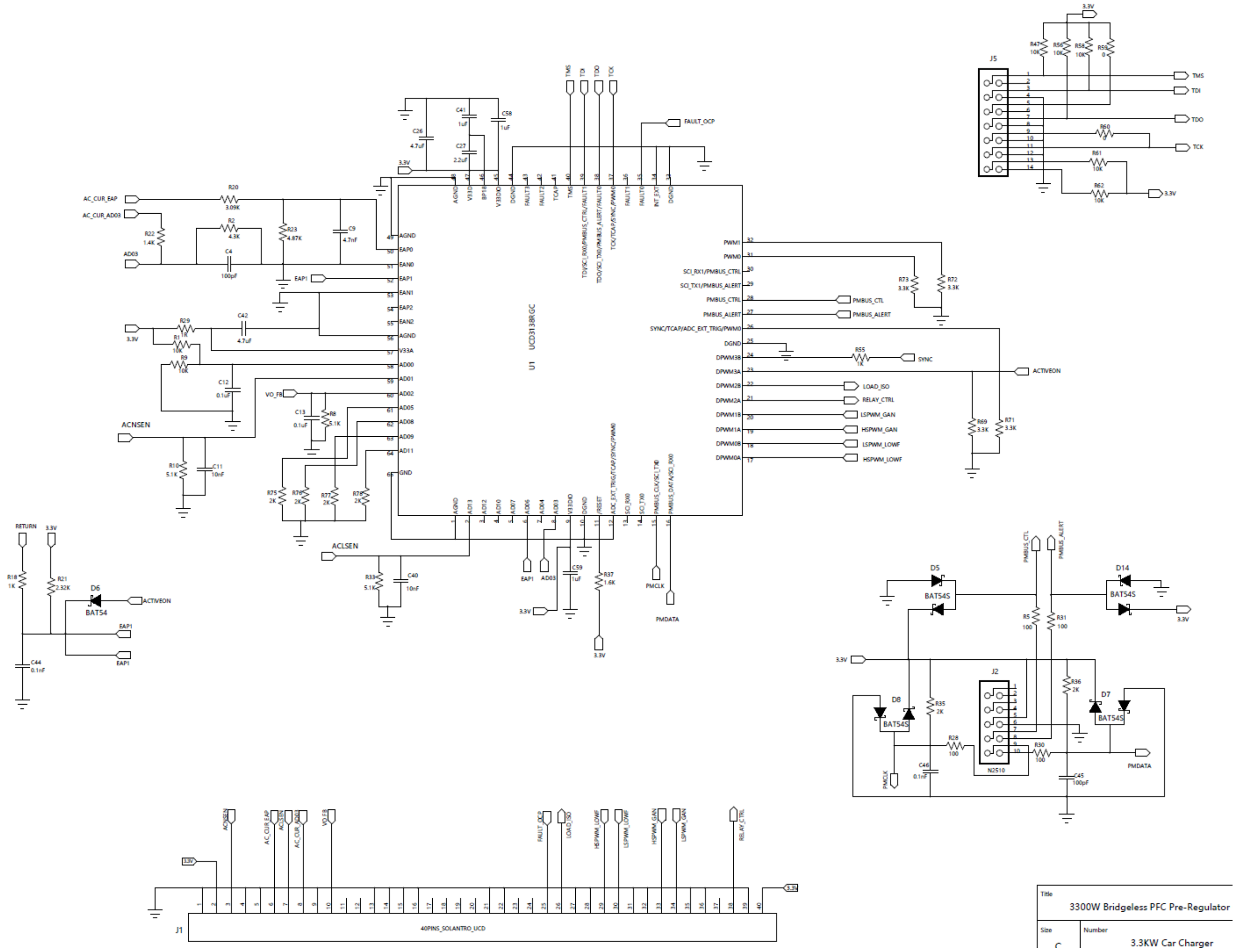


Figure. 20. The PFC Controller Daughter Board schematic

7.3. GaN E-HEMT Driver Board schematic

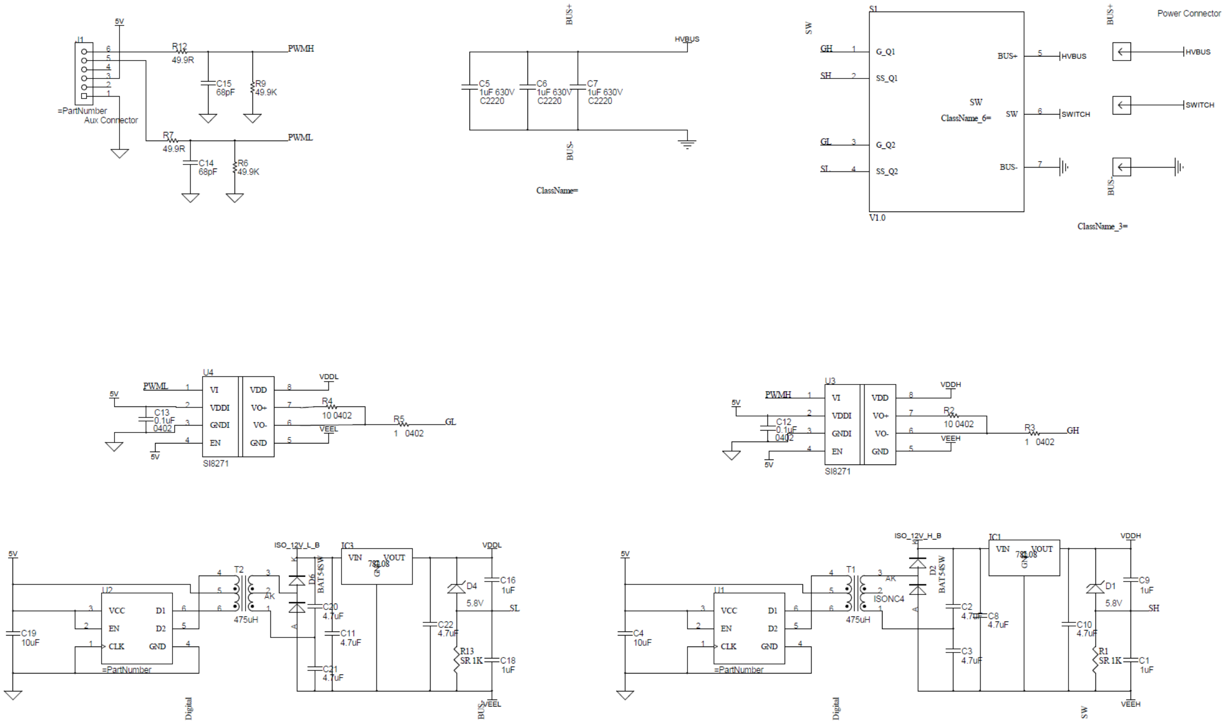


Figure. 21. GaN E-HEMT Driver Board schematic

7.4. Auxiliary power Board schematic

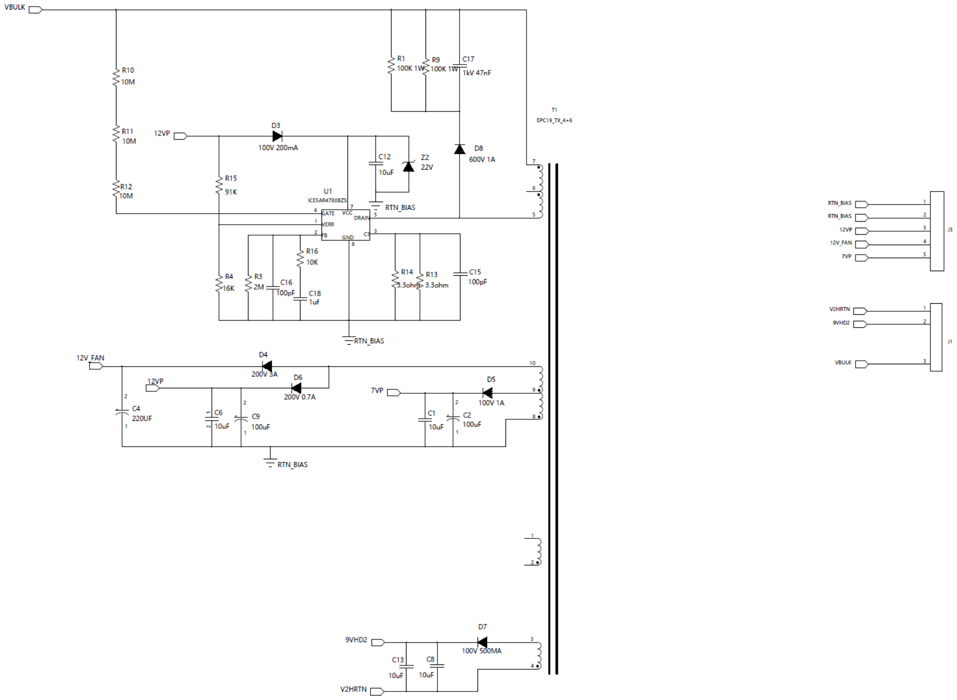


Figure. 22. Auxiliary power Board schematic

8. Appendix B – Layout

8.1. PCB Layout - Motherboard

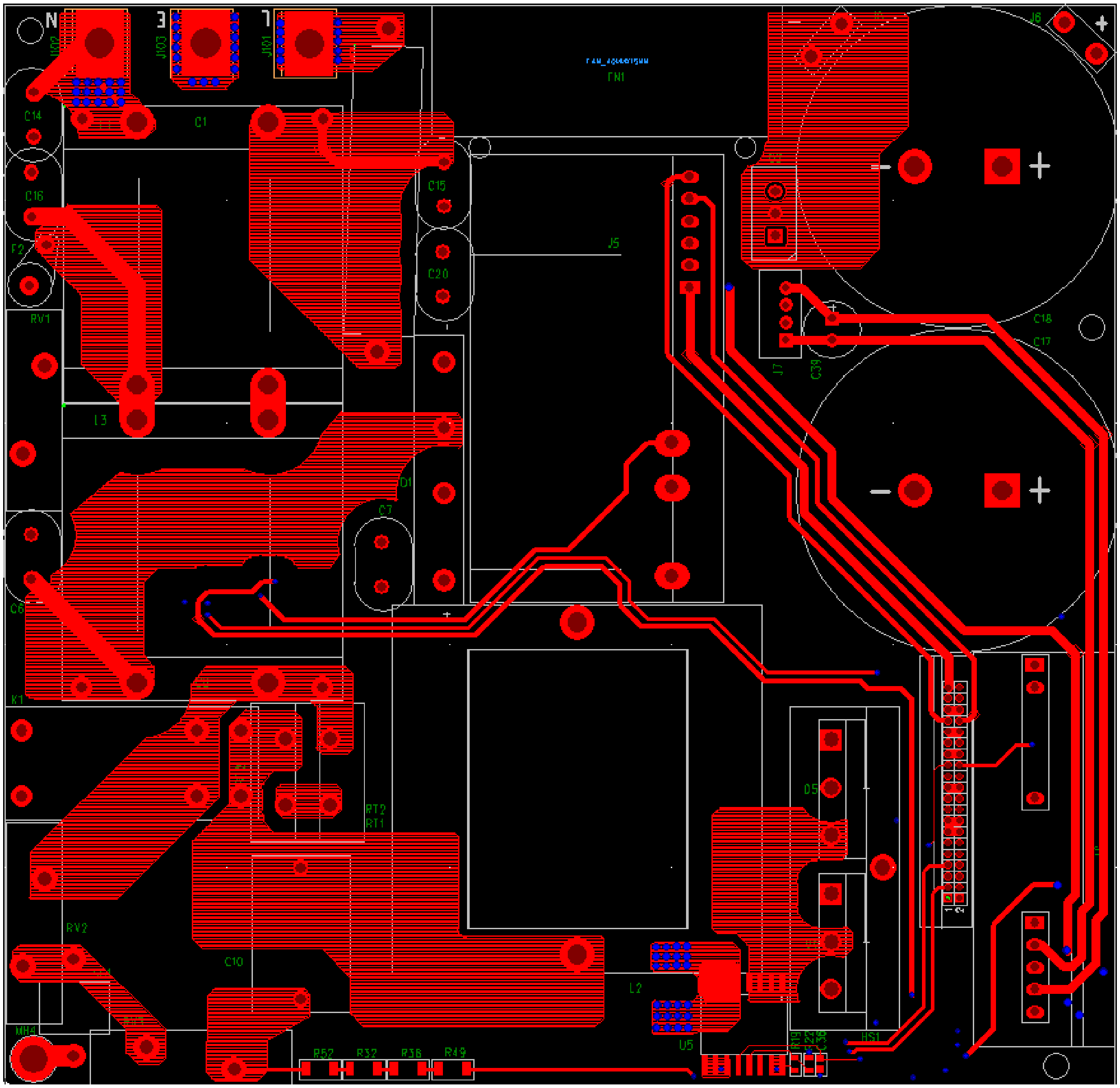


Figure. 23. Motherboard PCB layout

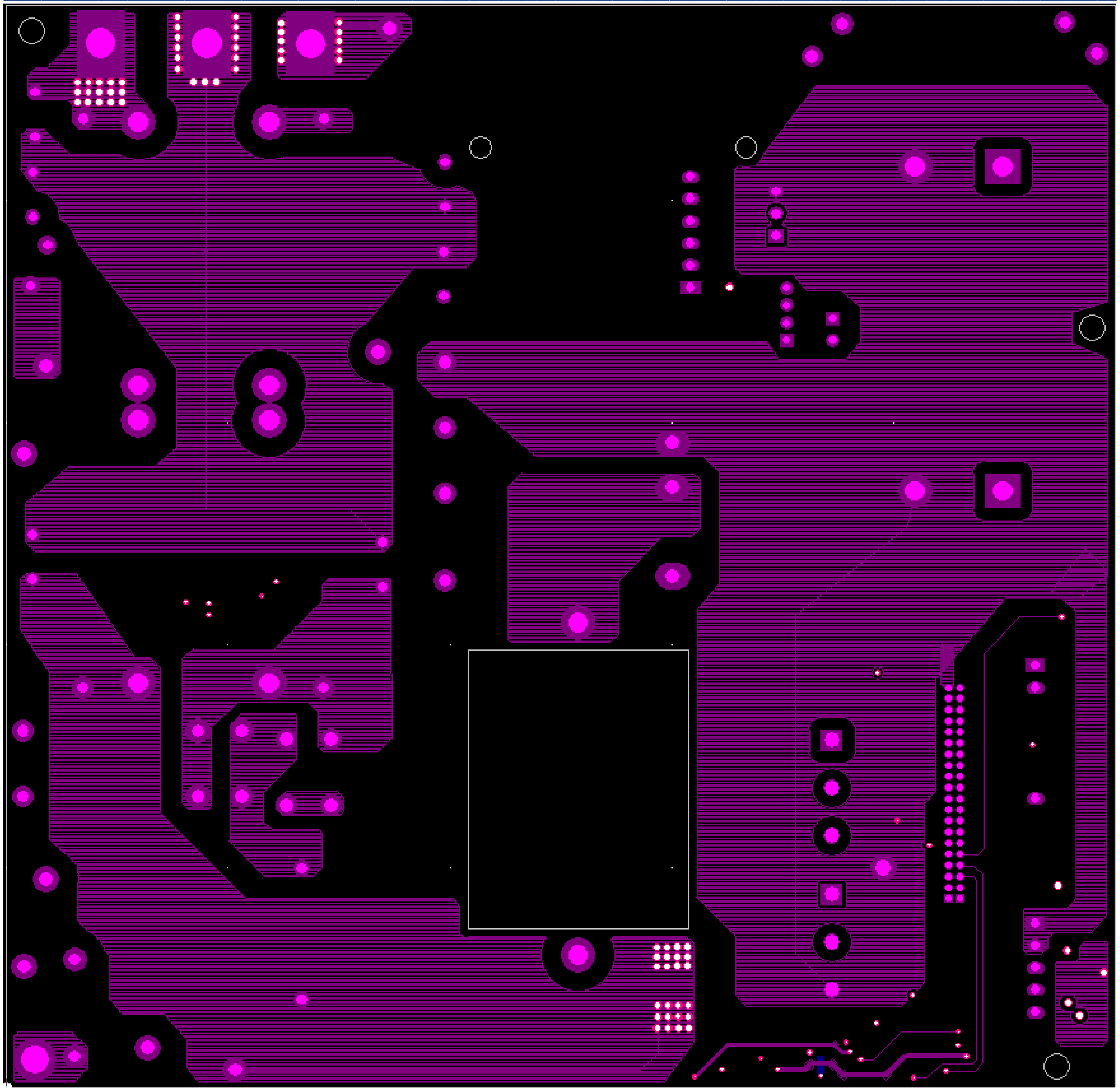


Figure. 24. Motherboard PCB layout mid layer 1

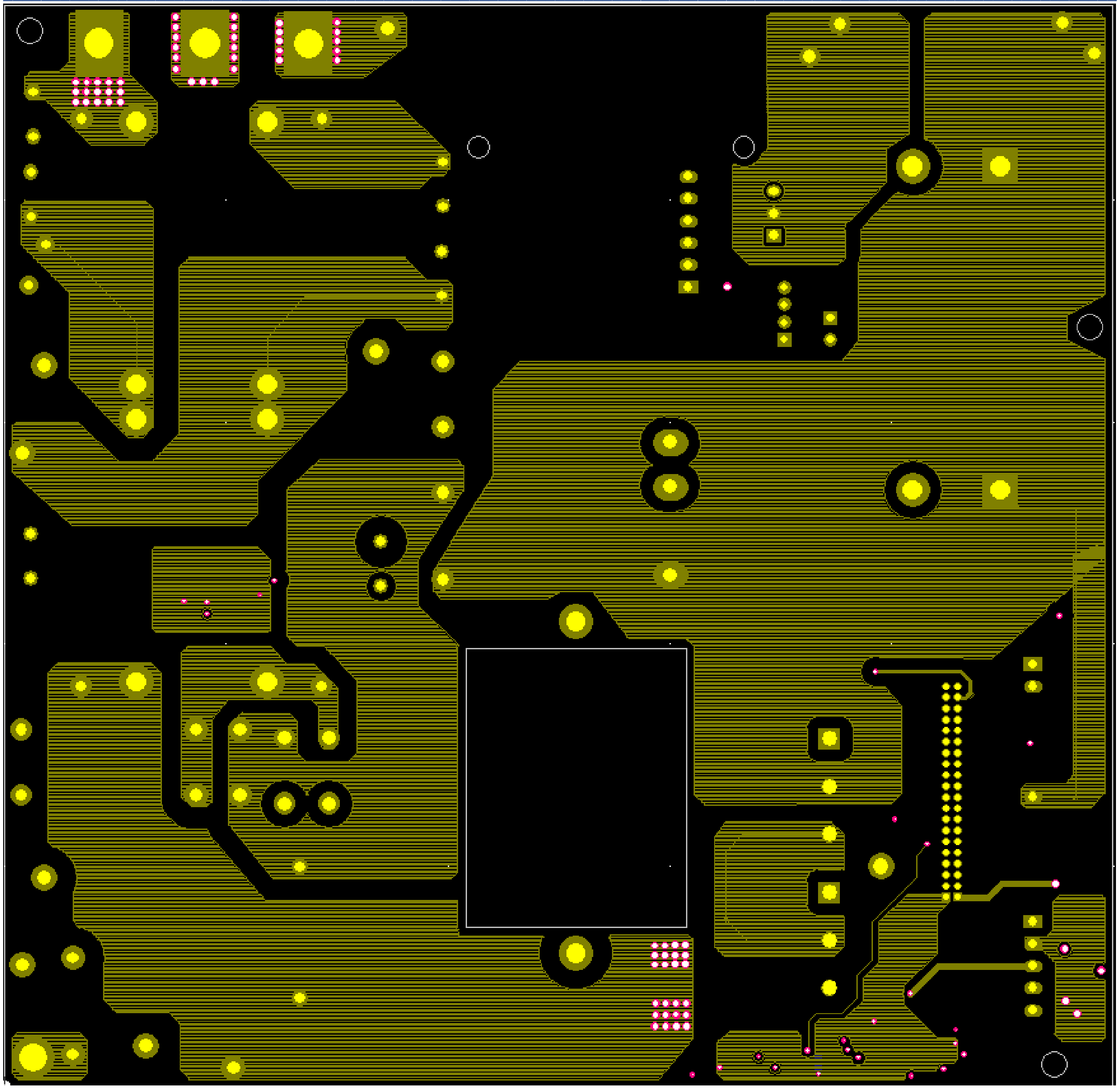


Figure. 25. Motherboard PCB layout mid layer 2

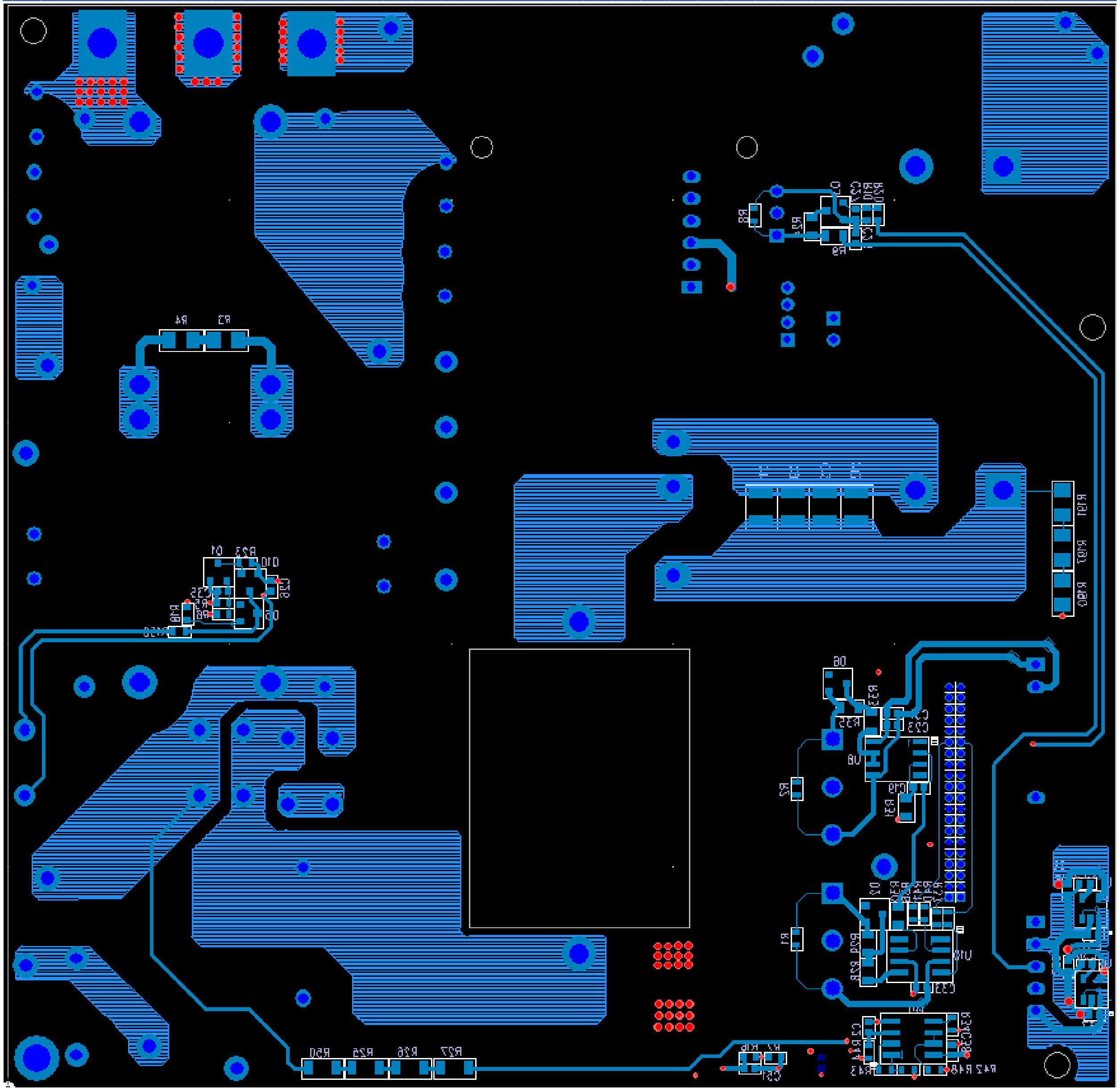


Figure. 26. Motherboard PCB layout: bottom layer

8.2. PCB layout – PCB Controller Daughter board

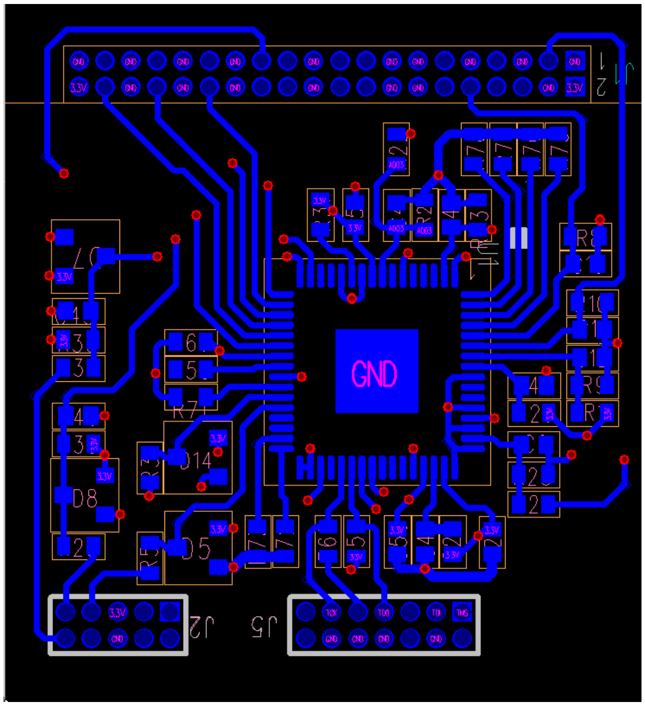


Figure. 27. PFC Controller Daughter Board PCB layout: top layer

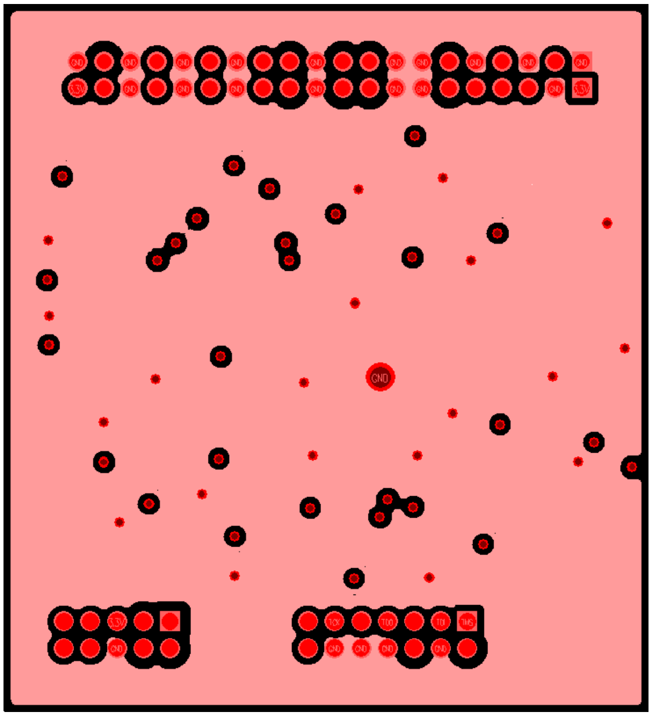


Figure. 28. PFC Controller Daughter Board PCB layout: mid layer 1

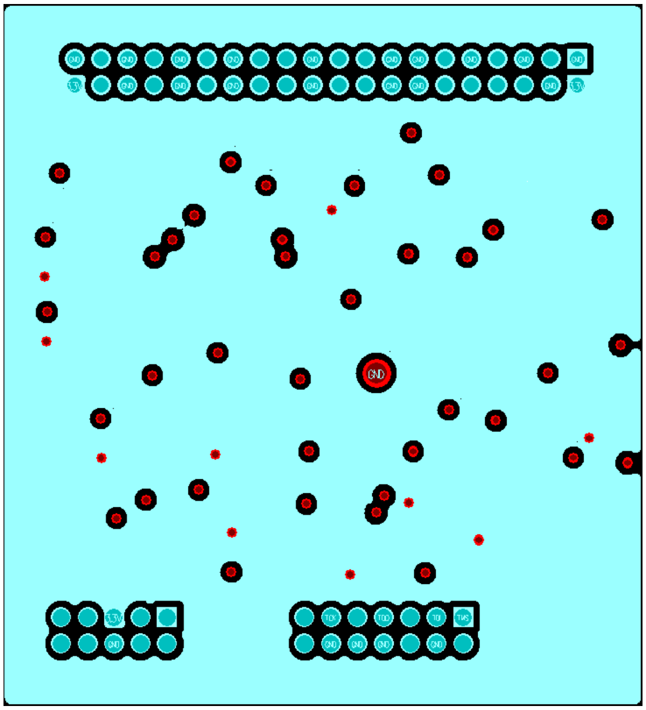


Figure. 29. PFC Controller Daughter Board PCB layout: mid layer 2

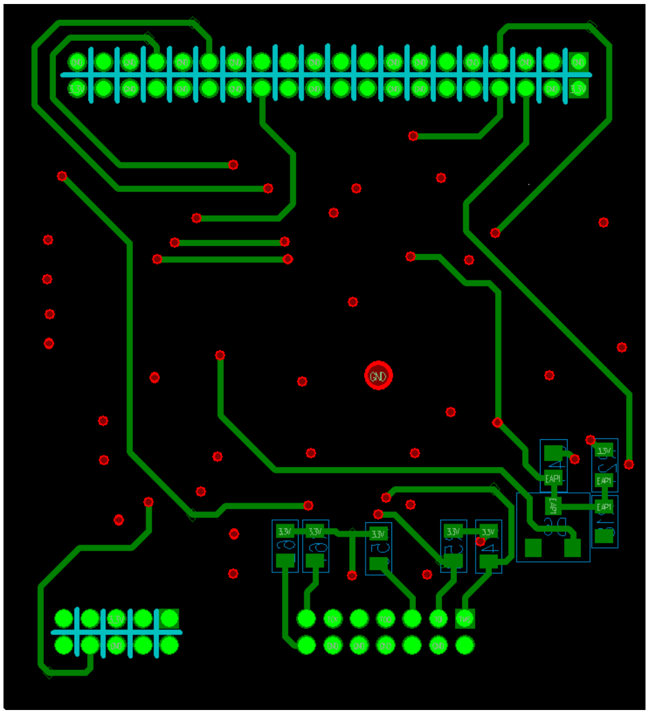


Figure. 30. PFC Controller Daughter Board PCB layout: bottom layer

8.3. PCB layout - GaN E-HEMT Driver Board

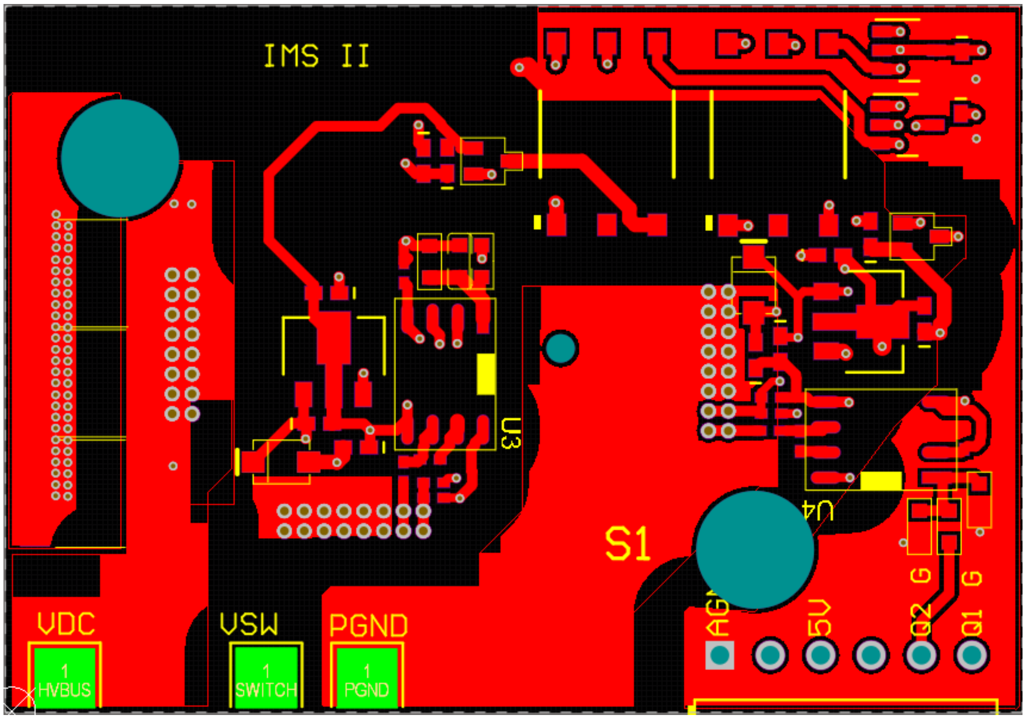


Figure. 31. GaN E-HEMT Driver board PCB layout: top layer

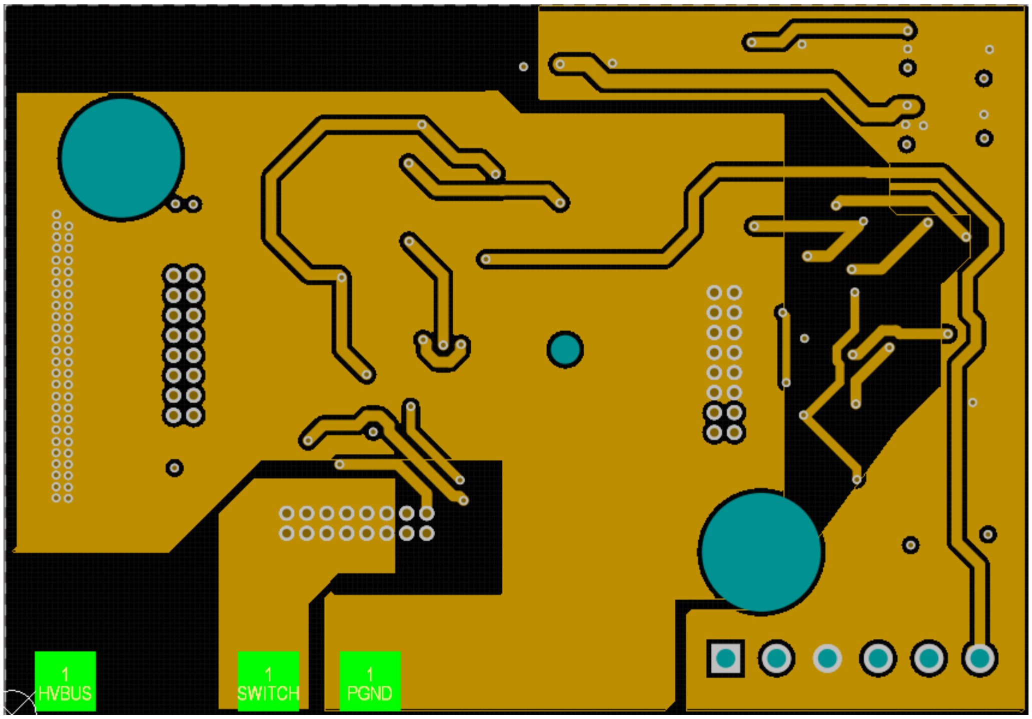


Figure. 32. GaN E-HEMT Driver board PCB layout: mid layer 1

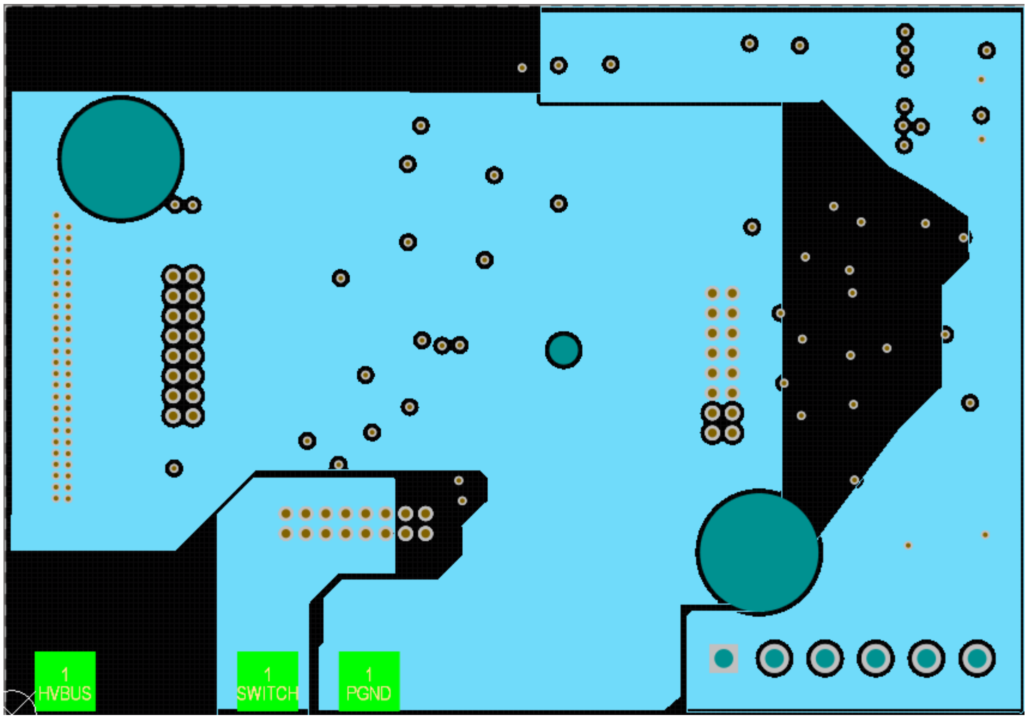


Figure. 33. GaN E-HEMT Driver board PCB layout: mid layer 2

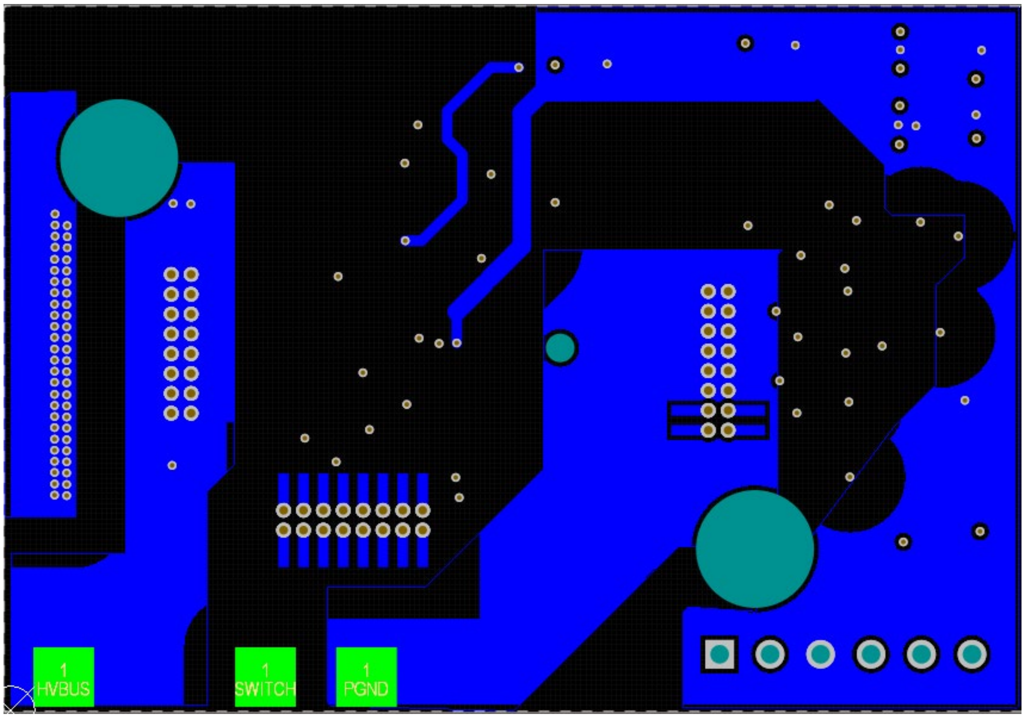


Figure. 34. GaN E-HEMT Driver board PCB layout: bottom layer

8.4. PCB layout - Auxiliary Power Board

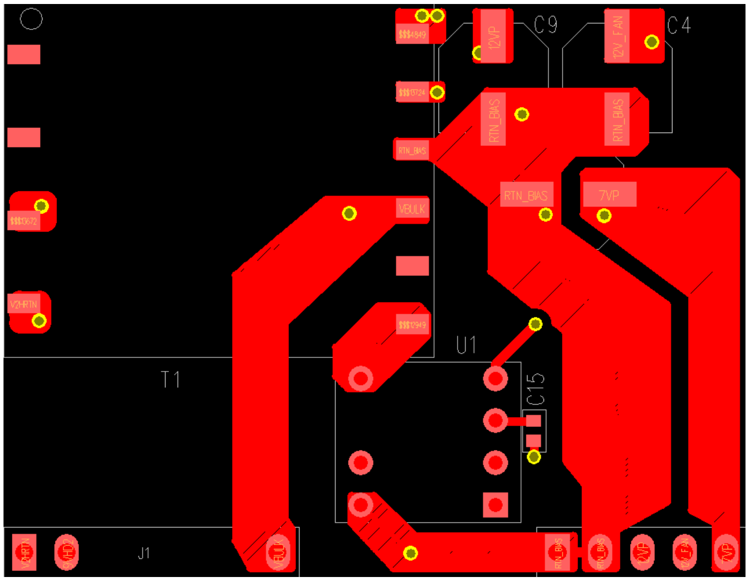


Figure. 35. Auxiliary power PCB layout: top layer

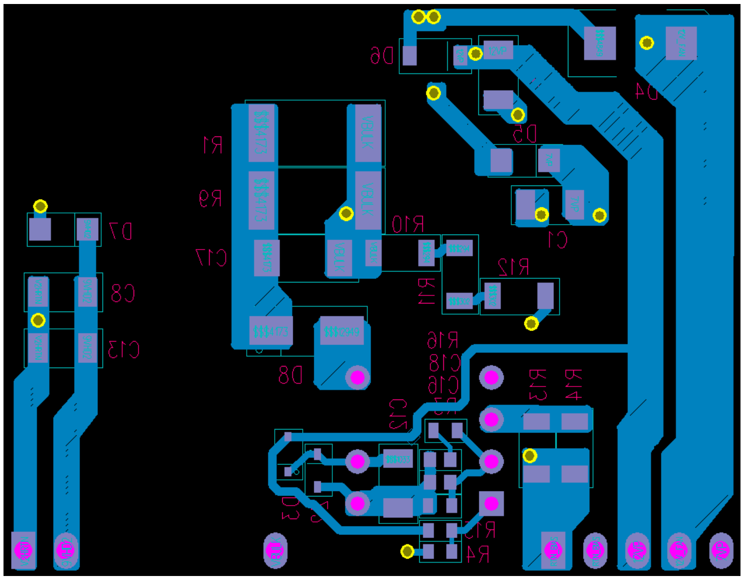


Figure. 36. Auxiliary power PCB layout: bottom layer

9. Appendix C – List of Materials

9.1. List of materials - Motherboard

Table 3. Motherboard list of materials

Ref_Des	Part Number	Description
U5	ACS733KLATR-40AB-T	SMD SOIC16 CURRENT SENSOR ACS733
D2	BAS16-7-F,BAS16	Diode 75V 200mA SOT23-3
D6	BAS16-7-F,BAS16	Diode 75V 200mA SOT23-3
D5	BAV99-7-F,BAV99	DIODE 75V 300mA SOT23
C29	10V_2.2UF_X7R	CAP 0603 10V 2.2uF X7R
C32	10V_2.2UF_X7R	CAP 0603 10V 2.2uF X7R
C37	10V_2.2UF_X7R	CAP 0603 10V 2.2uF X7R
C34	10V_2.2UF_X7R	CAP 0603 10V 2.2uF X7R
C23	25V_1UF_X7R	CAP 0603 25V 1uF X7R
C26	25V_1UF_X7R	CAP 0603 25V 1uF X7R
C28	25V_1UF_X7R	CAP 0603 25V 1uF X7R
C33	25V_1UF_X7R	CAP 0603 25V 1uF X7R
C51	25V_1UF_X7R	CAP 0603 25V 1uF X7R
C31	50V_0.1UF_X7R	CAP 0603 50V 0.1uF X7R
C27	50V_100PF_X7R	CAP 0603 50V 100pF X7R
C35	50V_10nF_X7R	CAP 0603 50V 10nF X7R
C36	50V_100PF_X7R	CAP 0603 50V 100pF X7R
C25	50V_10NF_X7R	CAP 0603 50V 10nF X7R
C30	50V_10NF_X7R	CAP 0603 50V 10nF X7R
C19	50V_1NF_X7R	CAP 0603 50V 1nF X7R
C9	650V_0.1UF_X7R	CAP SMD 1210 650V 0.1UF X7R
C11	650V_0.1UF_X7R	CAP SMD 1210 650V 0.1UF X7R
C12	650V_0.1UF_X7R	CAP SMD 1210 650V 0.1UF X7R
C13	650V_0.1UF_X7R	CAP SMD 1210 650V 0.1UF X7R
C17	LGM2W561MELC35	CAP AL TH 450V 560UF 35Dx35H
C18	LGM2W561MELC35	CAP AL TH 450V 560UF 35Dx35H
C39	16V_220UF_D6.3	CAP TH 16V 220uF D6.3mmX11mm
C1	CAP_X2_2.2UF_HORIZONTAL	CAP TH X2 310V 2.2UF
C8	CAP_X2_2.2UF_HORIZONTAL	CAP TH X2 310V 2.2UF
C14	CAP_Y2_100PF	CAP Y2 440VAC 100pF Y5S
C15	CAP_Y2_100PF	CAP Y2 440VAC 100pF Y5S
C16	CAP_Y2_10NF	CAP Y2 440VAC 10nF Y5U

Table 3. Motherboard list of materials (Continued)

Ref_Des	Part Number	Description
C20	CAP_Y2_10NF	CAP Y2 440VAC 10nF Y5U
L1	CM_CHOKE_1	CM CHOKE LONG LEAD HORIZONTAL
L3	CM_CHOKE_1	CM CHOKE LONG LEAD HORIZONTAL
J7	FAN_CONN_4PINS	CON 4PIN 2.0PITCH
F1	FUSE_250V_30A,30A	FUSE 250V AC 30A Fast Axial Lead
F2	FUSE_3.5A	FUSE 250V AC 3.5A TIME LAG
SG1	GASTUBE_2500V	GASTUBE 2500V TH
D1	GBO25-12NO1	DIODE BRIDGE 1PH 1200V SIP
L2	PI160694V1	Power inductor
Q2	IPP65R045C7_TO220	N MOSFET TO220
U10	IXDN604SIA,IXDN604	IC 4A Dual Output Drive SO8
U1	LP2992AIM5X-3.3/NOPB	LDO 3.3V 150mA SOT23-5
U2	LP2992AIM5X-5.0/NOPB	LDO 5V 150mA SOT23-5
C10	MKPX2,1uF	Capacitor, OS CON, vvV, zzmilliohm, [temp], 20%
Q5	IXFH80N65X2	MOS N-ch 650V 80A TO247
Q6	IXFH80N65X2	MOS N-ch 650V 80A TO247
Q1	SN7002N	N MOS 60V 0.2A SOT-23
Q3	SN7002N	N MOS 60V 0.2A SOT-23
RV1	MOV_560V	MOV_560V_20MM
RV2	MOV_560V	MOV_560V_20MM
RV3	MOV_560V	MOV_560V_20MM
RT1	SL22 7R010	NTC 7ohm D22mm 100J
RT2	SL22 7R010	NTC 7ohm D22mm 100J
K1	G2RL-1A-E2-CV-HA DC12	G2RL-1A-E2-CV-HA DC12
R1	10K_1/10W_1%	RES 0603 10k 1/10W
R2	10K_1/10W_1%	RES 0603 10k 1/10W
R5	10K_1/10W_1%	RES 0603 10k 1/10W
R10	10K_1/10W_1%	RES 0603 10k 1/10W
R23	10K_1/10W_1%	RES 0603 10k 1/10W
R40	10K_1/10W_1%	RES 0603 10k 1/10W
R41	10K_1/10W_1%	RES 0603 10k 1/10W
R6	10_1/10W	RES 0603 10ohm 1/10W 1%
R20	10_1/10W	RES 0603 10ohm 1/10W 1%

Table 3. Motherboard list of materials (Continued)

Ref_Des	Part Number	Description
R22	10_1/10W	RES 0603 10ohm 1/10W 1%
R36	10_1/10W	RES 0603 10ohm 1/10W 1%
R37	10_1/10W	RES 0603 10ohm 1/10W 1%
R150	10_1/10W	RES 0603 10ohm 1/10W 1%
R8	110K_1/10W	RES 0603 110k 1/10
R7	1K_1/10W	RES 0603 1k 1/10W
R16	1K_1/10W	RES 0603 1k 1/10W
R19	100K_1/10W	RES 0603 100k 1/10W
R18	220_1/10W	RES 0603 220 1/10W
R24	100_1/8W	RES 0805 100 1/8W
R29	10_1/8W	RES 0805 10 1/8W
R35	10_1/8W	RES 0805 10 1/8W
R28	2.2_1/8W	RES 0805 2.2 1/8W
R33	2.2_1/8W	RES 0805 2.2 1/8W
R9	2K_1/8W	RES 0805 2K 1/8W
R31	470_1/8W	RES 0805 470 1/8W
R30	620_1/8W	RES 0805 620 1/8W
R3	1M_1/4W	RES 1206 1M 1/4W
R4	1M_1/4W	RES 1206 1M 1/4W
R191	330K_0.25W_1%	Resistor, Metal Film, 1/4 watt, 1%
R197	330K_0.25W_1%	Resistor, Metal Film, 1/4 watt, 1%
R190	340K_1/4W_1%	RES 1206 340k 1/4 watt 1%
R25	360K_1/4W	RES 1206 360k 1/4W
R26	360K_1/4W	RES 1206 360k 1/4W
R27	360K_1/4W	RES 1206 360k 1/4W
R32	360K_1/4W	RES 1206 360k 1/4W
R38	360K_1/4W	RES 1206 360k 1/4W
R49	360K_1/4W	RES 1206 360k 1/4W
R50	0OHM,0ohm	RES SMD 1206 0ohm
R51	0OHM,0ohm	RES SMD 1206 0ohm
U8	SI8261BAC	ISOLATED DRIVE SO8
Q10	SI2309CDS-T1-E3	MOSFET, P-ch, -60V, -1.25A, 550 milliohms
R44	1K_1/10W_1%	RES 0603 1k 1/10W
R43	0_1/10W_1%	RES 0603 0 1/10W
R48	10_1/10W_1%	RES 0603 10 1/10W
R34	10_1/10W_1%	RES 0603 10 1/10W
R42	0_1/10W_1%	RES 0603 0 1/10W
C2	50V_4.7NF_X7R	CAP 0603 50V 4.7nF X7R
C38	50V_1uF_X7R	CAP 0603 50V 1uF X7R

9.2. List of Materials - PFC Controller Card

Table 4. PFC Controller card list of materials

Ref-Des	Part Number	Description
C44	C0603,0.1nF	Capacitor, Ceramic, Low Inductance, vvV, [temp], [tol]
C46	C0603,0.1nF	Capacitor, Ceramic, Low Inductance, vvV, [temp], [tol]
C12	C0603,0.1uF	Capacitor, Ceramic, Low Inductance, vvV, [temp], [tol]
C13	C0603,0.1uF	Capacitor, Ceramic, Low Inductance, vvV, [temp], [tol]
C45	C0603,100pF	Capacitor, Ceramic, Low Inductance, vvV, [temp], [tol]
C4	C0603,100pF	Capacitor, Ceramic, Low Inductance, vvV, [temp], [tol]
C11	C0603,10nF	Capacitor, Ceramic, Low Inductance, vvV, [temp], [tol]
C40	C0603,10nF	Capacitor, Ceramic, Low Inductance, vvV, [temp], [tol]
C41	C0603,1uF	Capacitor, Ceramic, Low Inductance, vvV, [temp], [tol]
C58	C0603,1uF	Capacitor, Ceramic, Low Inductance, vvV, [temp], [tol]
C59	C0603,1uF	Capacitor, Ceramic, Low Inductance, vvV, [temp], [tol]
C27	C0603,2.2uF	Capacitor, Ceramic, Low Inductance, vvV, [temp], [tol]
C9	C0603,4.7nF	Capacitor, Ceramic, Low Inductance, vvV, [temp], [tol]
C26	C0603,4.7uF	Capacitor, Ceramic, Low Inductance, vvV, [temp], [tol]
C42	C0603,4.7uF	Capacitor, Ceramic, Low Inductance, vvV, [temp], [tol]
D6	D-BAT54,BAT54	Diode, Schottky, 200-mA, 30-V
D5	D-BAT54S,BAT54S	Diode, Dual Schottky, 200-mA, 30-V
D7	D-BAT54S,BAT54S	Diode, Dual Schottky, 200-mA, 30-V
D8	D-BAT54S,BAT54S	Diode, Dual Schottky, 200-mA, 30-V
D14	D-BAT54S,BAT54S	Diode, Dual Schottky, 200-mA, 30-V
R59	R0603_1%,0	Resistor, Chip, 1/16W, 1%
R60	R0603_1%,0	Resistor, Chip, 1/16W, 1%
R22	R0603_1%,1.4K	Resistor, Chip, 1/16W, 1%
R37	R0603_1%,1.6K	Resistor, Chip, 1/16W, 1%
R5	R0603_1%,100	Resistor, Chip, 1/16W, 1%
R28	R0603_1%,100	Resistor, Chip, 1/16W, 1%
R30	R0603_1%,100	Resistor, Chip, 1/16W, 1%
R31	R0603_1%,100	Resistor, Chip, 1/16W, 1%
R1	R0603_1%,10K	Resistor, Chip, 1/16W, 1%
R9	R0603_1%,10K	Resistor, Chip, 1/16W, 1%
R47	R0603_1%,10K	Resistor, Chip, 1/16W, 1%
R56	R0603_1%,10K	Resistor, Chip, 1/16W, 1%
R58	R0603_1%,10K	Resistor, Chip, 1/16W, 1%
R61	R0603_1%,10K	Resistor, Chip, 1/16W, 1%
R62	R0603_1%,10K	Resistor, Chip, 1/16W, 1%
R18	R0603_1%,1K	Resistor, Chip, 1/16W, 1%
R55	R0603_1%,1K	Resistor, Chip, 1/16W, 1%

Table 4. PFC Controller card list of materials(Continued)

Ref-Des	Part Number	Description
R55	R0603_1%,1K	Resistor, Chip, 1/16W, 1%
R29	R0603_1%,1R	Resistor, Chip, 1/16W, 1%
R21	R0603_1%,2.32K	Resistor, Chip, 1/16W, 1%
R35	R0603_1%,2K	Resistor, Chip, 1/16W, 1%
R36	R0603_1%,2K	Resistor, Chip, 1/16W, 1%
R75	R0603_1%,2K	Resistor, Chip, 1/16W, 1%
R76	R0603_1%,2K	Resistor, Chip, 1/16W, 1%
R77	R0603_1%,2K	Resistor, Chip, 1/16W, 1%
R78	R0603_1%,2K	Resistor, Chip, 1/16W, 1%
R20	R0603_1%,3.09K	Resistor, Chip, 1/16W, 1%
R2	R0603_1%,4.3K	Resistor, Chip, 1/16W, 1%
R69	R0603_1%,3.3K	Resistor, Chip, 1/16W, 1%
R70	R0603_1%,3.3K	Resistor, Chip, 1/16W, 1%
R71	R0603_1%,3.3K	Resistor, Chip, 1/16W, 1%
R72	R0603_1%,3.3K	Resistor, Chip, 1/16W, 1%
R73	R0603_1%,3.3K	Resistor, Chip, 1/16W, 1%
R23	R0603_1%,4.87K	Resistor, Chip, 1/16W, 1%
R8	R0603_1%,5.1K	Resistor, Chip, 1/16W, 1%
R10	R0603_1%,5.1K	Resistor, Chip, 1/16W, 1%
R33	R0603_1%,5.1K	Resistor, Chip, 1/16W, 1%
U1	UCD3138RGC,UCD3138RGC	IC, Digital Power Controller

9.3. List of Materials - GaN E-HEMT Driver Board

Table 5. GaN E-HEMT Driver Board list of materials

Ref_Des	Part Number	Description
C1, C9, C16, C18	1uF	CAP, CERM, 1uF, 35 V,0402
C2, C3, C8, C10, C11, C20, C21, C22	4.7uF	CAP, CERM, 4.7uF, 35 V,0402
C4, C19	10uF	CAP, CERM, 10uF, 50 V,0402
C5, C6, C7	1uF_630V_2220	CAP CER 1UF 630V X7R 2220
C12, C13	0.1uF_0402	CAP, CER, 0.1uF, X7R, 0402
C14	68pF	CAP, CERM, 68 pF, 50 V, 0402
C15	68pF	CAP, CERM, 68 pF, 50 V, 0402
D1, D4	5.8V Zener	Zener, 5.8V, 500 mW, SOD-123
D2, D6	BAT54SW	D-SOT323_BAT
IC1, IC3	IC-78L08	LDO 8V
R1, R13	1K_0402	RES 1K
R2, R4	10_0402	RES, 1%, 0402
R3, R5	1_0402	RES, 1%, 0402
R7, R12	49.9ohm	RES, 49.9, 1%, 0.063 W, 0402
R6,R9	49.9kohm	RES,49.9k,1%, 0.063 W, 0402
T1, T2	760390014	Transformer, 475uH, SMT
U1, U2	SN6505BDBVR	1 A, 420 kHz Transformer Driver
U3, U4	SI8271	IC ISOL GATE DRIVER SINGLE

9.4. List of Materials - Auxiliary Power Board

Table 5. Auxiliary power board list of materials

Ref_Des	Part Number	Description
C18	0603_25V_1UF	CAP 0603 25V 1uF X7R
C4	16V_220UF_D6.3	CAP AL SMD 25V 220UF
C2	25V_100UF	CAP AL SMD 25V 100UF D6.3
C9	25V_100UF	CAP AL SMD 25V 100UF D6.3
C16	0603_50V_100PF	CAP SMD 0603 50V 100pF
C1	1206_25V_10UF	CAP SMD 1206 25V 10UF
C6	1206_25V_10UF	CAP SMD 1206 25V 10UF
C8	1206_25V_10UF	CAP SMD 1206 25V 10UF
C12	1206_25V_10UF	CAP SMD 1206 25V 10UF
C13	1206_25V_10UF	CAP SMD 1206 25V 10UF
C17	1808_1KV_0.047UF	CAP SMD 1808 1kV 0.047uF
J3	CONN_5PINS	
J1	CON_7PINS	
D4	ES3DB	DIODE SMD SMA 200V 3A
D8	ES1J	DIODE SMA 600V 1A ES1J
D5	SS1FH10	DIODE SMF 100V 1A
D7	ES07B	DIODE SMF 100V 500MA
D6	RF071MM2STR	DIODE SOD-123 200V 700mA
D3	BAV19WS-7-F	DIODE SOD323 100V 200mA
T1	EPC19_TX_4+6	

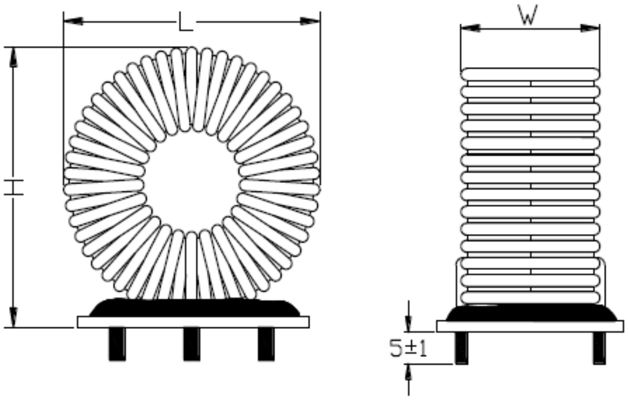
U1	ICE5AR4780BZS	IC Coolset
R4	0603_16K	RES 0603 16k 1/10W
R15	0603_91K	RES 0603 91k 1/10
R13	1206_3.3OHM	RES SMD 1206 3.3ohm 1/4W
R14	1206_3.3OHM	RES SMD 1206 3.3ohm 1/4W
R16	0603_10K	RES_0603_10K_1/10W
R10	1206_10MOHM	RES 1206 10Mohm 1/4W
R11	1206_10MOHM	RES 1206 10Mohm 1/4W
R12	1206_10MOHM	RES 1206 10Mohm 1/4W
R1	2512_100K_1W	RES SMD 2512 1W 100Kohm
R9	2512_100K_1W	RES SMD 2512 1W 100Kohm
Z2	SOD323F_22V	ZENER SOD323F 22V 500mW

P/N: PI160694V1

Inductance Solution

Irms	13 A
Ipeak	18.382 A
L @ 0 A	526.338μH ±10%
L @ 13 A	284.61μH (H=94.63Oe)
L @ 18.382 A	200.04μH (H=133.81Oe)
Core Loss	0.3790738 W
Copper Loss	5.655W
Total Loss	6.033592 W

Inductance View



Inductance Size:

L×W×H
L: 50
W: 40
H: 51

Inductance View

Figure. 37. Specification of L2 inductor (PI160694V1) on the mother board

References

[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, GS66516B bottom-side cooled 650 V E-mode GaN transistor datasheet, 2020, [Online].Available: https://gansystems.com/wp-content/uploads/2020/04/GS66516B-DS-Rev-200402.pdf

[4] GS66516BHB-EVBIMS22: GaN Systems, High Power IMS 2 Evaluation Platform [Online]. Available:https://gansystems.com/wp-content/uploads/2020/05/GSP665x-EVBIMS2_Technical-Manual_Rev_200514.pdf

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