UM11967

TEA2376DB1623 1 kW PFC standalone design example

Rev. 1.0 — 16 April 2024 User manual

Document information

Information	Content
Keywords	TEA2376, TEA2376DB1623, 1 kW, PFC, interleaved, controller, converter, burst mode, shedding, power supply, TEA2209, active bridge rectifier, programmable settings, I2C
Abstract	The TEA2376DT is a digital configurable two-phase interleaved PFC controller for high-efficiency power supplies. The PFC operates in discontinuous conduction mode or critical conduction mode with valley switching to optimize efficiency. The TEA2376 enables the design of a low-component count interleaved power factor converter. The digital architecture is based on a configurable hardware state machine, ensuring reliable real-time performance. During power supply development, many operation and protection settings of the PFC controller can be adjusted by loading new settings into the device with I2C to meet specific application requirements. Input current shaping is used for a high power factor and a low THD. For low-load operation with good efficiency, phase shedding and burst mode operation are included. In burst mode, the power consumption of the IC is reduced. The TEA2376 contains many protections, like internal and external overtemperature protection (OTP), overcurrent protection (OCP), dual overvoltage protection (OVP), inrush current protection (ICP), pin-open and pin-short protection, and phase fail protection (PFP). The protections can be configured independently using programmable parameters. The TEA2376DB1623 prototype demo board shows an interleaved PFC converter (TEA2376) in combination with an active bridge rectifier (TEA2209) without heatsinks. The converter can deliver 1 kW output power in lab conditions without forced cooling.

1 Important notice

IMPORTANT NOTICE

For engineering development or evaluation purposes only

NXP provides the product under the following conditions:

This evaluation kit or reference design is for use of ENGINEERING DEVELOPMENT OR EVALUATION PURPOSES ONLY.

It is provided as a sample IC pre-soldered to a printed circuit board to make it easier to access inputs, outputs, and supply terminals. This evaluation kit or reference design may be used with any development system or other source of I/O signals by connecting it to the host MCU or computer board via off-the-shelf cables. Final device in an application will be heavily dependent on proper printed circuit board layout and heat sinking design as well as attention to supply filtering, transient suppression, and I/O signal quality.

The product provided may not be complete in terms of required design, marketing, and or manufacturing related protective considerations, including product safety measures typically found in the end device incorporating the product. Due to the open construction of the product, it is the responsibility of the user to take all appropriate precautions for electric discharge. To minimize risks associated with the customers' applications, adequate design and operating safeguards must be provided by the customer to minimize inherent or procedural hazards. For any safety concerns, contact NXP sales and technical support services.

2 Safety warning

The application board is AC-mains voltage powered. Avoid touching the board while it is connected to the mains voltage and when it is in operation. An isolated housing is obligatory when used in uncontrolled, non-laboratory environments. Galvanic isolation from the mains phase using a fixed or variable transformer is always recommended.

Figure 1 shows the symbols on how to recognize these devices.

019aab173

a. Isolated

019aab174

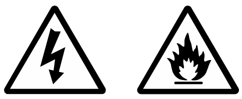
b. Not isolated

Figure 1. Isolation symbols

3 Introduction

WARNING

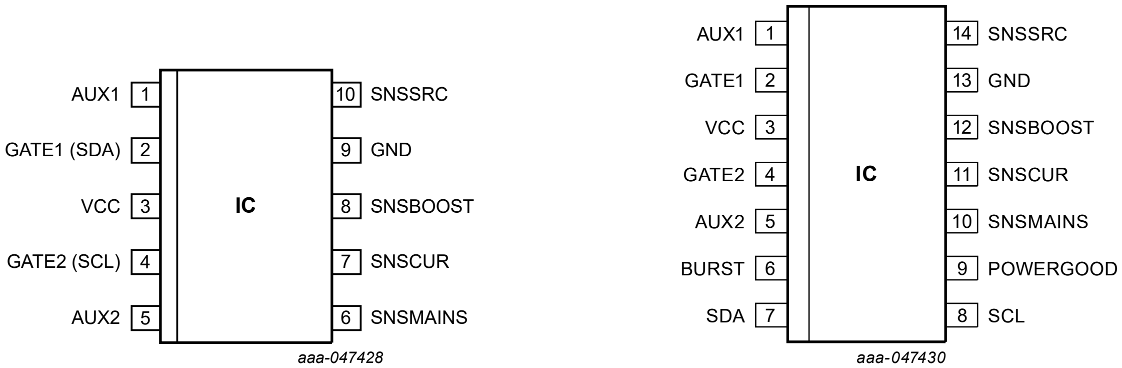
Lethal voltage and fire ignition hazard



The non-insulated high voltages that are present when operating this product, constitute a risk of electric shock, personal injury, death and/or ignition of fire. This product is intended for evaluation purposes only. It shall be operated in a designated test area by personnel qualified according to local requirements and labor laws to work with non-insulated mains voltages and high-voltage circuits. This product shall never be operated unattended.

The TEA2376 provides high efficiency at all power levels. Together with the TEA2209 active bridge rectifier controller, the TEA19161 LLC controller, and the TEA2095 SR controller, a high-performance, cost-effective resonant power supply can be designed, which meets modern power-supply efficiency regulations.

An extensive number of parameter settings for operation can define operation modes and protections. Protections can be stored/programmed in an internal memory. This feature provides flexibility and ease of design to optimize controller properties to application-specific requirements or even optimize/correct performance during power supply production. At start-up, the IC loads the parameter values for operation. For easy design work during product development, the TEA2376DT version is available to make setting changes on the fly.



a. SO10

b. SO14

Figure 2. TEA2376 pinning diagrams

The TEA2209 is an active bridge rectifier controller that replaces the traditional diode bridge. Using the TEA2209 with low-ohmic high-voltage external MOSFETs significantly improves the efficiency of the power converter because the typical rectifier diode-forward conduction losses are eliminated. In addition, the TEA2209 includes an X-capacitor discharge function. To reduce power consumption at a standby condition, an external signal via the COMP pin can disable the TEA2209.

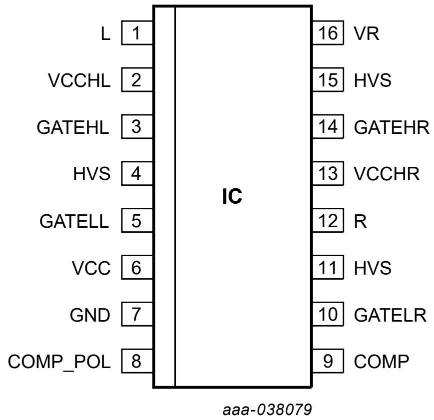


Figure 3. TEA2209 pinning diagram

4 Finding kit resources and information on the NXP website

NXP Semiconductors provides online resources for this user manual and its supported devices at https://www.nxp.com.

This design example user manual can be found at: https://www.nxp.com.

4.1 Collaborate in the NXP community

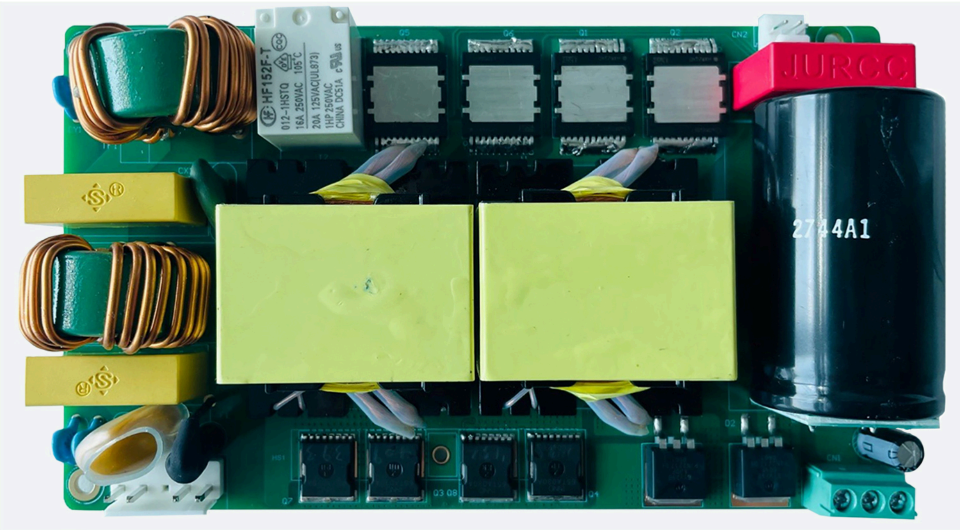
In the NXP community you can share ideas and tips, ask and answer technical questions, and receive input on just about any embedded design topic.

The NXP community can be found at https://community.nxp.com.

5 Getting ready

5.1 Box contents

The box contains the TEA2376DB1623 evaluation board, which incorporates the TEA2376DT in an SO-14 package and the TEA2209T in an SO-16 package. Figure 4 shows the top side and bottom side of the evaluation board.



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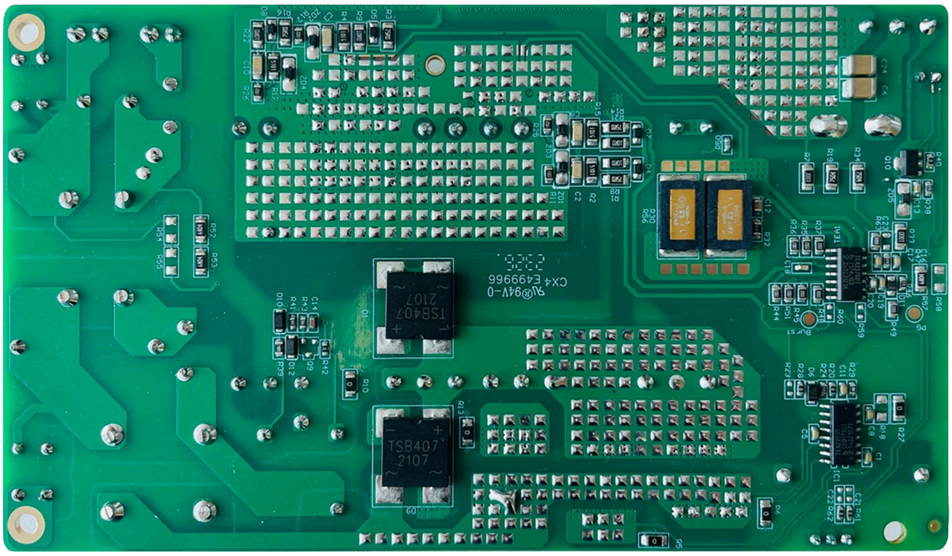
a. Top side



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b. bottom side

Figure 4. TEA2376DT 1 kW design example

6 Getting to know the hardware

6.1 Specifications

Table 1. Specifications

Symbol	Parameter	Value	Condition
Input			
V_{mains}	mains voltage	90 V to 264 V	AC
f_{mains}	mains frequency	47 Hz to 63 Hz	
PF	power factor	> 0.99	90 V (AC) to 264 V (AC); P_{out} = 1 kW
iTHD	total harmonic distortion (maximum power)	< 10 %	90 V (AC) to 264 V (AC)
Output			
V_{out}	output voltage	385 V	
$I_{out(max)}$	maximum output current	2.6 A	
$\eta_{100\%}$	maximum load efficiency	> 97.0 %	at 115 V/60 Hz; P_{out} = 1 kW
		> 98.5 %	at 230 V/60 Hz; P_{out} = 1 kW
Temperature			
T_{comp}	components temperature	see Section 7.10	at room temperature

6.2 Features

6.2.1 Distinctive features

- Interleaved PFC controller in an SO14 package
- Programmable phase shedding and burst-mode operation
- Dual output overvoltage protection
- Inrush current protection
- High power factor (PF) and low total harmonic distortion (THD), also at high input voltages
- Many parameters can be configured during evaluation with a graphical user interface (GUI)
- Good phase control over the full input voltage range
- Low audible noise
- Power good output and a burst mode input pin
- Live monitoring of (internal) IC signals over time with a GUI similar to oscilloscope reading
- I^2C communication while in operation mode

6.2.2 Green features

- Valley/zero voltage switching for minimum switching losses
- High efficiency from high load to medium load and low load through phase shedding and burst mode operation power

6.2.3 Protection features

- Protections can independently be set to latched, safe restart, or latched after several attempts to restart
- Dual output overvoltage protection (OVP)
- Supply undervoltage protection (UVP) and overvoltage protection (OVP)
- Internal and external overtemperature protection (OTP)
- Overcurrent protection (OCP)
- Inrush current protection (ICP)
- Brownin/brownout protection
- Open and short pin protection
- Coil short protection
- Output diode short protection
- Open control loop protection
- Phase fail protection

7 Performance measurement

7.1 Test facilities

- Oscilloscope: Agilent Technologies DSO9064A
- AC power source: Chroma 61504
- Electronic load: Chroma 63202E-600-140
- Digital power meter: WT210

7.2 Start-up behavior

- **Start-up operation**

TEA2376DT implements a soft start. The soft-start function gradually increases the PFC output voltage. This new soft-start method does not make overshoots on the PFC output voltage and there is no overstress on the PFC inductor current.

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a. PFC start-up at 115 V mains and 1 kW

- CH1: V_{BOOST} (100 V/div)
- CH2: $V_{CC\_External}$ (5 V/div)
- CH4: I_{MAINS} (20 A/div)
- Time: 100 ms/div

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b. PFC start-up at 230 V mains and 1 kW

- CH1: V_{BOOST} (100 V/div)
- CH2: $V_{CC\_External}$ (5 V/div)
- CH4: I_{MAINS} (20 A/div)
- Time: 100 ms/div

Figure 5. PFC start-up performance

7.3 Normal operation

TEA2376DT incorporates an average mode control. To achieve good power factor and total harmonic distortion performances, TEA2376DT controls the average PFC inductor current as a sinusoidal waveform. To compensate for a phase shift between the AC mains voltage and the average inductor current due to AC mains filter capacitors, the PFC starts switching after a delay in every mains voltage cycle. Because the mains filter capacitor is different for different power levels, MTP can select this shift factor.

To achieve the best efficiency, the TEA2376DT incorporates frequency clamping and foldback functions.

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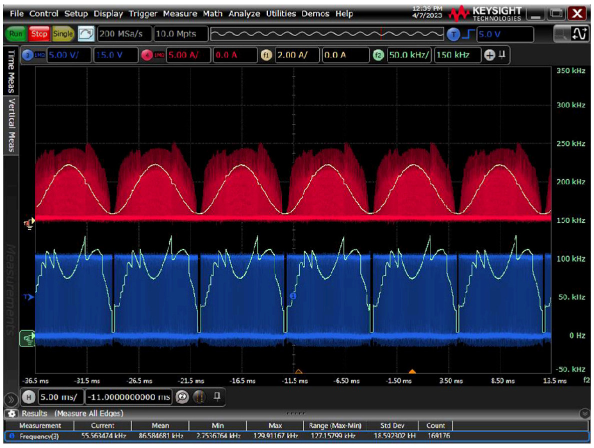
a. PFC operation at 115 V mains and 1 kW

- CH3: V_{GATE_PHASE1} (5 V/div)
- CH4: I_{DIODE_PHASE1} (5 A/div)
- F1: $I_{AVERAGE\_DIODE\_PHASE1}$ (2 A/div)
- F2: $Freq_{PHASE1}$ (50 kHz/div)
- Time: 5 ms/div



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b. PFC operation at 230 V mains and 1 kW

- CH3: V_{GATE_PHASE1} (5 V/div)
- CH4: I_{DIODE_PHASE1} (5 A/div)
- F1: $I_{AVERAGE\_DIODE\_PHASE1}$ (2 A/div)
- F2: $Freq_{PHASE1}$ (50 kHz/div)
- Time: 5 ms/div

Figure 6. PFC max power operation

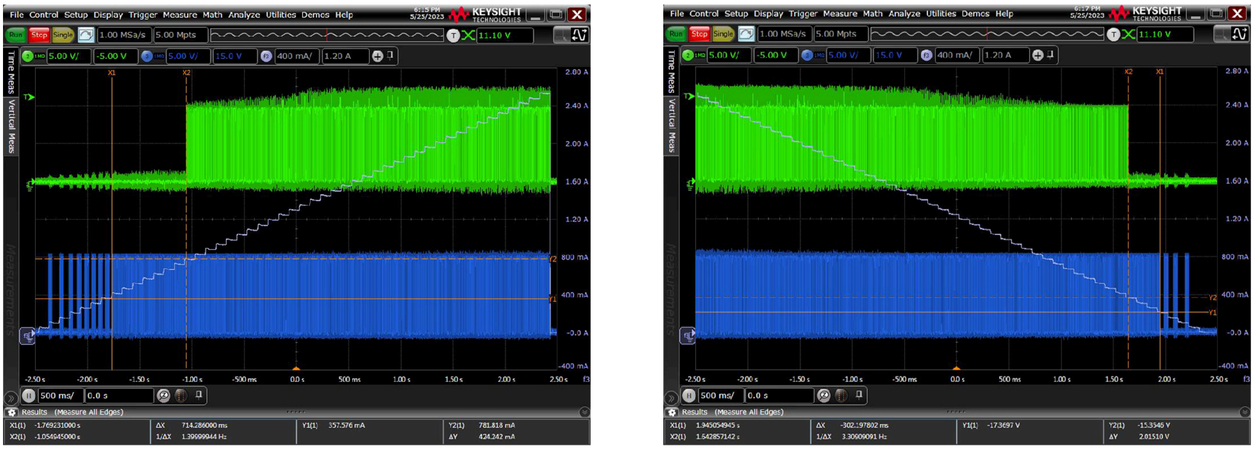
7.4 Operation mode transitions

There are three modes of operation:

- Normal mode
- Phase shedding
- Burst mode (BM):
  The transition level can be modified using MTP settings.

Table 2. Mode transitions

Mode	90 V (AC)	115 V (AC)	230 V (AC)	264 V (AC)
phase adding	316 W	317 W	317 W	312 W
phase shedding	212 W	213 W	209 W	209 W
entering burst mode	117 W	116 W	115 W	No PFC operation because $V_{in} > V_{boost}$
leaving burst mode	148 W	148 W	149 W	



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a. Phase adding at 115 V mains

- CH2: V_{GATE_PHASE2} (5 V/div)
- CH3: V_{GATE_PHASE1} (5 V/div)
- F3: I_{OUTPUT} (400 mA/div)
- Time: 500 ms/div

b. Phase shedding at 115 V mains

- CH2: V_{GATE_PHASE2} (5 V/div)
- CH3: V_{GATE_PHASE1} (5 V/div)
- F3: I_{OUTPUT} (400 mA/div)
- Time: 500 ms/div

Figure 7. Mode transitions performance

7.5 Phase control

TEA2376DT can regulate the phase difference of the two PFC channels to 180 degrees at all mains and with different loads.

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a. Interleaving at 90 V mains and 1 kW

- CH2: V_{GATE_PHASE2} (5 V/div)
- CH3: V_{GATE_PHASE1} (5 V/div)
- Time: 1 ms/div and 2 µs/div

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b. Interleaving at 264 V mains and 1 kW

- CH2: V_{GATE_PHASE2} (5 V/div)
- CH3: V_{GATE_PHASE1} (5 V/div)
- Time: 1 ms/div and 2 µs/div

Figure 8. Interleaving operation at full load

7.6 Dynamic load response

The undershoot and the overshoot of the output voltage during a dynamic load condition is measured at the PCB end. For the dynamic load, the output load is changed between maximum nominal load and no load. The slew rate is set as 2.5 A/µsec. The load step frequency is 2.5 Hz.

Table 3. Output undershoot and overshoot at load steps

	90 V (AC)	115 V (AC)	230 V (AC)	264 V (AC)
undershoot	333.6 V	335.7 V	337.5 V	341.9 V
overshoot	416.4 V	414.5 V	409.4 V	409.4 V

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a. Dynamic load response at 90 V mains

- CH2: V_{BOOST} (50 V/div)
- CH4: I_{OUT} (2 A/div)
- Time: 200 ms/div

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b. Dynamic load response at 264 V mains

- CH2: V_{BOOST} (50 V/div)
- CH4: I_{OUT} (2 A/div)
- Time: 200 ms/div

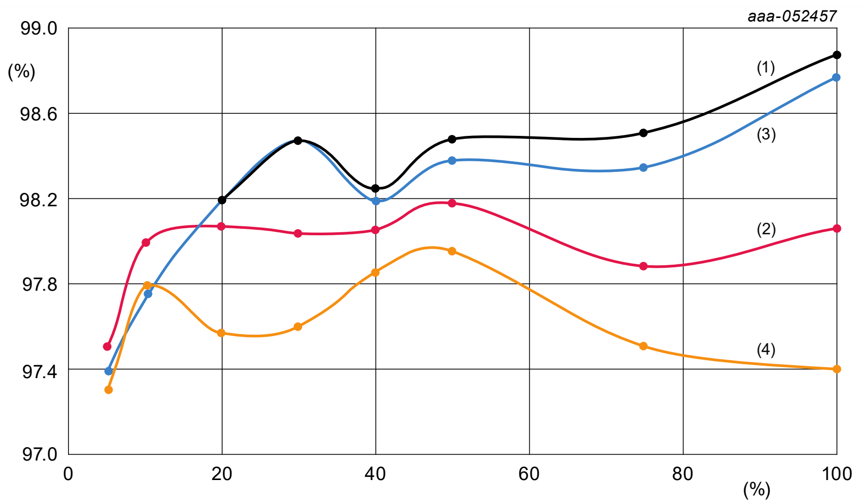
Figure 9. Dynamic load response at 2.5 Hz step load

7.7 Efficiency test results

Efficiency is measured at maximum power rating. It is over 98.5 % at high mains.

Table 4. Efficiency test results

Mains condition	Output condition	Specification	Test result
115 V/60 Hz	1 kW; 385 V; 2.6 A	> 97.0 %	98.06 %
230 V/50 Hz	1 kW; 385 V; 2.6 A	> 98.5 %	98.76 %



(1) 264 V (AC)
(2) 115 V (AC)
(3) 230 V (AC)
(4) 90 V (AC)

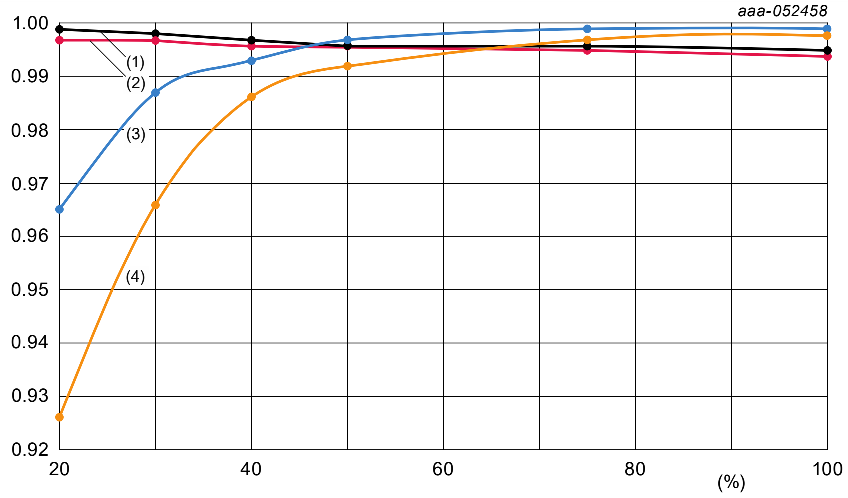
Figure 10. Efficiency

7.8 Power factor test results

Table 5 shows the power factor correction specification and its results. Figure 11 shows additional power factor test results at each mains condition and different load conditions.

Table 5. Power factor

Mains condition	Output condition	Specification	Test result
90 V/60 Hz	1 kW; 100 % load	> 0.99	0.994
115 V/60 Hz	1 kW; 100 % load	> 0.99	0.995
230 V/50 Hz	1 kW; 100 % load	> 0.99	0.999
264 V/50 Hz	1 kW; 100 % load	> 0.99	0.997



(1) 115 V (AC)
(2) 90 V (AC)
(3) 230 V (AC)
(4) 264 V (AC)

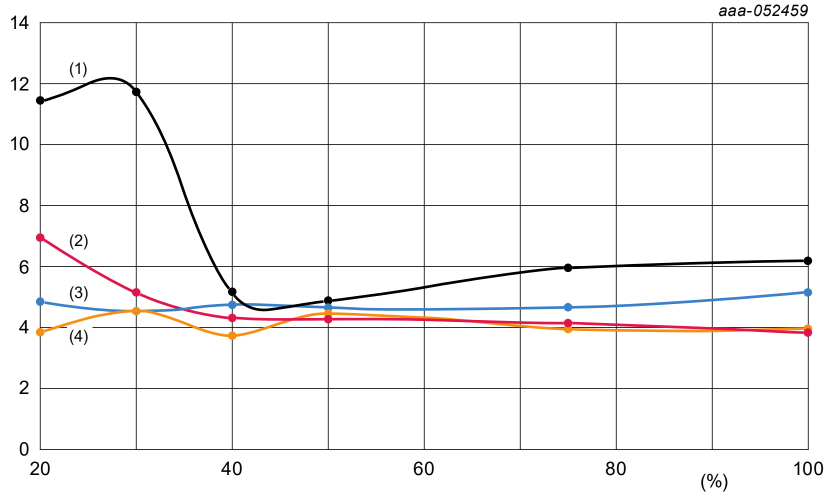
Figure 11. Power factor

7.9 Total harmonic distortion test results

Table 6 shows the total harmonic distortion specification and its results. Figure 12 shows additional power factor test results at each mains condition and different load conditions.

Table 6. Total harmonic distortion

Mains condition	Output condition	Specification	Test result
90 V/60 Hz	1 kW; 50 % load	< 10 %	4.6 %
115 V/60 Hz	1 kW; 50 % load	< 10 %	4.4 %
230 V/50 Hz	1 kW; 50 % load	< 10 %	4.3 %
264 V/50 Hz	1 kW; 50 % load	< 10 %	4.8 %

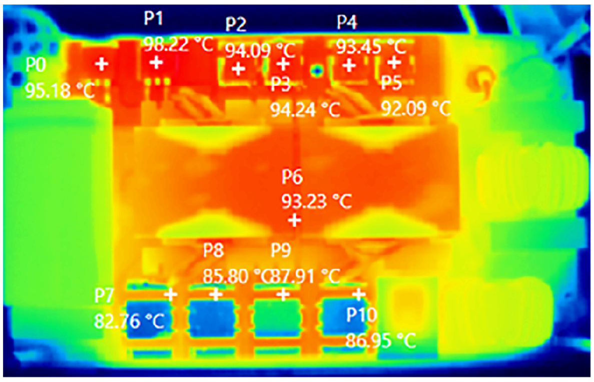


(1) 264 V (AC)
(2) 230 V (AC)
(3) 90 V (AC)
(4) 115 V (AC)

Figure 12. Total harmonic distortion

7.10 Components temperature performance

Temperature is measured at a room-temperature condition.



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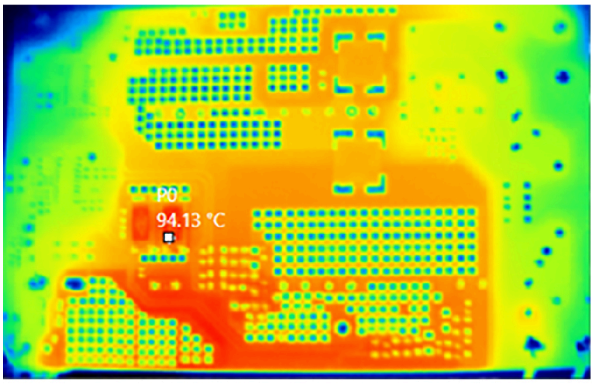
a. Top



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b. Bottom

Figure 13. Temperature performance at 1 kW and 90 V mains condition

Table 7. Temperature test results at 1 kW and 90 V mains condition

Components	Specification	Test result
active bridge MOS	< 100 °C	87.91 °C
Phase1 GaN	< 100 °C	94.24 °C
Phase1 diode	< 100 °C	95.18 °C
Phase1 inductor	< 100 °C	93.23 °C
Phase2 GaN	< 100 °C	93.45 °C
Phase2 diode	< 100 °C	98.22 °C
Phase2 inductor	< 100 °C	93.23 °C
R_{sense}	< 100 °C	94.13 °C

8 Schematic and bill of materials

8.1 Schematic

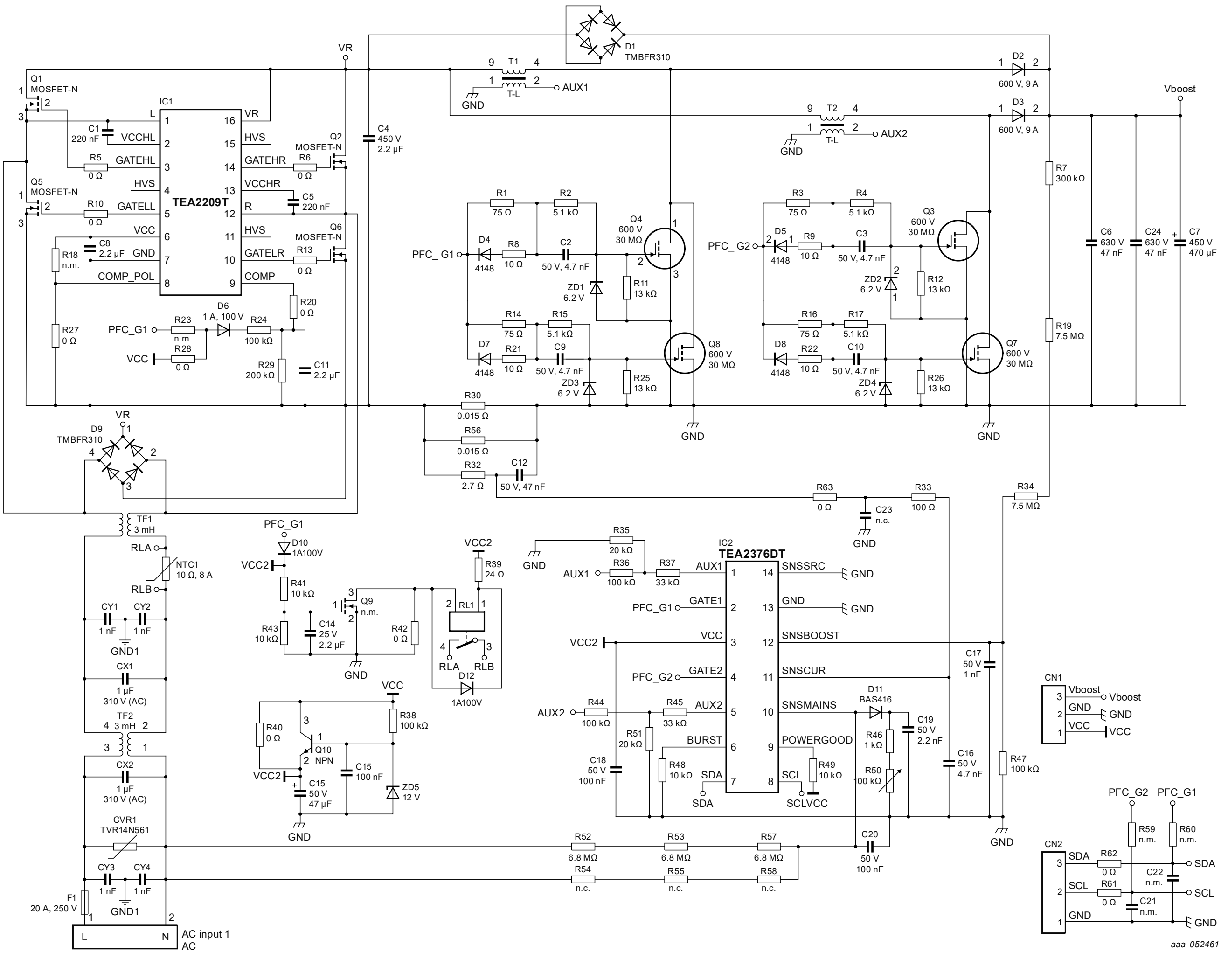


Figure 14. Design example schematic

8.2 Bill of materials

Table 8. Bill of materials

Part	Description and values	Part number	Manufacturer
C1; C5	capacitor; 220 nF; 50 V; 5 %; 0603	-	-
C2; C3; C9; C10	capacitor; 4.7 nF; 50 V; 5 %; 1206	-	-
C4	capacitor; 2.2 μF; 630 V; 10 %; P22.50603	C352J225K9SC000	Faratronic
C6; C24	capacitor; 47 nF; 630 V; 5 %; 1812	-	-
C7	capacitor; 470 μF; 450 V; 30 * 50	450MXH470MEFCSN30X50	Rubycon
C12	capacitor; 47 nF; 50 V; 5 %; 0805	-	-
C13	capacitor; 100 nF; 50 V; 5 %; 0603	-	-
C8; C11; C14	capacitor; 2.2 μF; 50 V; 5 %; 0603	-	-
C15	capacitor; 47 μF; 50 V; 6.3 * 11	-	-
C16	capacitor; 4.7 nF; 50 V; 5 %; 0603	-	-
C17	capacitor; 1 nF; 50 V; 5 %; 0603	-	-
C18	capacitor; 100 nF; 50 V; 5 %; 0603	-	-
C19	capacitor; 2.2 nF; 100 V; 5 %; 0603	-	-
C20	capacitor; 100 pF; 50 V; 5 %; 0603	-	-
C21; C22; C23	capacitor; not mounted	-	-
CN1	connector; output and V_{CC} supply	-	-
CN2	connector; I^2C communication	-	-
CVR1	varistor; 320 V (AC)/418 V (DC); P14	14D511	Weiqin Electronics
CX1; CX2	X-capacitor; 1 μF; 275 V; 10 %; P22	X2P2105KT1B0265170085 ES0	Songtian
CY1; CY2; CY3; CY4	Y-capacitor; 1 nF; 250 V; 20 %; P10	Q07F1D102MN0B0S0N0	Songtian
D1; D9	diode; bridge rectifier; 1000 V; 10.5 * 7.5	TSB407	Yangjie Electronics
D2; D3	diode; 600 V/9 A; TO263	BYV29B-600P	WeEn Semiconductors
D4; D5; D7; D8	diode; 75 V; 200 mA; SOD323	1N4148	Diodes Incorporated
D6; D10; D12	diode; 100 V; 1 A; SOD323	S1B-13-F	Diodes Incorporated
D11	diode; 85 V; 200 mA; SOD323	BAS416	Nexperia
F1	ceramic tube fuse; 20 A; diameter: 6.0 mm * 22.5 mm	0215020.MXP	Littel
NTC1	NTC dip; 10 Ω/8 A; 10 % F7.5	'-	-
R1; R3; R14; R16	resistor; 75 Ω; ¼ W; 1 %; 1206	-	-
R2; R4; R15; R17	resistor; 5.1 kΩ; ¼ W; 1 %; 1206	-	-

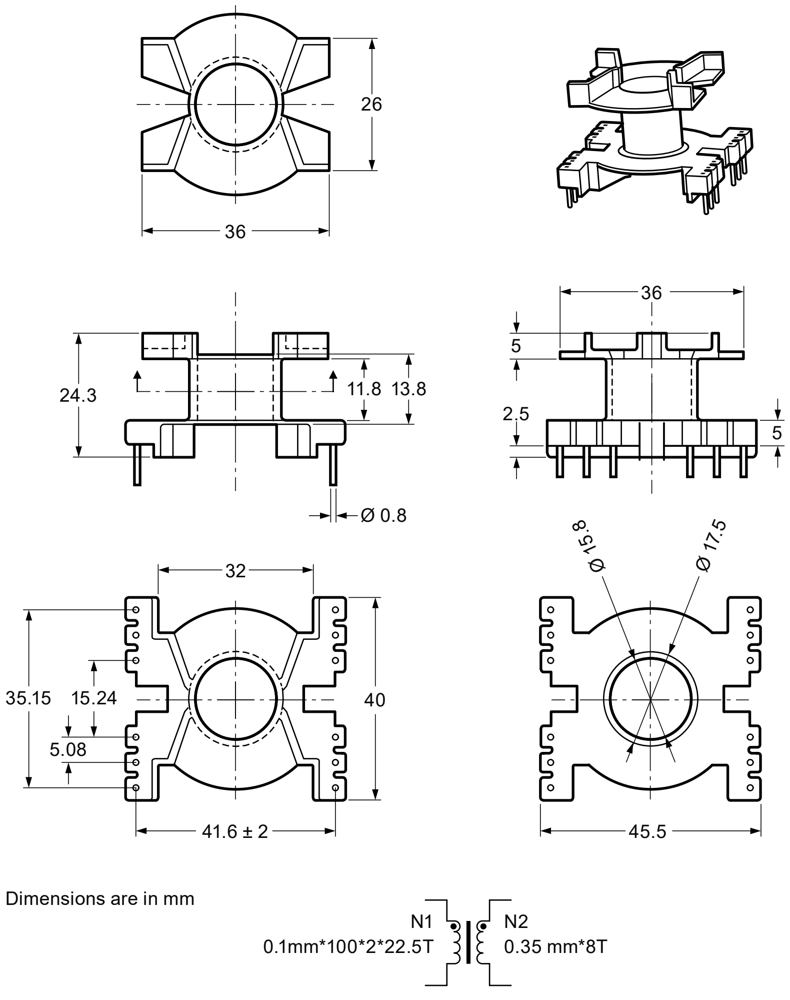
Table 8. Bill of materials*...continued*

Part	Description and values	Part number	Manufacturer
R5; R6; R10; R13; R27	resistor; 0 Ω; ¼ W; 1 %; 1206	-	-
R7	resistor; 300 kΩ; ¼ W; 1 %; 1206	-	-
R8; R9; R21; R22	resistor; 10 Ω; ¼ W; 1 %; 1206	-	-
R11; R12; R25; R26	resistor; 13 kΩ; ⅛ W; 1 %; 0805	-	-
R18; R23; R59; R60	resistor; not mounted	-	-
R20; R28; R40; R42	resistor; 0 Ω; ⅒ W; 1 %; 0603	-	-
R24; R38; R47	resistor; 100 kΩ; ⅒ W; 1 %; 0603	-	-
R29	resistor; 200 kΩ; ⅒ W; 1 %; 0603	-	-
R30; R56	resistor; 15 mΩ; 5 W; 1 %; 4527	WSR5R0150FEA	Vishay
R32	resistor; 2.7 Ω; ⅛ W; 1 %; 0805	-	-
R33	resistor; 100 Ω; ¼ W; 1 %; 1206	-	-
R35; R51	resistor; 20 kΩ; ⅛ W; 1 %; 0805	-	-
R36; R44	resistor; 100 kΩ; ⅛ W; 1 %; 0805	-	-
R37; R45	resistor; 33 kΩ; ⅛ W; 1 %; 0805	-	-
R39	resistor; 24 Ω; ⅛ W; 1 %; 0805	-	-
R41; R43	resistor; 10 kΩ; ⅒ W; 1 %; 0603	-	-
R46	resistor; 1 kΩ; ⅒ W; 1 %; 0603	-	-
R48; R49	resistor; 10 kΩ; ⅛ '; 1 %; 0805	-	-
R50	resistor; NTC; 100 kΩ; 1 %; 0603	-	-
R52; R53; R57	resistor; 6.8 MΩ; ¼ W; 1 %; 1206	-	-
R54; R55; R58	resistor; not mounted	-	-
R61; R62	resistor; 0 Ω; ⅒ W; 1 %; 0603	-	-
R63	resistor; 0 Ω; ⅛ W; 1 %; 0805	-	-
RL1	relay; 12 V (DC); 16 A/250 V (AC); 0.36 W; 21 * 16 * 20	HF152F-T	Hongfa
Q1; Q2; Q5; Q6	MOSFET; N-channel; 600 V; 0.01 Ω	IPDQ60R010S7	Infineon
Q3; Q4; Q7; Q8	GaN enhancement-mode power transistor	INN650TA30AH	Innoscience
Q9	not mounted	-	-
Q10	transistor; NPN; 80 V; 1 A; SOT-89L	-	-
TF1; TF2	common choke; 3 mH; T26*16*6	-	-

Table 8. Bill of materials *...continued*

Part	Description and values	Part number	Manufacturer
T1; T2	PFC inductor; 95 µH; 5 %	PQ4025	TBG
ZD1; ZD2; ZD3; ZD4	Zener diode; 0.5 W; 6.2 V; 5 %; SOD323	-	-
ZD5	Zener diode; 0.5 W; 12 V; 5 %; SOD323	-	-
IC1	active bridge controller	TEA2209T	NXP Semiconductors
IC2	interleaved PFC controller	TEA2376DT	NXP Semiconductors

8.3 PFC inductor specification



Parameter	Value	Condition
Inductance, 4-9	95 µH, 5 %	10 kHz, 100 mV, LS
Operating temperature	-40 degree to 125 degree	Including temperature rise
Core, PQ4025	Ae, 240 mm^2	PC95

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Figure 15. PFC inductor specification

9 Abbreviations

Table 9. Abbreviations

Acronym	Description
BM	burst mode
GaN	gallium nitride
GUI	graphical user interface
I^2C	inter integrated circuit
IC	integrated circuit
ICP	inrush current protection
MOSFET	metal-oxide semiconductor field-effect transistor
MTP	multitime programmable
OCP	overcurrent protection
OTP	overtemperature protection
OVP	overvoltage protection
PCB	printed-circuit board
PFP	phase-fail protection
PF	power factor
PFC	power factor correction
THD	total harmonic distortion
UVP	undervoltage protection

10 References

[1] **TEA2376DT data sheet** — Digital configurable interleaved PFC controller; 2023, NXP Semiconductors

[2] **TEA2209T data sheet** — Active bridge rectifier controller; 2021, NXP Semiconductors

[3] **AN14200 application note** — TEA2376 application note (working title); 2024, NXP Semiconductors

[4] **UM12042 user manual** — TEA2376 development software with GUI; 2024, NXP Semiconductors

[3] **PCB layout** — Contact NXP Semiconductors

[4] **TEA2376DT MTP settings** — Contact NXP Semiconductors

11 Revision history

Table 10. Revision history

Document ID	Release date	Description
UM11967 v.1.0	16 April 2024	• Initial version

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