Application Note_PNDM06P332A1:
3.3kW CCM Bi-directional Totem Pole PFC with 650V SiC MOSFET

About this document

This document demonstrates a Bi-directional bridgeless totem-pole power factor correction (PFC) with PN Junction Semiconductor's 650V SiC MOSFET in TO-247-4 package (P3M06040K4/P3M06060K4). The reference board is intended for those applications which require high efficiency (80+ Titanium) and high power density, such as high-end servers and telecoms. In addition, the bi-directional power flow capability would allow this design to be used in battery chargers or energy storge systems.

Demo Product Name: PNDM06P332A1

PN Junction Semiconductor (PNJ) Co., Ltd
PNJ Application Team

The Evaluation and Reference Boards are addressed only to qualified and skilled technical staff, for laboratory usage, and shall be used and managed according to the terms and conditions set forth in this document.

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1. Introduction

1.1 Efficiency Requirement for Power Supply

In applications such as IT equipment power supply, household energy storge systems, electrical vehicle chargers, ets, high efficiency and high power density power supplies are needed in order to minimize the overall energy consumption and the total cost of ownership. The importance of this issue is highlighted in US Energy Star 80PLUS efficiency specifications, which has been certificating high efficiency AC/DC rectifiers in different efficiency levels ranges from Gold to Titanium.

Power factor correction (PFC) as front-end AC/DC rectifier is one of the most important parts of a power supply, especially for applications above 100W. The 80PLUS Titanium efficiency standard requires half-load efficiency of 94% at low line and 96% efficiency at high line. Considering the DC/DC stage´s efficiency is typically above 97.5%, the PFC stage´s efficiency needs to be higher than 98.5% to meet the 80PLUS Titanium standard. Bridgeless PFC is one of the most attractive high efficiency topologies that reduce the conduction loss by reducing the number of semiconductor components in the line-current path. Various bridgeless PFC topologies have been proposed to overcome the high diode bridge losses [1].

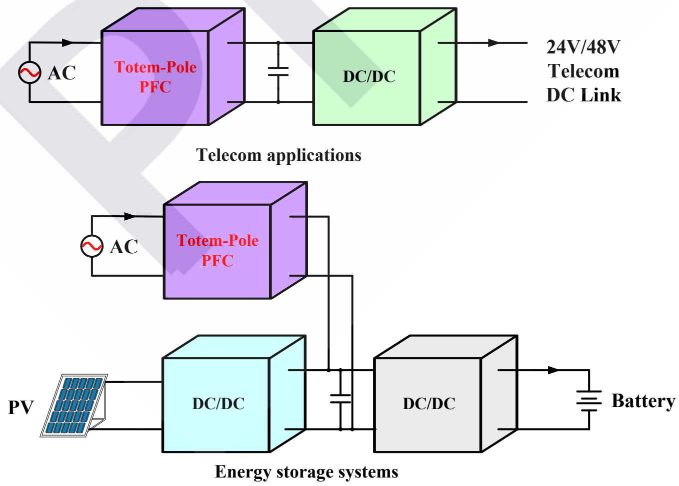

Fig. 1 Totem-Pole PFC Applications

Among all the bridgeless PFC topologies, totem-pole PFC is a rather simple topology with low boom cost. Also, it has the flexibility to implement multiple control such as continuous current mode (CCM), discontinuous current mode (DCM) and critical conduction mode (CRM). Besides, this topology has bi-directional power flow capability when the line frequency AC diodes are replaced by active switches, such as low-Rds(on) synchronous MOSFETs. However, this CCM totem-pole PFC hasn´t been a viable solution in a long time due to the turn-on current spike issue and large reverse-recovery loss, which often results in power device failure. The emerge of wide-band gap (WBG) power devices, such as silicon carbide (SiC) devices, has made it possible to implement CCM totem-pole PFC. The reverse-recovery loss of SiC MOSTE body diode is much lower than Si MOSFET body diode, as well as the output capacitance. These advantages of SiC devices can greatly reduce the turn-on current spike and the reverse-recovery loss. Therefore, totem-pole PFC converter has been drawing attention again in recent years along with the widely adoption of WBG devices.

1.2 Operation Principle of CCM Totem-Pole PFC

CCM totem-pole PFC operates in two modes based on the polarity of input AC voltage, as shown in Figure 2. S1, S2 are high frequency SiC MOSFET devices and S3, S4 are AC line frequency Si devices.

During the positive half cycle: SiC MOSFET S2 is the main switch, and S1 is driven with a complementary PWM signal. S1/S2 and Lg form a boost converter. During this positive half cycle, S4 is turned on and S3 is off. When S2 is turned on, the AC current flow through Lg, S2 and back to AC source ground via S4. When S2 is turned off, S1 is turned on, current flows through S1 and back to AC source ground via S4. The DC bus ground Vbus- is tied to AC source ground N potential as S4 is conducting all the time.

The operation of the negative half cycle is similar to the positive half cycle, except the role of top and bottom switches are swapped for both phase leg. Now, SiC MOSFET S1 becomes the main switch, and S2 is synchronous device, and S3 is on, and S4 is off.

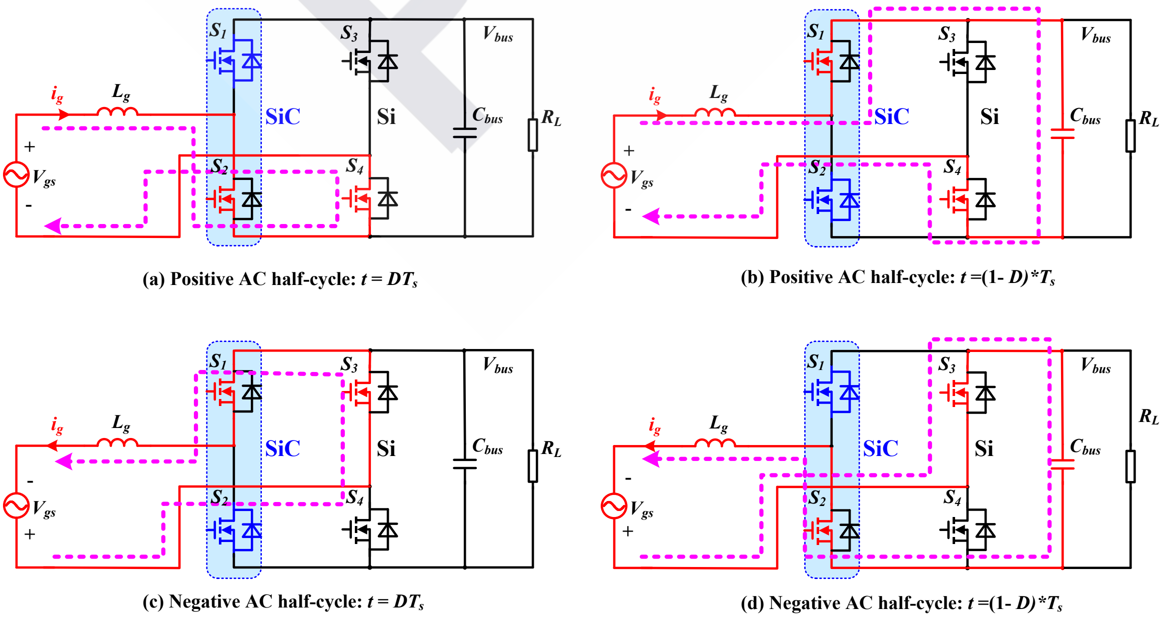

Fig. 2 Current flow path in Totem-Pole PFC during positive and negative AC half-cycles

2. Board Overview

2.1 Design Specification

The design specification of PNJ's PNDM06P332A1, 3.3kW CCM Totem-Pole PFC Demo board are listed in Table 1.

Tab.1 Technical Specification

Electrical Parameter	PFC Mode	Inverter Mode (grid-tied)
Input Voltage	90-265Vac rms	400Vdc
Input Frequency	44Hz~67Hz	-
Input max Current	16Aac rms	8.3Adc rms
Output Voltage	400Vdc	90-265Vac
Output max Current	8.3Adc rms	16Aac rms
Nominal Output Power	1.65kW @ 110Vac；3.3kW @ 220Vac	
Efficiency	Peak 98.7% at 220-Vrms input, Peak>97.7% at 110-Vrms input	Peak 98.3% at 220-Vrms output, Peak >97.3% at 110-Vrms output
Current THD	<5%	
Switch Frequency	65kHz	
DC Bus Ripple	5%	
Inductor Current Ripple	20%	

2.2 System Structure

As shown in Figure.3, the 3.3kW bi-directional Totem-Pole PFC reference design consists of three boards.

1) Power board: This board consists of an EMI filter, a start-up circuit, two PNJ´s SiC MOSFETs, two Si MOSFETs and their gate drive circuits. Also, the voltage and current sensing circuits and LDOs are included.

2) Controller Board: The control board TMDSCNCD280049C from Texas Instruments is used. The control board senses inductor´s AC current, DC link voltage and grid-side voltage. It generates four channels of PWM signal to control the MOSFETs on power stage board. Two general purpose IO pins are used to control an input AC relay and a fan.

3) Aux-Power Board: This board is a 24W QR-flyback DC-DC converter. It offers power for all control circuits, device driver and fan. The input voltage of this board is from 120VDC to 900VDC. It has two outputs 12Vdc for the control circuit and fan power respectively.

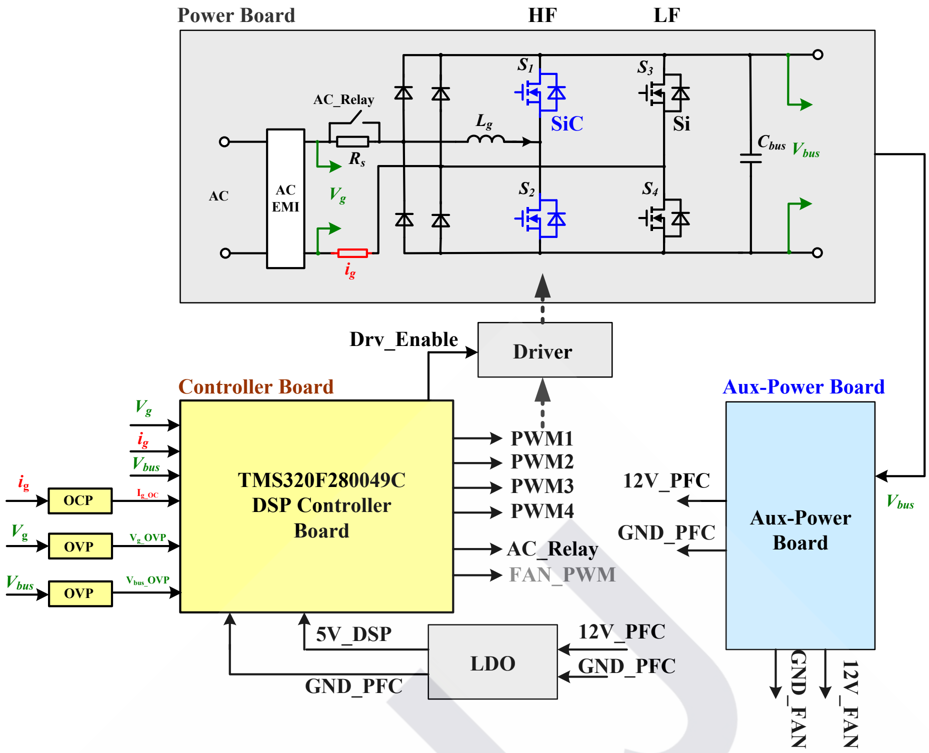

Fig. 3 The System Structure of Totem-Pole PFC Demo Board

2.3 Physical Dimensions and Pinouts

The Physical dimensions and the pinouts of PNJ's PNDM06P332A1 3.3kW totem-pole PFC board have been shown in Figure 4 and Figure 5. The board has a size of 114.3mm x210m x 65mm.

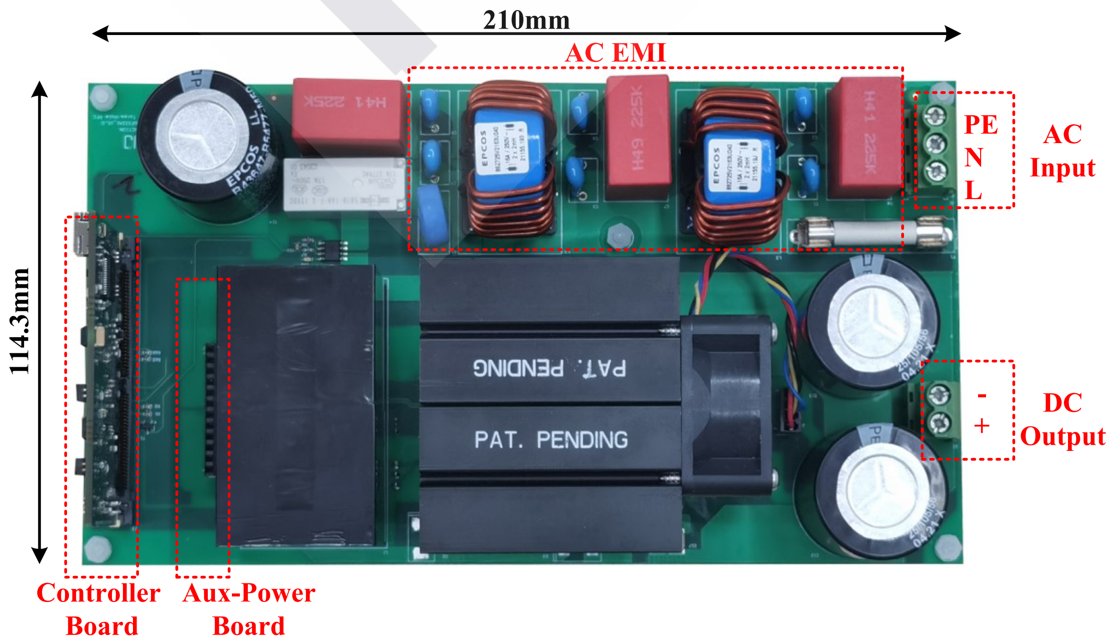

Fig. 4 Top View of PNJ's 3.3kW Totem-Pole PFC Demo board

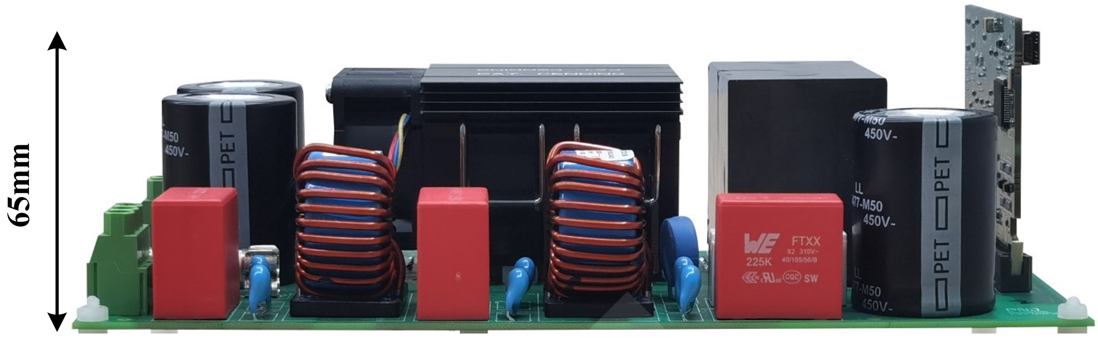

Fig. 5 Front View of PNJ's 3.3kW Totem-Pole PFC Demo board

2.4 Control Strategy

The proposed demo board adopts conventional dual-loop control strategy as shown in Figure 6. The outer loop measures the DC output voltage Vbus and generates the AC current reference signal. The inner loop measures the average inductor current by a high bandwidth hall sensor IC and generates the duty cycle signal to the pulse generator block to generate PWM signals for the high frequency switches. The grid voltage is sensed by a phase detector circuit and the output is fed into pulse generator block to control the line frequency switches. The calculation and compensator design follows conventional methods which are widely adopted in industry.

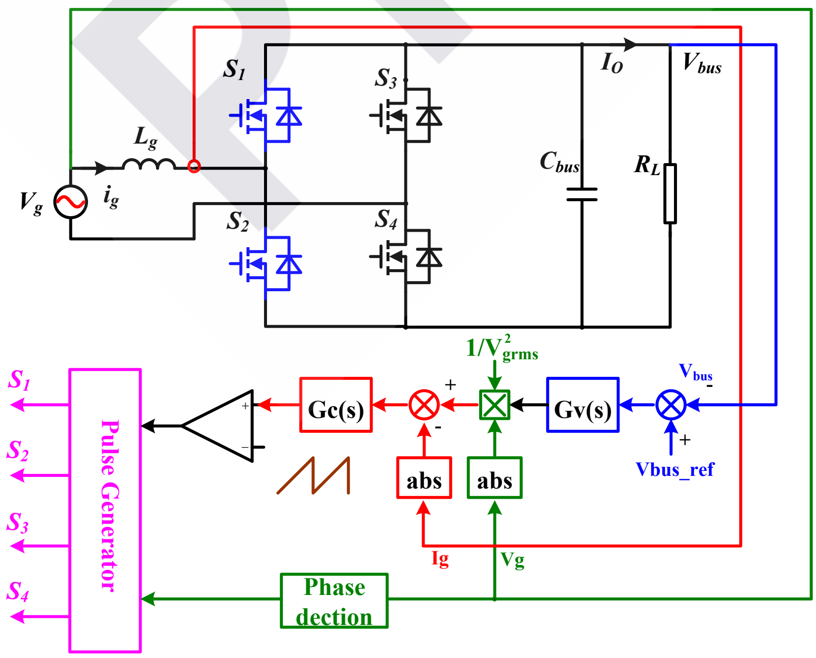

Fig.6 Control Block of CCM Totem-Pole PFC

3. Reference Board Description

3.1 Schematic of Main Power Board

Figure 7-11 shows the schematic of main power board for this reference board.

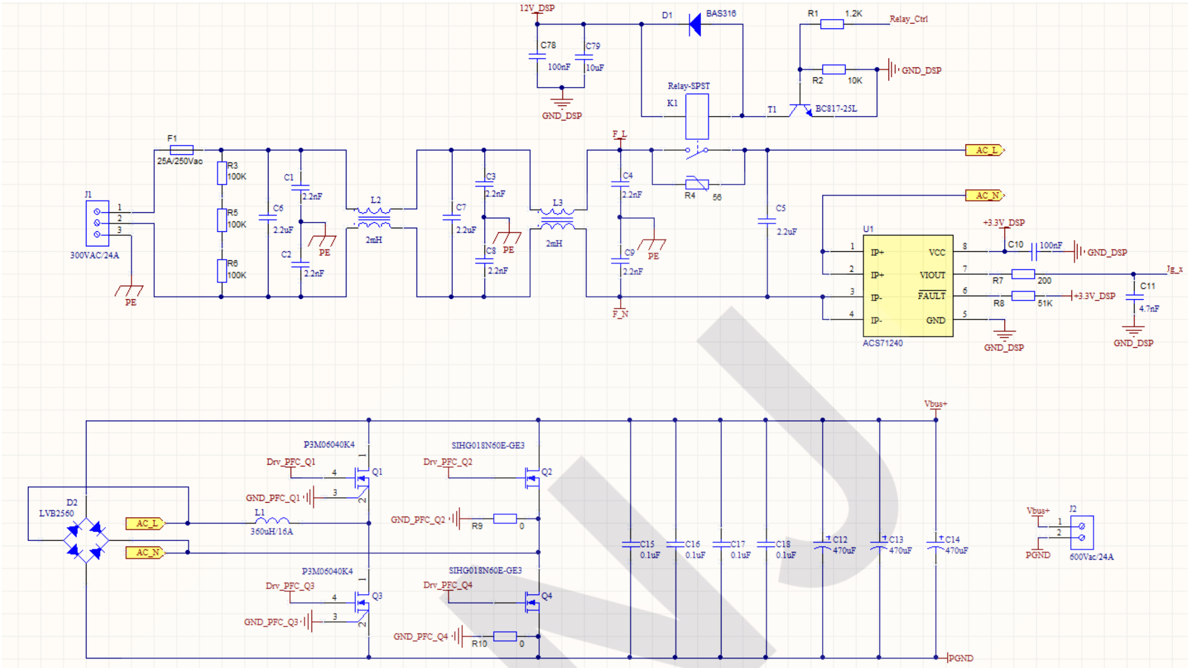

Fig.7 Schematic of PNJ's 3.3kW Totem-Pole PFC Power board I

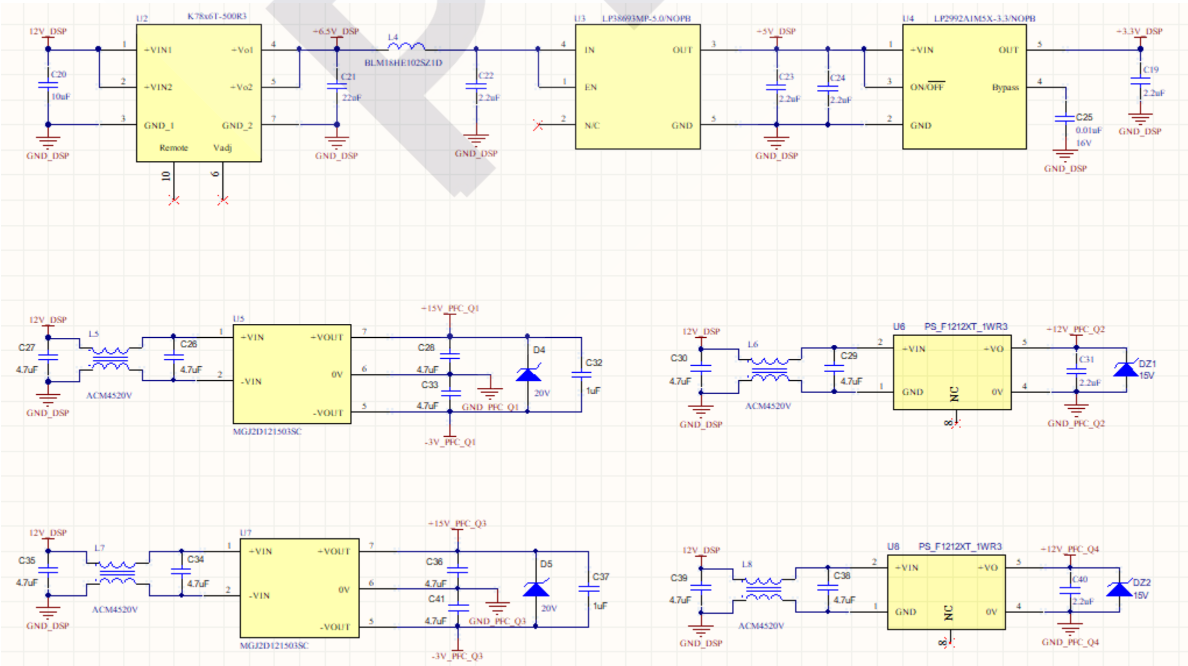

Fig.8 Schematic of PNJ's 3.3kW Totem-Pole PFC Power board II

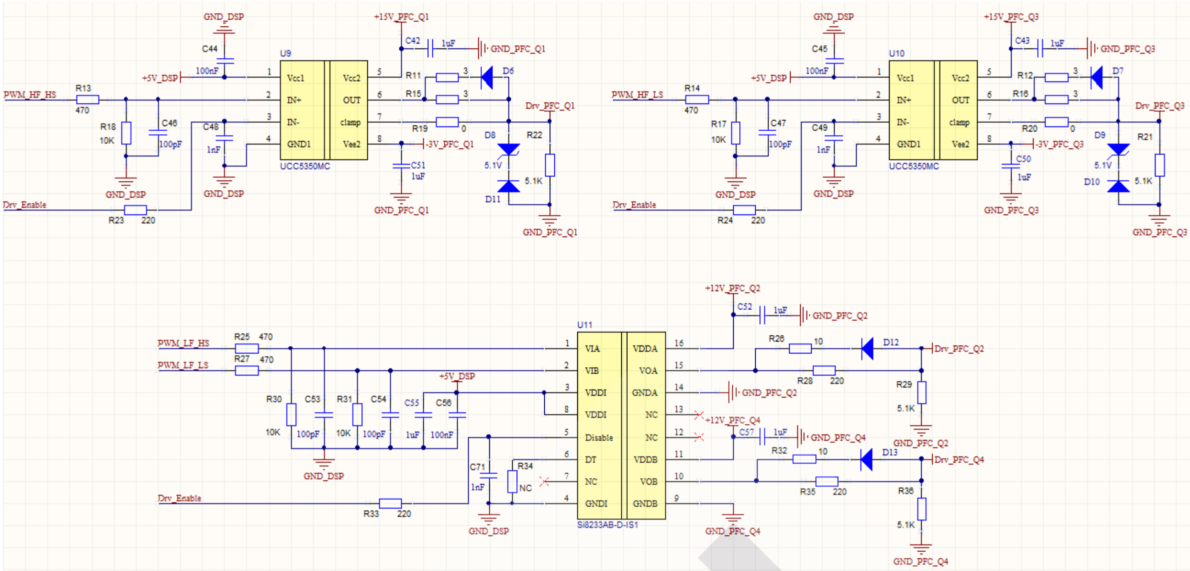

Fig.9 Schematic of PNJ's 3.3kW Totem-Pole PFC Power board III

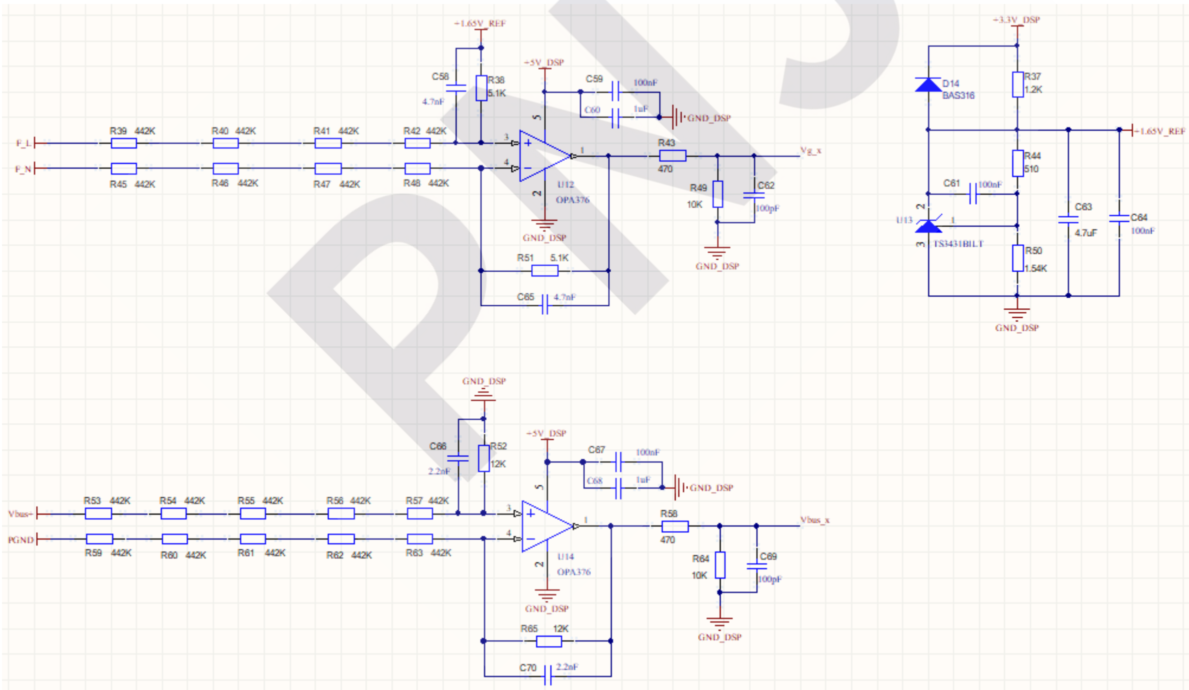

Fig.10 Schematic of PNJ's 3.3kW Totem-Pole PFC Power board IV

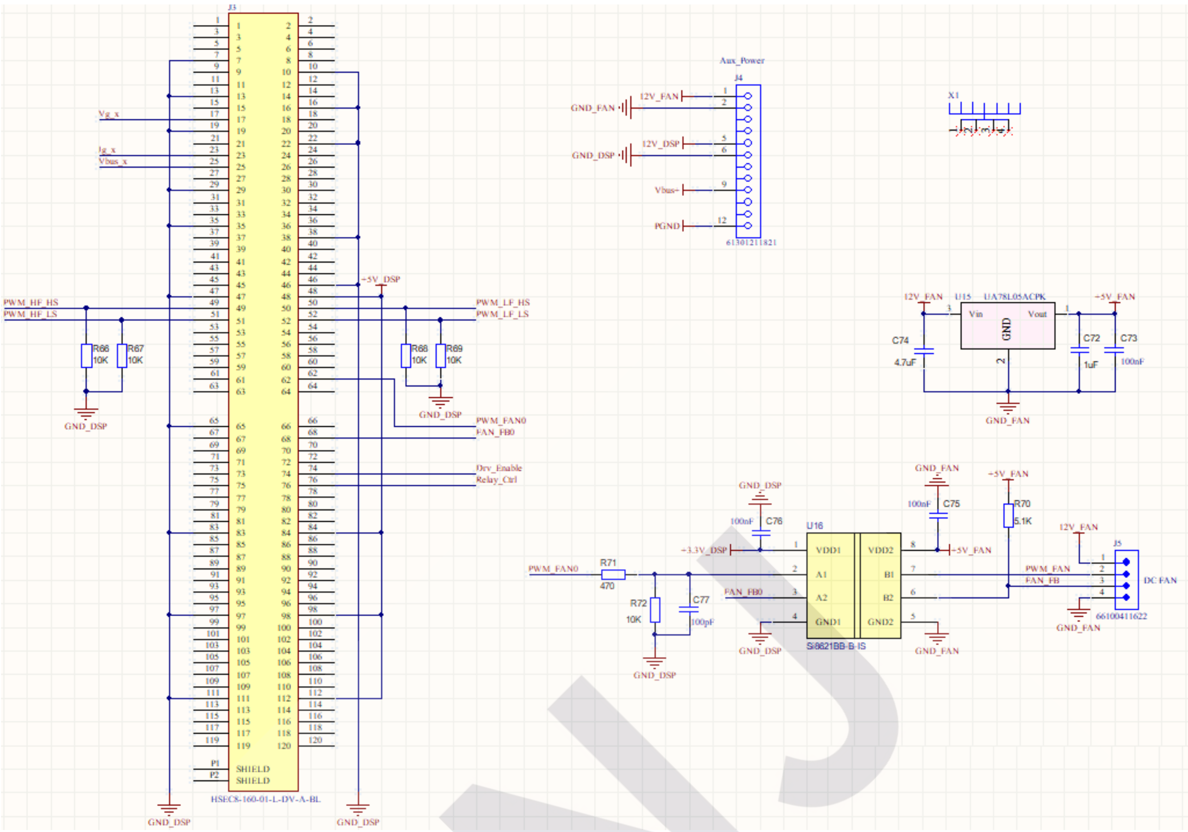

Fig.11 Schematic of PNJ’s 3.3kW Totem-Pole PFC Power board V

3.2 Layout

The layout of main power board is shown in Figure 12-15.

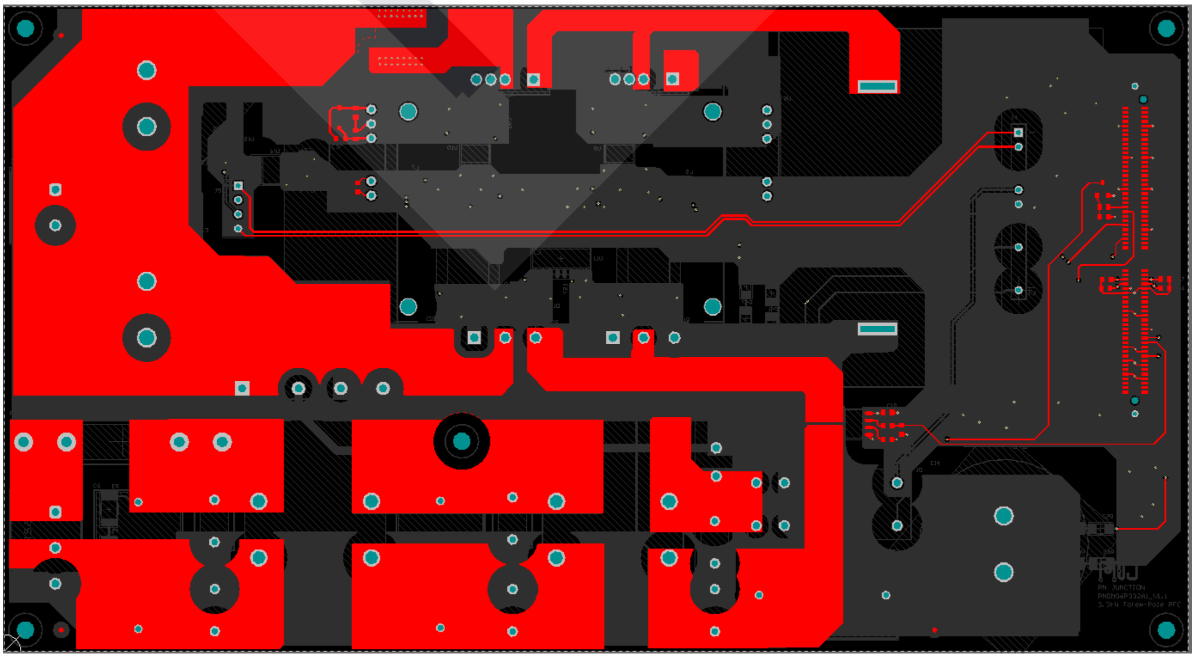

Fig.12 Top layer of the PCB

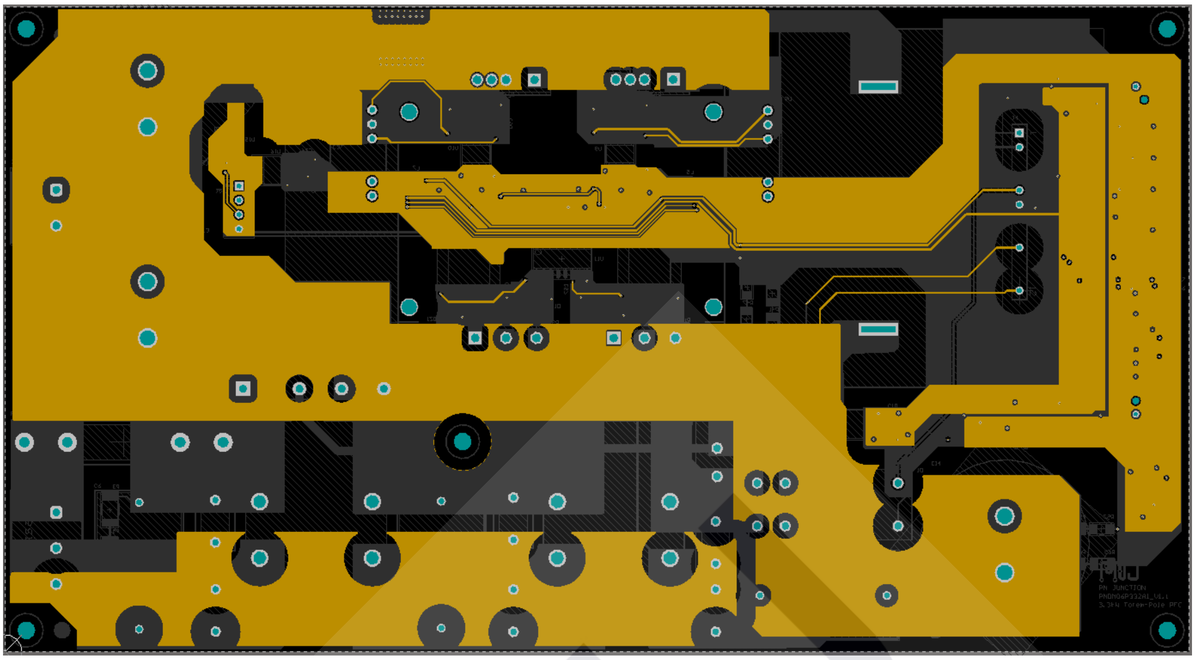

Fig.13 The first mid layer of the PCB

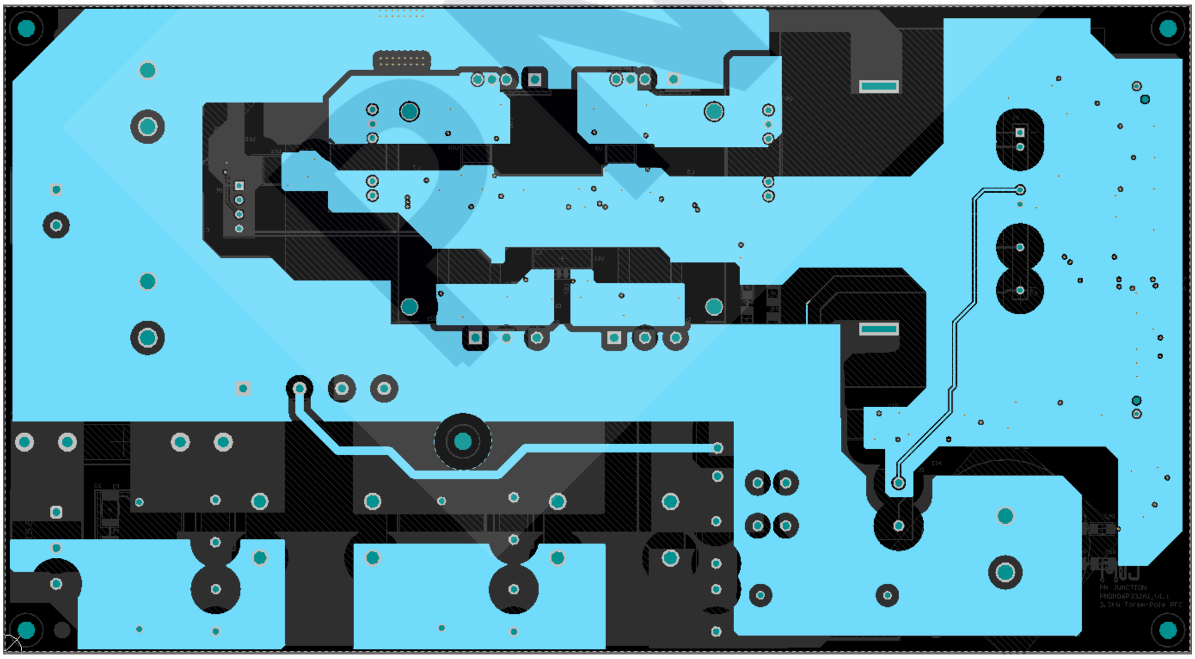

Fig.14 The second mid layer of the PCB

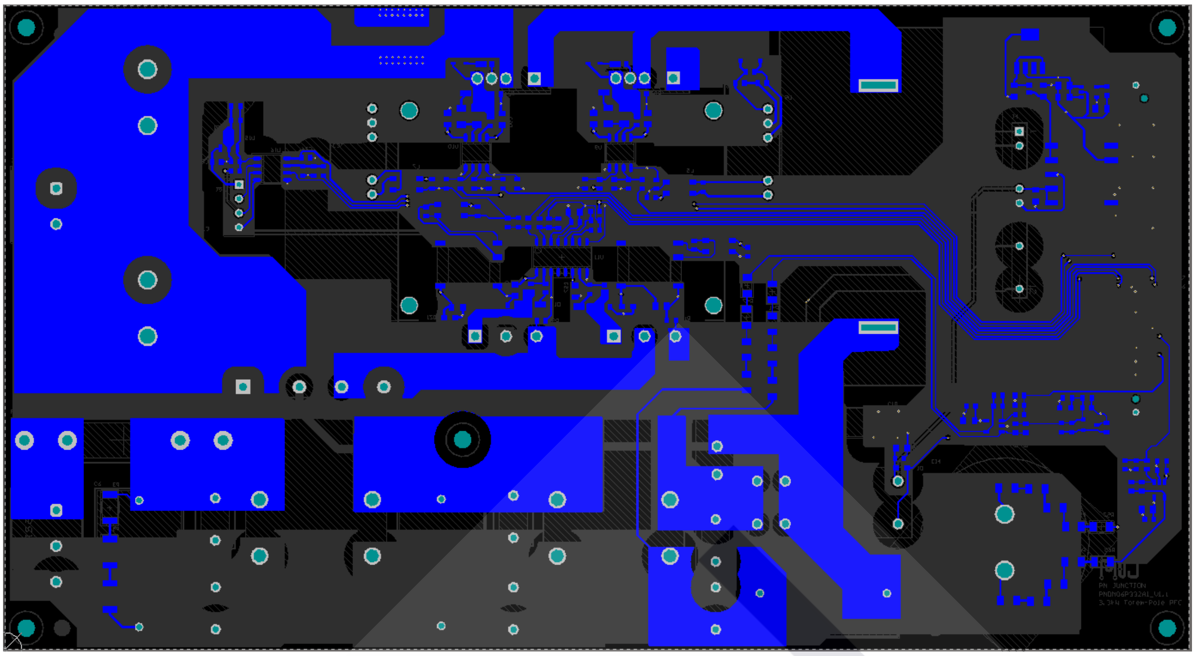

Fig.15 Bottom layer of the PCB

3.3 BOM

The BOM list of all components used for the Power Board is in shown in Tab 2.

Tab.2 Bill of Material of Main Power Board

Designator	Description	Manufacturer P/N	Manufacturer	Quantity
C1, C2, C3, C4, C8, C9	Y Capacitors, 2.2nF, 300Vac	DE6E3KJ222MA3B	Murata Electronics	6
C5, C6, C7	WCAP-FTXX Film Capacitor, THT, L26W15H25, 2.2uF, 310V	890334026034	Wurth Elektronik	3
C10, C44, C45, C56, C59, C61, C64, C67, C73, C75, C76, C78	CFCAP X7R S 100nF 50V 0603_H9 belt	06035C104K4T2A	AVX	12
C11, C58, C65	CAP X7R 4.7nF 50V 0603_H35	06035C472JAT2A	AVX	3
C12, C13, C14	E_Capacitor,470uF/450V,3040mm	B43647B5477M050	TDK	3
C15, C16, C17, C18	0.1μF ±10% 630V Ceramic Capacitor X7R 1812_H25	CGA8N4X7R2J104K230KA	TDK	4
C19, C22, C23, C24, C31, C40	CFCAP X7R 2.2μF 16V 0805_H16 belt	0805YC225KAT4A	AVX	6
C20, C79	CFCAP X7R S 10μF 25V 0805_H16 belt	08053D106KAT4A	AVX	2
C21	CFCAP X5R 22μF 16V 0805_H14 belt	C2012X5R1C226K125AC	TDK	1
C25	CAP X7R 0.01uF 16V 0603_H04	0603YC103KAT2A	AVX	1
C26, C27, C28, C29, C30, C33, C34, C35, C36, C38, C39, C41, C63, C74	MLCC - SMD/SMT 0603 25Vdc 4.7uF X5R 10%	GRT188R61E475KE13D	Murata	14
C32, C37, C72	MLCC_SMD/SMT 0603 35Vdc 1 uF X7R 10%	0603DC105KAT2A	AVX	3

C42, C43, C50, C51, C52, C55, C57, C60, C68	CFCAP X7R S 1μF 25V 0805_H14 belt	08053C105K4T2A	AVX	9
C46, C47, C53, C54, C62, C69, C77	CAP C0G S 100pF 50V 0603_H09	06035A101JAT2A	AVX	7
C48, C49, C71	CFCAP X7R S 1nF 50V 0603_H9 belt	06035C102K4T2A	AVX	3
C66, C70	CAP X7R 2.2nF 50V 0603_H35	06035C222JAT2A	AVX	2
D1, D14	Diode,100V,250mA, SOD323	BAS316Z	Nexperia	2
D2	Full Wave Diode Bridge	LVB2560	Vishay	1
D4, D5	DIODE ZENER 20V 500MW SOD123	MMSZ20T1G	ON Semiconductor	2
D6, D7, D10, D11, D12, D13	Schottky barrier diode,30V/1A, IFSM=5A, SOD-323HE	RSX101VYM30FH	ROHM	6
D8, D9	Z-DIO S 5.1V. BZX84J-B5V1 belt	BZX84J-B5V1,115	Nexperia	2
DZ1, DZ2	Z-DIO S 15V/300mW SOD323	MM3Z15VST1G	On Semiconductor	2
F1	25A/250Vac, Cartridge Fast-acting Fuse	0314025.MXP	Littlefuse	1
J1	WR-TBL Serie 2506 Horizontal Entry , THT, pitch 6.35mm, 3p	691250610003	Wurth Elektronik	1
J2	WR-TBL Serie 2506 Horizontal Entry, THT, pitch 6.35mm, 2p	691250610002	Wurth Elektronik	1
J3	120 Position Female Connector Dual Edge Gold 0.031 _0.80mm_ Black	HSEC8-160-01-L-DV-A-BL	Samtec	1
J4	WR-PHD Socket Header, THT, pitch 2.54mm, Single Row, Vertical, 12p	61301211821	Wurth Elektronik	1
J5	WR-WTB Male Vertical Shrouded Header, pitch 2.54mm, 4p	66100411622	Wurth Elektronik	1
K1	Single-Pole Single-Throw Relay,16A/240Vac	507H-1AH-F-C-12VDC	SONG CHUAN	1
L1	AC inductor,16A	HTR354561-511M	MAGSONDER	1
L2, L3	Common chock_2mH/16A	B82725V2163U040	TDK	2
L4	Ferrite Beads,1kohms 500mA,0603	BLM18HE102SZ1D	Murata	1
L5, L6, L7, L8	Common chock_230R@100MHZ,1.5A/50V, ACM4520V	ACM4520V-231-2P-T00	TDK	4
Q1, Q3	SiC MOSFET,650V,40mOhms	P3M06040K4	PN Junction Semiconductor	2
Q2, Q4	Si MOSFET,650V,23mOhms	SIHG018N60E-GE3	Vishay	2
R1, R37	RES SMD 1.2K OHM 1% 1/10W 0603_H6	RC0603FR-071K2L	Yageo	2
R2, R17, R18, R30, R31, R49, R64, R66, R67, R68, R69, R72	RES SMD 10K OHM 1% 1/10W 0603_H6	RC0603FR-0710KP	Yageo	12
R3, R5, R6	RES SMD 100K Ohms 5% 3/4W 2010_H6	RC2010JK-07100KL	Yageo	3
R4	PTC, C1451,56R/440Vac	B59451C1130B070	TDK	1
R7	RES SMD 200 OHM 1% 1/10W 0603_H6	RC0603FR-07200RL	Yageo	1
R8	RES SMD 51K OHM 1% 1/10W 0603_H6	RC0603FR-0751KL	Yageo	1
R9, R10, R19, R20	RES SMD 0 OHM 1% 1/10W 0603_H6	RC0603FR-130RL	Yageo	4
R11, R12, R15, R16	RES SMD 3 Ohms 1% 1/4W 1206_H6	RC1206FR-073RL	Yageo	4
R13, R14, R25, R27, R43, R58, R71	RES SMD 470 OHM 1% 1/10W 0603_H6	AC0603FR-07470RL	Yageo	7
R21, R22, R29, R36, R38, R51, R70	RES SMD 5.1K OHM 1% 1/10W 0603_H6	RC0603FR-075K1L	Yageo	7

R23, R24, R28, R33, R35	RES S 220 Ohm 1.% 0603_H6 belt	AC0603FR-07220RL	Yageo	5
R26, R32	RES SMD 10 OHM 1% 1/10W 0603_H6	RC0603FR-0710RL	Yageo	2
R34	RES SMD 1 KOHM 1% 1/10W 0603_H6	RC0603FR-071KL	Yageo	1
R39, R40, R41, R42, R45, R46, R47, R48, R53, R54, R55, R56, R57, R59, R60, R61, R62, R63	RES SMD 442K Ohms ,1% 1/4W 1206_H6	RC1206FR-07442KL	Yageo	18
R44	RES SMD 510 OHM 0.1% 1/10W 0603_H6	RT0603BRD07510RL	Yageo	1
R50	RES SMD 1.54K OHM 0.1% 1/10W 0603_H6	RT0603BRD071K54L	Yageo	1
R52, R65	RES SMD 12K OHM 1% 1/10W 0603_H6	RC0603FR-0712KL	Yageo	2
T1	NPN BJT,500mA/45V, SOT23	SBC817-25LT3G	On Semiconductor	1
U1	30A, Galvanically isolated current sensor, SOIC	ACS71240LLCBTR-030B3	Allergro Micro System	1
U2	No-isolated DC-DC Converters,12V/6.5V,500mA	K78x6T-500R3	Mornsun	1
U3	LDO,5V/500mA, SOT223	LP38693MP-5.0/NOPB	Texas Instruments	1
U4	LDO,3.3V/250mA, SOT23	LP2992AIM5X-3.3/NOPB	Texas Instruments	1
U5, U7	Isolated 2W DC-DC Converters,12-15V/-3V	MGJ2D121503SC	Murata	2
U6, U8	DC/DC CONV SMD 1W	F1212XT-1WR3	Mornsun	2
U9, U10	High CMTI 3kV 12V UVLO single isolated driver	UCC5350MCD	Texas Instruments	2
U11	High CMTI 2.5 kV 5 V UVLO single isolated driver	Si8233AB-D-IS1	Silicon Labs	1
U12, U14	Low noise, Precision OPA, SOT235	OPA376	Texas Instruments	2
U13	Shunt Adjustable Precision References, SOT23-3	TS3431BILT	ST	1
U15	IC REG LINEAR 5V 100MA SOT89-3	UA78L05ACPK	Texas Instruments	1
U16	High CMTI 2.5 kV dual digital isolator	Si8621BB-B-IS	Silicon Labs	1

4. Test Result

4.1 Waveforms

PNJ´s PNDM06P332A1 reference design has been tested under various input and load conditions to demonstrate the performance of the proposed CCM totem-pole PFC converter solution. The test waveforms are shown in Figure 16-19 respectively. Figure 16 shows the operation waveforms of full load at the grid voltage Vg=220VAC. The start-up waveform is shown in Figure 17. The load-transient response of the converter is shown in Figure 18 and Figure 19. Figure 18 shows the transient response when the DC load current steps down from 8.3A to 4A first, then steps down to 0A eventually. Figure 19 shows the transient response when the DC load current steps up from 0.8A (10% of full load) to 7.5A (90% of full load).

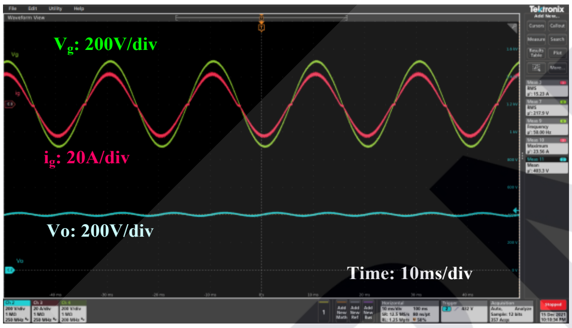

Fig. 16 Steady-state waveform at 220 V, 50 Hz AC at full load (3.3kW)

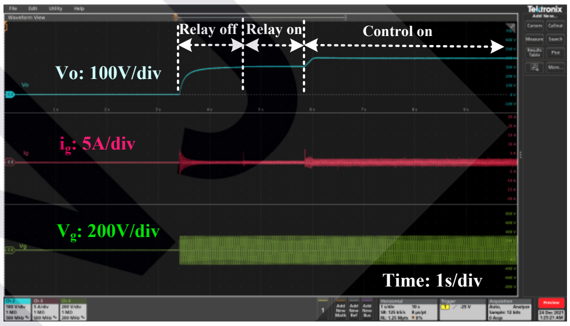

Fig. 17 Soft start-up waveform at 220V,50Hz AC Voltage

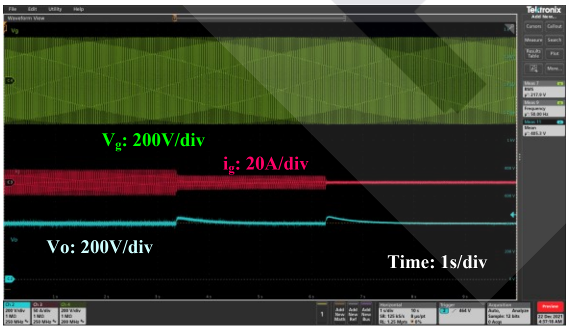

Fig. 18 Transient response from full load to half load, and from half-load to no-load step at Vg=220Vac

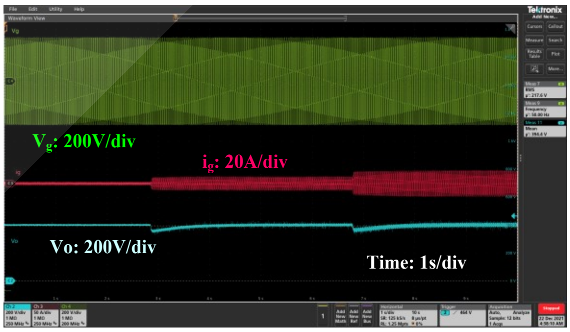

Fig. 19 Transient response from 10% load to 90% load step at Vg=220Vac

4.2 Efficiency

The efficiency of PNJ' s PNDM06P332A1, 3.3kW Totem-Pole PFC board was tested by Power Analyzer WT1804E in different load as shown in Figure 20. These measurements (without DC Fan and Aux-Power loss) are taken at 176V, 220V, 265 V AC input voltage respectively. PNJ´s SiC MOSFET P3M06040K4 was used as high frequency switches. The peak efficiency measured at each input voltage is 98.51% at 176 Vac, 98.84% at 220 Vac and 99.05% at 265 Vac.

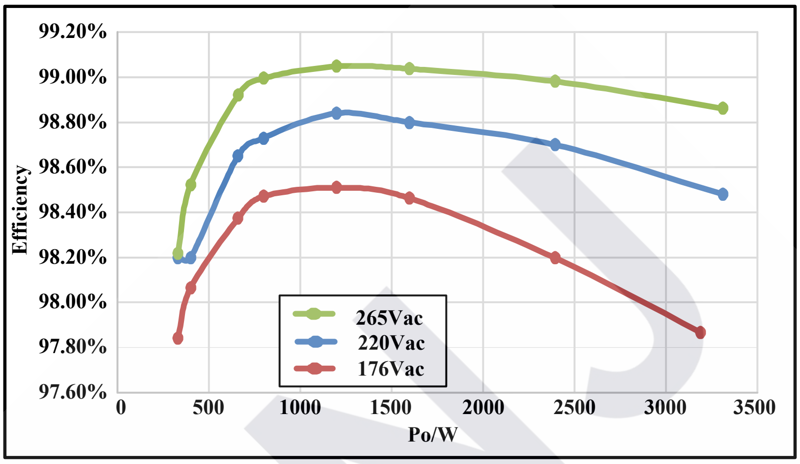

Fig. 20 Efficiency measurements of PNJ's PNDM06P332A1 3.3kW Totem-Pole PFC board at 176 Vac, 220Vac and 265Vac input in different load with P3M06040K4 SiC Device

The peak efficiency of PNJ's PNDM06P332A1 increase when the high frequency SiC MOSFET P3M06040k4 was replaced by P3M06060K4. As can be seen in Figure 21, the peak efficiency is 98.63% at 176 Vac, 98.89% at 220 Vac and 99.19% at 265 Vac. Due to smaller switch loss and higher Rds(on) of P3M06060K4, the efficiency is higher at light load but lower at full load.

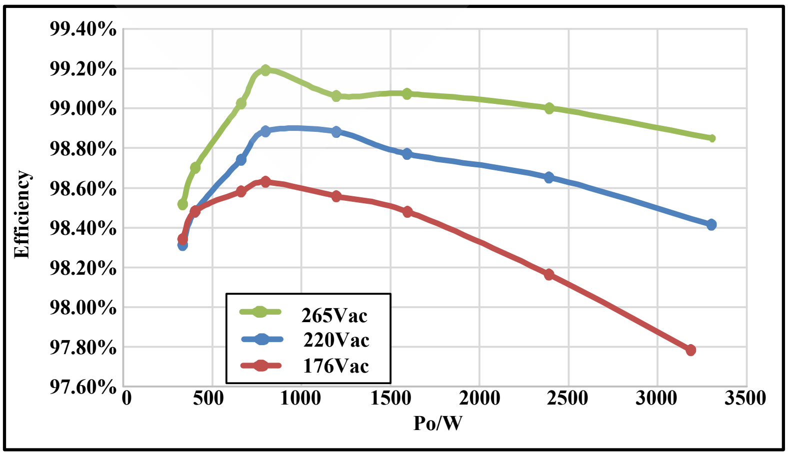

Fig. 21 Efficiency measurements of PNJ's PNDM06P332A1 3.3kW Totem-Pole PFC board at 176 Vac, 220Vac and 265Vac input in different load with P3M06060K4 SiC Device

4.3 Thermal Performance

Thermal images for the demo board with SiC MOSFET P3M06040K4 were taken at 220 Vac, 400 Vdc, full load (8.3 A DC) and the ambient temperature was 25 °C with forced air cooling. As shown in Figure 22 and 23, the boost inductor temperature is 46.1 °C. The case temperature of SiC MOSFET is 60.7 °C, which is the maximum temperature observed on board. The test is conducted again at 176Vac input voltage as shown in Figure 24 and 25. The inductor´s temperature is 45.4 °C and the maximum temperature observed is 66.1°C at the case of the SiC MOSFET.

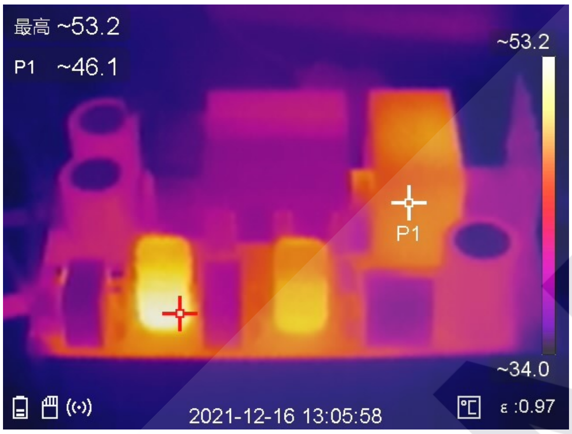

Fig. 22 Thermal Image of PCB at input voltage of 220Vac, full load Io=8.3A

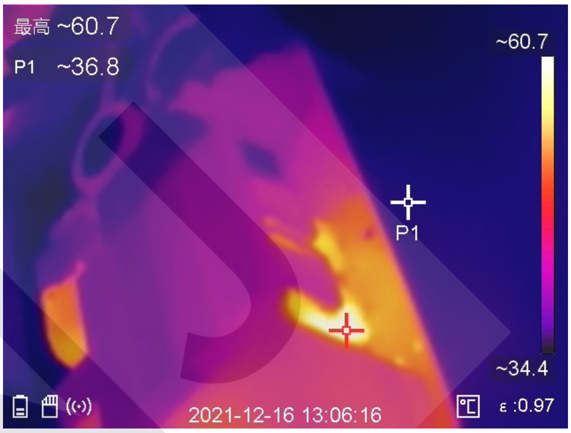

Fig. 23 Thermal Image of high frequency device at input voltage of 220Vac, full load Io=8.3A

Fig. 24 Thermal Image of PCB at input voltage of 176Vac, full load Io=8.3A

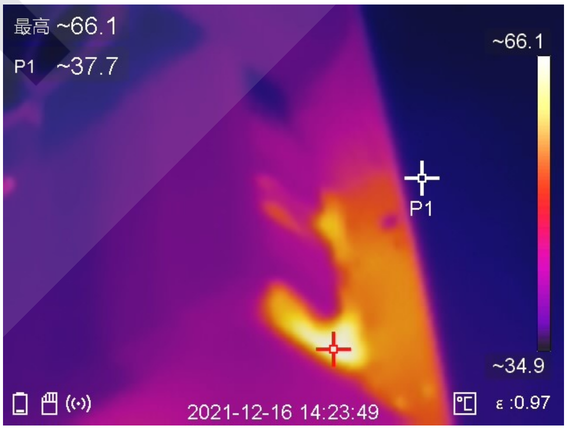

Fig. 25 Thermal Image of high frequency device at input voltage of 176 Vac, full load Io=8.3A

Reference

[1] L.Huber,Y.Jang and M.M Jovanivić : Performance Evaluation of Bridgeless PFC Boost Rectifiers, IEEE Transactions on Power Electronics,Vol.23,No.3,pp.1381-1390,2008

[2] P3M06040K4/P3M06060KE datasheet, 650V SiC MOSFET

4 Revision History

Date	Revision	Description of change
2022.01.07	V1.0	Initial Version