TI Designs
Universal, 350-W CCM PFC With >98% Efficiency and Small Form Factor Reference Design

TEXAS INSTRUMENTS

Description

The TIDA-00776 is a 350-W power factor regulator designed for refrigerator and other cost competitive appliances applications. This reference design is a continuous-conduction-mode (CCM) boost converter. It is implemented using TI's UCC28180 power factor correction (PFC) controller, which has all necessary and recommendable protections built in. The hardware is designed and tested to pass the current harmonic requirement of IEC61000-3-2 (2014) for household appliances.

The key highlights of this reference design are:

- Provides a fully tested supply platform for front-end PFCs to address power level requirements for appliances below 350 W
- Up to 98.2% peak converter efficiency under high line input enable a competitive high power density and small heat sink design
- Robust output supply protection against output overcurrent, output overvoltage, and output undervoltage failure conditions

Resources

TIDA-00776	Design Folder
UCC28180	Product Folder
UCC28881	Product Folder
TPS54202	Product Folder

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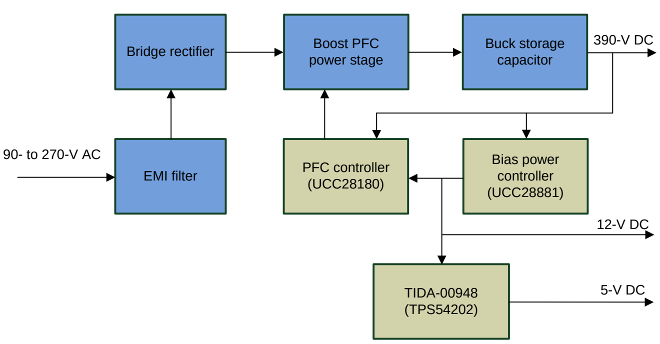

Features

- Universal Input From 90- to 265-V AC
- Meeting IEC 61000-3-2 Class D Requirement With Respect to Current Harmonics
- Conversion Efficiency >98.2% (Hi-Line)
- 135-kHz Switching Frequency
- Small PCB Form Factor of 82 mm × 80 mm × 25 mm
- Enhanced Dynamic Response During Output Overvoltage and Undervoltage Conditions
- Very Low Standby Power Consumption of Less Than 300 mW
- Soft Overcurrent and Cycle-by-Cycle Peak Current Limit Protection
- Integrated Bias Power Supply of 12-V DC and 5-V DC With 3-W Output
- Operating Ambient Temperature Range: –20°C to 55°C

Applications

- Refrigerators and Freezers
- Power Tools Chargers
- Washing Machines
- Appliances Application With Brushless DC Motor (BLDC) Below 350 W

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1 System Overview

1.1 System Description

Major appliance equipment such as refrigerators and washers use three-phase, pulse-width modulated brushless DC (BLDC) or permanent magnet synchronous motor (PMSM) drives. These motor drives typically have fractional or low horsepower (HP) ratings ranging from 0.25 HP (186 W) to 5 HP (3,750 W). An electronic drive is required to control the stator currents in a BLDC or PMSM motor. A typical electronic drive consists of:

- Power stage with a three-phase inverter with the required power capability
- Microcontroller unit (MCU) to implement the motor control algorithm
- Motor voltage and current sensing for closed-loop speed or torque control
- Gate driver for driving the three-phase inverter
- Power supply to power up the gate driver and MCU

These drives require a front-end power PFC regulator to shape the input current of the power supply and to meet the standards for power factor and current total harmonic distortion (THD), such as IEC61000-2-3.

A PFC circuit shapes the input current of the power supply to be in phase with the mains voltage and helps to maximize the real power drawn from the mains.

The following list highlights key benefits of the PFC circuit:

- *Reduces RMS input current*
  For instance, a power circuit with a 230-V/5-A rating is limited to about 575 W of available power with a power factor (PF) of 0.5. Increasing the PF to 0.99 almost doubles the deliverable power to 1138 W, allowing the operation of higher power loads.
- *Facilitates power supply hold-up*
  The active PFC circuit maintains a fixed, intermediate DC bus voltage that is independent of the input voltage so that the energy stored in the system does not decrease as the input voltage decreases. This enhanced storage capability allows the use of smaller, less expensive bulk capacitors.
- *Improves efficiency of downstream converters*
  The PFC reduces the dynamic voltage range applied to the downstream inverters and converters, resulting in lower forward drops allowing lower voltage ratings for the downstream rectifiers. The operating duty-cycle can also be increased, resulting in lower current in the switches.

This reference design is a boost power factor regulator implemented using the UCC28180 device as a PFC controller for use in all appliances that demand a power factor correction of up to 350 W. The design provides a ready platform of an active front-end to operate downstream inverters or DC-DC converters operating on a universal AC voltage range from 90- to 270-V AC.

This design demonstrates a high power density power factor stage in a small form factor (82 mm × 80 mm × 25 mm) that operates from 90- to 270-V AC and delivers up to 350 W of continuous power output to drive inverters or converters at more than a 98% efficiency rate.

Above all, the design meets the key challenges of appliances to provide safe and reliable power supply including built-in protections, while delivering a high performance with low power consumption and a very competitive bill of material (BOM) cost.

1.2 Key System Specifications

Table 1. Electrical Performance Specifications

PARAMETER	SYMBOL	TEST CONDITIONS	MIN	NOM	MAX	UNIT
INPUT CHARACTERISTICS						
Input voltage	V_{IN}	—	90	230	270	VAC
Line frequency	f_{AC}	—	47	—	64	Hz
Power factor	PF	V_{IN} = nom, I_{OUT} = max	—	0.99	—	—
Input current	I_{IN}	V_{IN} = nom, I_{OUT} = max	—	10	—	A
OUTPUT CHARACTERISTICS						
Output voltage	V_{OUT}	V_{IN} = nom, I_{OUT} = min to max	—	390	—	V
Output current	I_{OUT}	V_{IN} = 90-V AC to max	0	—	0.9	A
Output power	P_{OUT}	V_{IN} = 90-V AC to max	—	—	350	W
Line regulation	—	V_{IN} = min to max, I_{OUT} = nom	—	—	2	%
Load regulation	—	V_{IN} = min to max, I_{OUT} = nom	—	—	3	%
Output voltage ripple	V_{OUT_RIPPLE}	V_{IN} = nom, I_{OUT} = max	—	—	22	V
Output overvoltage	V_{OVP}	I_{OUT} = min to max	—	—	415	V
Output overcurrent	I_{OCP}	V_{IN} = min to max	1.5	—		A
SYSTEM CHARACTERISTICS						
Switching frequency	f_{SW}	—	—	135	—	kHz
Peak efficiency	η_{PEAK}	V_{IN} = max test with MOSFET	—	—	98.2	%
Operation temperature	T_{NOM}	With air flow	–25	—	55	°C

1.3 Block Diagram

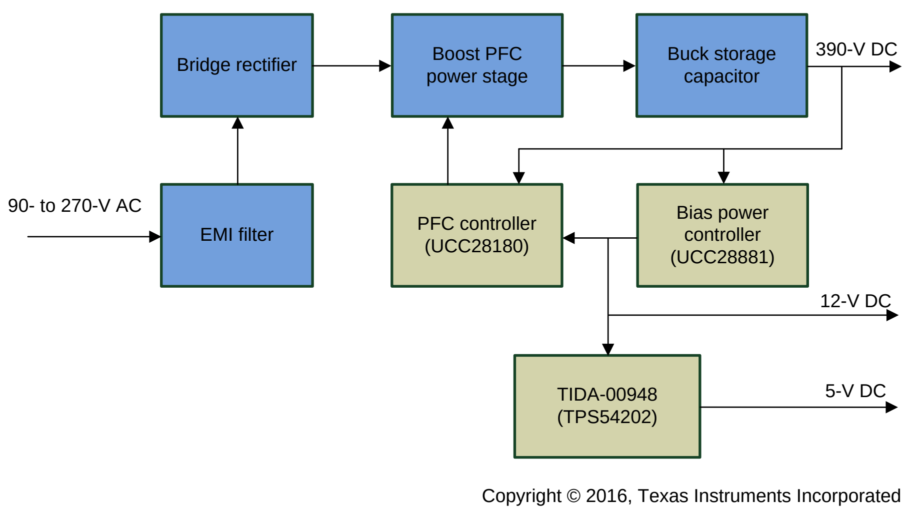

Figure 1. Block Diagram of 350-W PFC Regulator

1.4 Highlighted Products

The following subsections detail the highlighted products used for the PFC controller, the bias power controller and the step-down-converter in this reference design, including the key features for their selection. See their respective product datasheets for complete details on any highlighted device.

1.4.1 UCC28180—Boost PFC Controller

The UCC28180 is a high performance, compact continuous conduction mode (CCM), 8-pin programmable frequency PFC controller. The wide and programmable operating frequency of the controller provides flexibility to design at a high frequency to optimize the components. The UCC28180 uses trimmed current loop circuits to achieve less than a 5% THD from a medium-to-full load (50% to 100%). A reduced current sense threshold enables the UCC28180 device to use a 50% smaller shunt resistor, resulting in lower power dissipation while maintaining low THD. The UCC28180 also consists of an integrated fast gate driver, with a drive of 2-A source current and −1.5-A sink current, which eliminates the need for an external gate driver.

The UCC28180 device also has a complete set of system protection features that greatly improves reliability and further simplifies the design:

- Soft overcurrent
- Cycle-by-cycle peak current limit
- Output overvoltage
- VCC undervoltage lockout (UVLO) protection
- Open pin protections (ISENSE and VSENSE pins)

1.4.2 UCC28881—700-V Lowest Quiescent Current Off-Line Switcher

The UCC28881 integrates a controller and a 14-Ω, 700-V power MOSFET into one monolithic device. The device also integrates a high-voltage current source, enabling start-up and operation directly from the rectified mains voltage. The UCC28881 is from the same family as the UCC28880 with higher current handling capability.

The low quiescent current of the device enables excellent low load efficiency. With the UCC28881, the most common converter topologies such as buck, buck-boost and flyback can be built using a minimum number of external components.

The UCC28881 incorporates a soft-start feature for controlled startup of the power stage, which minimizes the stress on the power-stage components.

The key features that make the device ideal for this application are:

- Integrated 14-Ω, 700-V power MOSFET
- Integrated high-voltage current source for internal device bias power
- Integrated current sense
- Internal soft start
- Self-biased switcher (start-up and operation directly from rectified mains voltage)
- Supports buck, buck-boost and flyback topologies
- <100-µA device quiescent current
- Robust current protection during load short circuit
- Protection
  - Current limit
  - Overload and output short circuit
  - Over temperature

1.4.3 TPS54202—4.5- to 28-V Input, 2-A Output, Synchronous Step-Down Converter

The TPS54202 is a 4.5- to 28-V input voltage range, 2-A synchronous buck converter. The device includes two integrated switching FETs, internal loop compensation, and a 5-ms internal soft start to reduce component count.

By integrating the MOSFETs and employing the SOT-23 package, the TPS54202 achieves high power density and offers a small footprint on the PCB.

Advanced Eco-mode™ implementation maximizes light-load efficiency and reduces power loss. In the TPS54202, the frequency spread spectrum operation reduces electromagnetic interference (EMI) respectively emissions.

Cycle-by-cycle current limit in both high-side MOSFETs protect the converter in an overload condition and is enhanced by a low-side MOSFET freewheeling current limit, which prevents current runaway. Hiccup mode protection is triggered if the overcurrent condition has persisted for longer than the present time.

The key features that make the device ideal for this application are:

- 4.5- to 28-V wide input voltage range
- Integrated 148-mΩ and 78-mΩ MOSFETs for 2-A, continuous output current
- Low 2-µA shutdown, 45-µA quiescent current
- Internal 5-ms soft start
- Fixed 500-kHz switching frequency
- Frequency spread spectrum to reduce EMI
- Advanced eco-mode pulse skip
- Peak current mode control
- Internal loop compensation
- Overcurrent protection for both MOSFETs with hiccup mode protection
- Overvoltage protection
- Thermal shutdown
- SOT-23 (6) package

2 System Design Theory

This reference design is a 350-W boost PFC regulator that operates in CCM and is implemented using the UCC28180 PFC controller. The design is specifically tailored for inverter fed drives for use in major appliances, such as refrigerator. This TI Design serves as a simple and superior alternative to existing bulk, passive PFC circuits that are used to meet the power harmonic standards like IEC61000-3-2.

2.1 Setting Switching Frequency

The UCC28180 switching frequency is user programmable with a single resistor on the FREQ pin to GND.

This design uses a 135-kHz switching frequency. Calculate the suitable resistor value to program the switching frequency using Equation 1:

$$R_{FREQ} = \frac{f_{TYP} \times R_{TYP} \times R_{INT}}{\left(f_{SW} \times R_{INT}\right) + \left(R_{TYP} \times f_{SW}\right) - \left(R_{TYP} \times f_{TYP}\right)} \tag{1}$$

where:

- f_{TYP} = 65 kHz
- R_{TYP} = 32.7 kΩ
- R_{INT} = 1 MΩ

f_{TYP}, R_{TYP}, and R_{INT} are constants values. See the device's datasheet for more details[2].

Applying these constants in Equation 1 yields the appropriate resistor that must be placed between the FREQ and GND pins.

$$R_{FREQ} = \frac{65\ \text{kHz} \times 32.7\ \text{k}\Omega \times 1\ \text{M}\Omega}{\left(1355\ \text{kHz} \times 1\ \text{M}\Omega\right) + \left(135\ \text{kHz} \times 32.7\ \text{k}\Omega\right) - \left(65\ \text{kHz} \times 32.7\ \text{k}\Omega\right)}$$

R_{FREQ} = 15.4 kΩ

A typical value of 15.4 kΩ for the FREQ resistor results in a switching frequency of 136 kHz.

2.2 Calculating Output Capacitance

Assuming that the percentage of non-conducting period is minimal, the required output capacitance can be calculated as Equation 2 shows:

$$C_O = \frac{2 \times P_{LOAD}}{\pi \times V_O \times \Delta V_O \times f_{LINE}} \tag{2}$$

where:

- ΔV_{OUT} is the peak-to-peak voltage ripple on the output
- f_{LINE} is the input line frequency
- P_{LOAD} is the output load power

Insert the values into the Equation 2 for:

$$C_O = \frac{2 \times 350}{\pi \times 390 \times 75 \times 50} = 152\ \mu\text{F}$$

A capacitance of 150 µF has been selected.

2.3 Calculating of PFC Choke Inductor

The UCC28180 is a CCM controller; however, if the chosen inductor allows relatively high-ripple current, the converter can operate in discontinuous mode (DCM) at light loads. High-inductor ripple current affects the CCM/DCM transition boundary and results in a higher light-load THD. This type of current also affects the choices for the input capacitor, RSENSE, and CICOMP values.

Choosing an inductor ripple current, ΔI_{RIPPLE}, of 20% or less enables CCM operation over the majority of the operating range. However, this low inductor ripple current requires a boost inductor with higher inductance value and lager physically size. This design trades the ripple performance off with solution size and cost. The inductor is sized to have a 40% ΔI_{RIPPLE} to minimize inductor and PCB size. Though the converter operates in DCM at the higher input voltages and at light loads; it is optimized for a nominal input voltage of 230-V AC at the full load.

The minimum value of the duty cycle, D_{MIN}, is calculated as Equation 3 shows:

$$D_{MIN} = 1 - \frac{\sqrt{2} \times V_{IN\_MIN} \times \left|\sin\left(2\pi \times f_{LINE} \times t\right)\right|}{V_O} = \frac{\sqrt{2} \times 90 \times 1}{390} = 0.15 \tag{3}$$

where:

- V_{IN_MIN} is the minimum input voltage

Then the maximum inductor peak current, I_{PK}, is calculated as Equation 4 shows:

$$I_{PK} = \frac{\sqrt{2} \times PO}{\eta \times V_{IN\_MIN}} = \frac{\sqrt{2} \times 350}{0.98 \times 90} = 5.62\ A \tag{4}$$

The PFC choke inductor (L_{MIN}) can now be calculated based upon the minimum duty cycle, the maximum inductor peak current, and the inductor ripple current, as Equation 5 shows:

$$L_{MIN} \geq \frac{\sqrt{2} \times V_{IN\_MIN} \times D_{MIN}}{I_{PK} \times 0.4 \times f_{SW}} = \frac{\sqrt{2} \times 90 \times 0.15}{5.62 \times 0.4 \times 135 \times 10^3} = 65\ \mu H \tag{5}$$

2.4 Setting Switching Frequency

The switching element needs to be chosen according to its voltage rating as well as its parasitic performance. Some additional considerations have to be taken in order to drive it properly; these considerations are discussed in this section.

The MOSFET switch is driven by a GATE output that is clamped at 15.2 V internally for VCC bias voltages greater than 15.2 V. An external gate drive resistor is recommended to limit the rise time and to dampen any ringing caused by the layout and MOSFET parasitic inductances and capacitances. This resistor also helps to meet EMI requirements of the converter. This TI Design uses a 2-Ω resistor. The value depends on the parasitic elements associated with the actual layout and was optimized for good-natured settling and low resistive losses during initial testing. To facilitate a fast turnoff a standard 100-V, 1-A Schottky diode or switching diode is placed anti-parallel with the gate drive resistor. A 3.3-kΩ resistor is placed between the gate of the MOSFET and ground to discharge the gate capacitance and protect from inadvertent fast transient triggered turn on.

The maximum voltage across the FET is the maximum output boost voltage (that is 425 V), which is the overvoltage set point of the PFC converter used to shut down the output. Considering a voltage derating of 30%, the voltage rating of the MOSFET must be greater than 550-V DC. As a result, this design uses an IPP60R380E6 MOSFET with a maximum voltage rating of 600 V.

For the cost competitive consideration, this design also can use an IGBT to replace the MOSFET. A heat sink of appropriate size is needed for the MOSFET.

2.5 Bias Power

This TI Design also provides a bias power supply of 12 V, which can deliver up to 3-W output power. The heart of the supply is the UCC28881, a low-cost high-voltage buck controller. The device can be used for converting a high-voltage DC input with a wide range from 90- to 380-V DC, or converting an AC input ranging from 85- to 270-V AC, to standard power rails. As per the requirements of appliances, the design meets the requirements of high efficiency (> 75%) and a low standby power consumption of less than 100 mW in idle mode. The bias supply reference design offers the following key benefits:

- Works for a wide input range for both a DC input (90- to 380-V DC) or an AC input (85- to 270-V AC)
- Integrated high-voltage current source for internal device bias power
- Combination of frequency and peak current modulation causes high conversion efficiency

The controller has an inherent safety feature that detects a broken, open feedback loop. In such a case, the controller turns off the MOSFET to safeguard the low-voltage system components against potential overvoltage conditions and damage. In addition, the controller provides output protection for short-circuit, overcurrent, and overvoltage conditions.

This TI Design does not include test of the bias supplies. For more details on the AC input to 12-V conversion with the UCC28881, see the TIDA-00940 design. For more details on the 12-V to 5-V (or 3.3-V) conversion based on the TPS54202, see the DC/DC based LDO replacement reference designs:

- TIDA-00946 (5 V, dual layer)
- TIDA-00947 (3.3 V, dual layer)
- TIDA-00948 (5 V, single layer)
- TIDA-00949 (3.3 V, single layer)

3 Getting Started Hardware

To ease the conduction of any testing on the TIDA-00776 AC/DC power converter, this section gives an overview of the connections and recommended startup sequence.

3.1 PCB Overview

Figure 2 shows a picture of the PCB with the functional blocks.

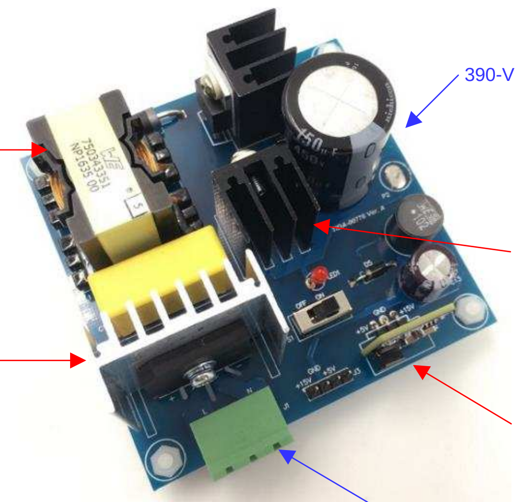

Figure 2. TIDA-00776 PCB With Functional Blocks

3.2 Connectors Settings

To ease connecting the converter to the supply and loads for evaluation, the pinout details of all the connectors of the board (J1, J2, J3, and output connector) are provided in Table 2.

Table 2. Connector Settings of the Board

CONNECTOR	FUNCTION	DESCRIPTION
J1		
J1-1	Live	Live line of AC input power
J1-2	—	Not used
J1-3	Neutral	Neutral line of AC input power
J2		
J2-1	5 V	5-V output of bias power
J2-2	PGND	Ground of bias power
J2-3	12 V	12-V output of bias power
J3		
J3-1	12 V	12-V output of bias power
J3-2	PGND	Ground of bias power
J3-3	5 V	5-V output of bias power
J3-4	—	Not used
OUTPUT		
P1	VDCBUS	PFC output
P2	PGND	Ground of bias power

3.3 Procedure for Powering On

The following six steps outline the recommended power on procedure for the AC/DC power converter:

1. Connect input terminal J1 of the reference board to the AC power source as defined in Table 2.
2. Connect output terminals (P1 and P2) to the electronic load, ensuring correct polarity (P1 is the 390-V DC output and P2 is the GND terminal).
3. Gradually increase the input voltage from 0 V to turn on the voltage of 230-V AC.
4. Push the switch of S1 to "ON" state to supply the PFC controller internally.
5. Turn on the load to draw current from the output terminals of the PFC.
6. Conduct the desired tests to evaluate the performance of the power converter.

4 Testing and Results

The test results are divided into six parts:

- Test conditions
- Test equipment
- Steady-state performance characteristics of the power converter
- Tabular summary of these characteristics
- Transient waveforms and characteristic behaviors
- Thermal measurements

4.1 Test Setup and Conditions

This section describes the test setup and conditions briefly. Commonly, two general purpose meters, for output voltage and output current, and one power analyzer are used. The power analyzer measures the input voltage, input current, power factor and THD of input current, unless otherwise indicated the measurements are conducted at a room temperature of 22.5ºC.

The input voltage (V_{IN}) range for the power supply source (during testing) is 90- to 270-V AC. The input current limit of the AC source of the power analyzer is set to 5 A. The output is loaded with a variable electronic load rated for ≥ 400 V, which can vary the load current from 0 mA to 1 A.

Figure 3 shows the setup and operating AC/DC converter on the test bench.

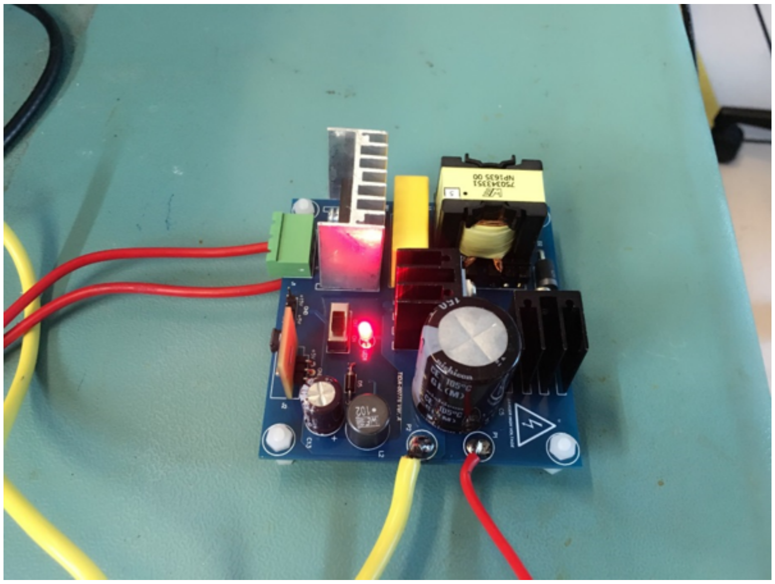

Figure 3. Operating AC/DC Converter on Test Bench

4.2 Test Equipment

This section list in Table 3 the test equipment used to test the TIDA-00776.

Table 3. Test Equipment

TEST EQUIPMENT	PARTNUMBER
Oscilloscope	Tektronix DPO 3054
Voltage probe	Tektronix P6139A
Current probe	Tektronix TCP202
Multimeter	Fluke 287C
Electronic load	Chroma 63204
Thermal camera	Fluke TI110
Power analyzer	Voltech PM100

4.3 Steady-State Converter Performance Characteristics

This section covers the relevant steady state characteristics of the AC/DC power converter. The measured characteristics are grouped into four parts:

- Efficiency
- Power factor and total harmonic distortion
- Load regulation
- Harmonics

4.3.1 Efficiency

Figure 4 shows the measured efficiency of the AC/DC power converter versus load current for three typical AC input voltage levels.

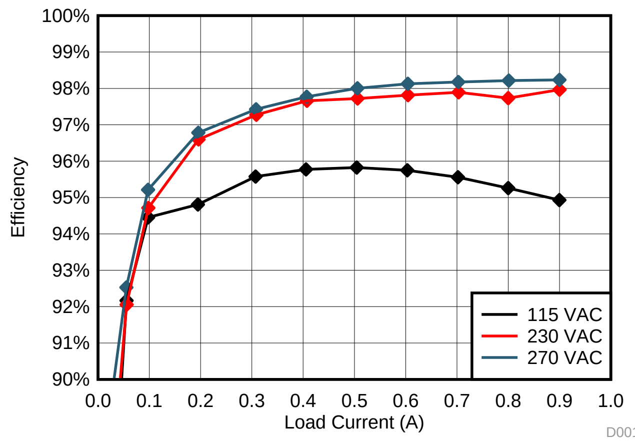

Figure 4. Efficiency versus Load Current

For a high line input, the converter achieves very high efficiency 98.2%. Even at low line input levels the maximum efficiency is close to 96%. Consequentially less cooling is required, which reduces overall system size and cost. Also for very low loads (5% of rated full load) the converter efficiency is still excellent and above 90%.

4.3.2 Power Factor and Total Harmonic Current Distortion

Figure 5 depicts the measured power factor of the converter versus load current for the three typical AC input levels. At 60% of the rated load the power factor is above 0.99. And even under very low load conditions at 10% of the rated load, the power factor is already above 0.9 even for high line input voltages, so the power factor corrections works very well under all operation conditions.

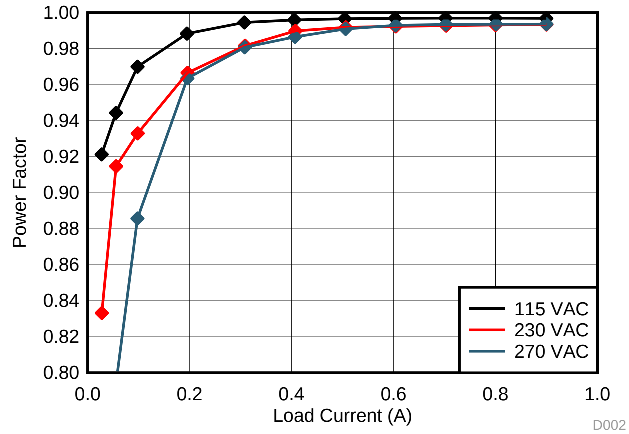

Figure 5. Power Factor versus Load Current

Figure 6 plots the measured total harmonic distortion (THDi) of the input current of the converter versus load current for the three typical AC input levels. For loads exceeding 50% of the rated full load, the THDi of input current is much below 7%. Even for loads as low as 20% of the rated full load, the THDi is already below 10%. Therefore, the high order current harmonic can meet the requirement of IEC61000-3-2 reliably.

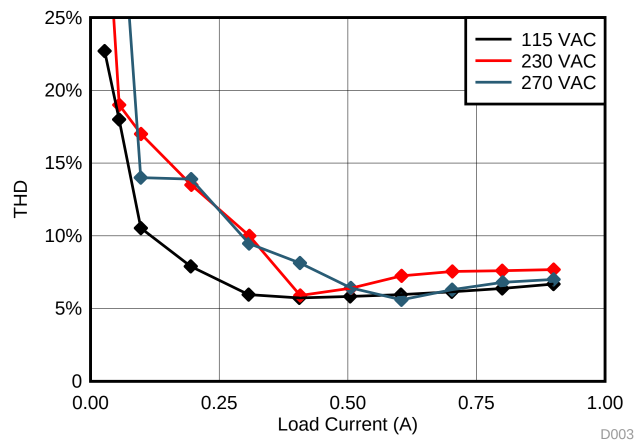

Figure 6. THDi versus Load Current

4.3.3 Load Regulation

Figure 7 depicts the measured load regulation of the converter for load conditions ranging from no load to full load. The load regulation is the variation of output voltage with load current in relation to the average output voltage. Its maximum below 0.2% proofs the UCC28180's excellent load regulation capabilities.

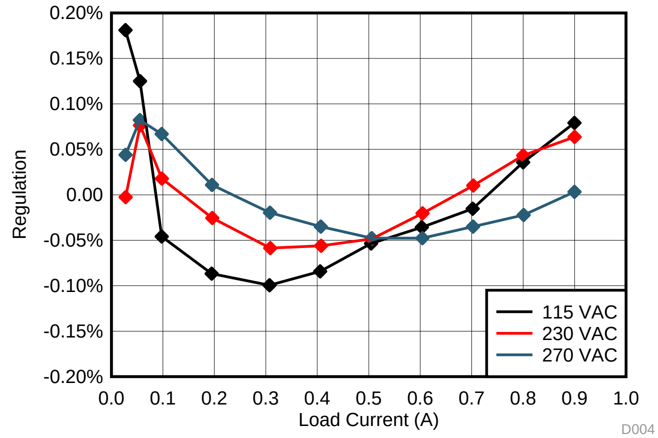

Figure 7. Relative Output Voltage Regulation versus Load Current

4.3.4 Harmonics Measurement

Meeting required standards is among the most important requirements for any practical design. The following chapter proofs that the converter harmonics are below the limits as defined by the stringent IEC 61000-3-2:2014 standard at 10%, 60%, and 100% loading of the rated output power level. This subsection starts with the listing of the levels defined in the standard and sequentially covers the harmonics characteristic for three increasing load conditions.

The input current at harmonic frequencies the BSI IEC 61000-3-2:2014 standard requires AC/DC power converters not to exceed is listed in Table 4.

Table 4. Limits for IEC61000-3-2 Class D Equipment

HARMONIC ORDER (n)	MAXIMUM PERMISSIBLE HARMONIC CURRENT PER WATT (mA/W)	MAXIMUM PERMISSIBLE HARMONIC CURRENT (A)
3	3.4	2.30
5	1.9	1.14
7	1.0	0.77
9	0.5	0.40
11	0.35	0.33
13 ≤ n ≤ 39 (odd harmonics only)	3.85/n	See Table 1 of the IEC 61000-3-2:2014

The IEC61000-3-2, class D is the most stringent norm, because the limit value of class D depends on output power level, which means at the low load condition, it is most difficult to pass.

Table 5 provides an overview of the target output voltage and applied load current versus percentage of rated output power at 10%, 60%, and 100% loading.

Table 5. Output Voltage and Current Load versus Percentage of Rated Output Power

PARAMETER	PERCENTAGE OF RATED OUTPUT POWER		
	10%	60%	100%
Rated power (W)	39	200	350
Output voltage (V)	390	390	390
Output current (A)	0.10	0.50	0.90

Figure 8 compares the measured current level of the converter and limit specified by the IEC 61000-3-2:2014 up to the 39th harmonic of the line frequency with a constant load of 10% of the rated output power. The converter's input current "TIDA-00776_40W Load" at all harmonic frequencies is below the corresponding "IEC61000-3-2 Class D" limit.

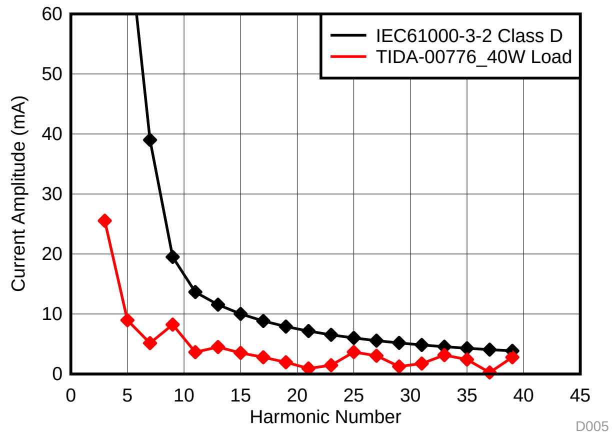

Figure 8. Current Harmonic Limit and Converter Current for 10% Rated Output Power

Figure 9 compares the measured current level and limit specified versus harmonics at a constant 60% load of the rated output power. Also for a 60% rated load, the converter's current "TIDA-00776_200W Load" is for all harmonics also for this load level with margin below the "IEC61000-3-2 Class D" limit.

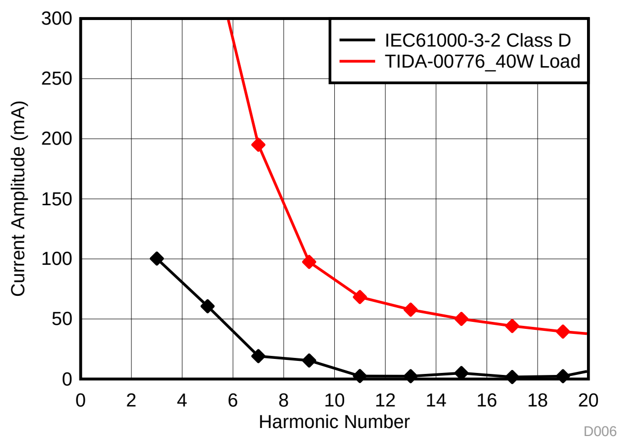

Figure 9. Current Harmonic for 200-W Input Power

Figure 10 compares the measured current level and limit specified versus harmonics. This time the load in the specific test draws 100% of the rated output power. Also in this full load condition, the converter's current "TIDA-00776_350W Load" remains for all harmonics with margin significant margin below the "IEC61000-3-2 Class D" limit.

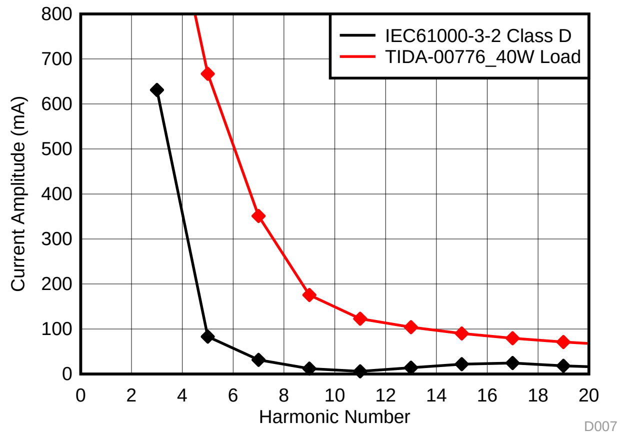

Figure 10. Current Harmonic Under 350-W Input

Table 12 summarizes the previously depicted measured current values in a single table. The power converter current and the applicable limit according to IEC61000-3-2 for output power levels of 10%, 60%, and 100% loading of the rated output power can be compared and looked up for reference up to the 39th harmonic.

4.4 Tabular Summary of Steady-State Measurements

Tabular summaries of the steady-state characteristics of the AC/DC power converter are grouped according to the relevant operation states of the power converter into loaded, unloaded, standby, and over loaded operation characteristics. A comparison table of the harmonics and the applicable limits completes this subsection.

4.4.1 Efficiency and Regulation Characteristics versus Load

The following three tables summarize the performance characteristics of the power converter versus increasing load current for different line voltage levels. These characteristics include efficiency, power factor, total harmonic current distortion (THDi), output voltage, as well as power and current levels.

Table 6 recaps the steady-state power converter performance characteristics for a 115-V AC line voltage input level versus increasing load current.

Table 6. Performance Data Including Efficiency, Power Factor, and THD for 115-V AC Line Input

V_{INAC} (V)	I_{INAC} (A)	PF	P_{INAC} (W)	i_{THD} (%)	V_{OUT} (V)	I_{OUT} (A)	P_{OUT} (W)	η (%)
115	0.12	0.92	12.5	22.70	392.8	0.03	10.8	85.9
115	0.22	0.94	23.6	18.00	392.6	0.06	21.8	92.2
115	0.36	0.97	40.6	10.53	391.9	0.10	38.3	94.5
115	0.71	0.99	80.5	7.90	391.8	0.19	76.3	94.8
115	1.10	0.99	125.9	5.96	391.7	0.31	120.3	95.6
115	1.45	1.00	165.9	5.73	391.8	0.41	158.9	95.8
115	1.80	1.00	206.4	5.83	391.9	0.50	197.7	95.8
115	2.16	1.00	246.9	5.96	392.0	0.60	236.4	95.7
115	2.52	1.00	288.0	6.15	392.0	0.70	275.2	95.6
115	2.88	1.00	329.4	6.38	392.2	0.80	313.8	95.3
115	3.25	1.00	371.9	6.68	392.4	0.90	353.0	94.9

Table 7 sums up the converter's characteristics for a 230-V AC line voltage input level.

Table 7. Performance Data Including Efficiency, Power Factor, and THD for 230-V AC Line Input

V_{INAC} (V)	I_{INAC} (A)	PF	P_{INAC} (W)	i_{THD} (%)	V_{OUT} (V)	I_{OUT} (A)	P_{OUT} (W)	η (%)
230	0.06	0.83	12.4	34.60	392.7	0.03	10.9	87.4
230	0.11	0.91	23.8	19.00	393.0	0.06	21.9	92.1
230	0.19	0.93	40.6	17.00	392.8	0.10	38.5	94.7
230	0.36	0.97	79.7	13.50	392.6	0.20	76.9	96.6
230	0.55	0.98	124.6	10.00	392.5	0.31	121.2	97.3
230	0.72	0.99	163.8	5.90	392.5	0.41	159.9	97.7
230	0.89	0.99	203.3	6.40	392.5	0.51	198.6	97.7
230	1.06	0.99	242.6	7.25	392.6	0.60	237.3	97.8
230	1.24	0.99	282.1	7.55	392.7	0.70	276.2	97.9
230	1.41	0.99	321.6	7.60	392.9	0.80	314.3	97.7
230	1.58	0.99	361.0	7.68	393.0	0.90	353.7	98.0

Table 8 provides the converter's characteristics for a 270-V AC line voltage input level.

Table 8. Performance Data Including Efficiency, Power Factor, and THD for 270-V AC Line Input

V_{INAC} (V)	I_{INAC} (A)	PF	P_{INAC} (W)	i_{THD} (%)	V_{OUT} (V)	I_{OUT} (A)	P_{OUT} (W)	η (%)
270	0.07	0.61	12.1	55.00	393.1	0.03	10.8	89.6
270	0.11	0.79	23.5	35.00	393.2	0.06	21.7	92.5
270	0.17	0.89	40.3	14.00	393.1	0.10	38.4	95.2
270	0.30	0.96	79.4	13.90	392.9	0.20	76.8	96.8
270	0.47	0.98	124.2	9.47	392.8	0.31	121.0	97.4
270	0.61	0.99	163.5	8.13	392.7	0.41	159.8	97.8
270	0.76	0.99	202.7	6.42	392.7	0.51	198.6	98.0
270	0.90	0.99	241.8	5.60	392.7	0.60	237.3	98.1
270	1.05	0.99	281.1	6.30	392.7	0.70	276.0	98.2
270	1.19	0.99	320.3	6.80	392.8	0.80	314.6	98.2
270	1.34	0.99	359.9	7.00	392.9	0.90	353.5	98.2

From these tables, even at a very low load, the power factor is easily to get the value more than 0.9, and the THD of input current is lower than 10%. Under a high line input, the TIDA-00776 can achieve a very high converter efficiency up to 98.2%—even a low line input can get the efficiency near to 96%. Also, a very low load (3% of rated power) gets very excellent light load efficiency.

4.4.2 No Load Power Consumption

The no load power consumption of the power converter was captured at multiple AC line voltage input levels. During the test the PFC controller was enabled. Table 9 shows the tabulated results for the no load power consumption.

Table 9. No Load Currents and Power Consumption for Regulated Output

V_{INAC} (VAC)	I_{INAC}(mA)	P_{INAC} (W)	V_{OUT} (V)	I_{OUT} (mA)	P_{OUT} (W)	NO LOAD POWER (W)
90	18.5	1.23	392.8	0	0	1.23
115	18.3	1.34	391.8	0	0	1.34
150	14.6	0.86	391.5	0	0	0.86
195	11.3	0.62	391.6	0	0	0.62
230	10.9	0.58	391.5	0	0	0.58
270	12.8	0.47	391.3	0	0	0.47

Due to the active output regulation in this operation mode, the output voltage is 390-V DC and the power consumption is for high line voltage below 0.6 W. This power consumption can be further reduced by switching into standby mode.

4.4.3 Standby Power

The standby power was measured at multiple AC input line voltages with the PFC controller disabled. Table 10 shows the tabulated results for rectified output configuration.

Table 10. Standby Power Consumption With Rectified Output

V_{INAC} (VAC)	I_{INAC} (mA)	P_{INAC} (W)	V_{OUT} (V)	I_{OUT} (mA)	P_{OUT} (W)	STANDBY POWER (W)
90	9.0	0.22	125.2	0	0	0.22
115	8.1	0.22	160.6	0	0	0.22
150	7.7	0.25	210.2	0	0	0.25
195	7.3	0.28	273.9	0	0	0.28
230	7.7	0.32	323.4	0	0	0.32
270	7.9	0.38	380.0	0	0	0.38

In this operation mode, the PFC controller is disabled. Only the bias power supply and feedback resister consume power, so the standby power is always very low, less than 0.4 W.

4.4.4 Overload and Current Measurements

Table 11 shows the output voltage and total harmonic distortion under increasing overload conditions. Even for 17% overloads, the THD remains low around 7.5%.

Table 11. Overcurrent Measurements

% LOAD	V_{INAC} (VAC)	CURRENT (A)	VOLTAGE (V)	THDi (%)	POWER (W)
100%	230	0.89	391.5	7.3	347
105%	230	0.93	391.7	7.4	363
108%	230	0.96	391.8	7.4	375
113%	230	1.00	391.8	7.5	391
117%	230	1.04	391.8	7.5	408
122%	230	1.08	391.8	7.6	424

4.4.5 Harmonics Measurement

The test results of Section 6.3.4 are documented in this section for reference in Table 12. The converters harmonics at 10%, 60%, and 100% loading of the rated output power level are listed up to the 39th harmonic. Besides them, the corresponding limits as defined by the stringent IEC 61000-3-2:2014 standard are listed.

Table 12. Current Harmonic Limit and Converter Current for 10% Rated Output Power

HARMONIC NO	PERCENTAGE OF RATED OUTPUT POWER					
	10%		60%		100%	
	AMPLITUDE AT HARMONIC (mA)					
	MEASURED	LIMIT	MEASURED	LIMIT	MEASURED	LIMIT
1	177.25	—	884.6	—	1569.6	—
3	25.54	132.6	100.3	663.0	631.0	1193.4
5	8.96	74.1	60.6	370.5	82.9	666.9
7	5.14	39.0	19.1	195.0	31.4	351.0
9	8.23	19.5	15.4	97.5	12.0	175.5
11	3.64	13.7	2.5	68.3	5.8	122.9
13	4.50	11.6	2.4	57.8	13.9	104.0
15	3.52	10.0	5.0	50.1	21.8	90.1
17	2.78	8.8	1.7	44.2	24.4	79.5
19	1.95	7.9	2.4	39.5	18.2	71.1
21	0.92	7.2	11.0	35.8	13.9	64.4
23	1.46	6.5	11.7	32.6	9.6	58.8
25	3.65	6.0	14.1	30.0	7.6	54.1
27	3.04	5.6	18.5	27.8	4.9	50.1
29	1.25	5.2	15.6	25.9	3.5	46.6
31	1.74	4.8	12.3	24.2	3.8	43.6
33	3.15	4.6	7.6	22.8	3.4	41.0
35	2.41	4.3	3.2	21.5	4.6	38.6
37	0.25	4.1	1.2	20.3	4.0	36.5
39	2.79	3.9	3.6	19.3	1.8	34.7

For light load to full load conditions, the converter's current remains with a robust margin below the "IEC61000-3-2 Class D" limit for all harmonics at 230-V AC.

4.5 Transient Behavior and Characteristics

Relevant transient characteristics of power converters are discussed in this subsection in the following order:

- Startup and shutdown behavior
- Full load input voltage and current waveform
- Output voltage ripple at line and switching frequency
- PFC choke current, gate, and switching node transient behavior
- Transient abrupt load change step response behavior

4.5.1 Startup and Shutdown Behavior

Startup and shutdown are important tests to assess the capability of a power converter to operate stable and robustly. Such test were conducted and documented for line frequencies of 50 Hz and 60 Hz, respectively. The line voltage level was chosen to be 230-V AC in all cases.

Figure 11 shows the converters line input current transient in bright blue and rising output voltage in dark blue and shows a 200-ms period of the initial startup. The current initially increases rapidly and then settles into CCM and the output voltage on the bulk capacitor is charged swiftly. The small input current peaks in the first cycles disappear, when the PFC regulation sets in. Charging current and consequently the voltage increase vary with the line frequency of 50 Hz. The converter starts up as expected.

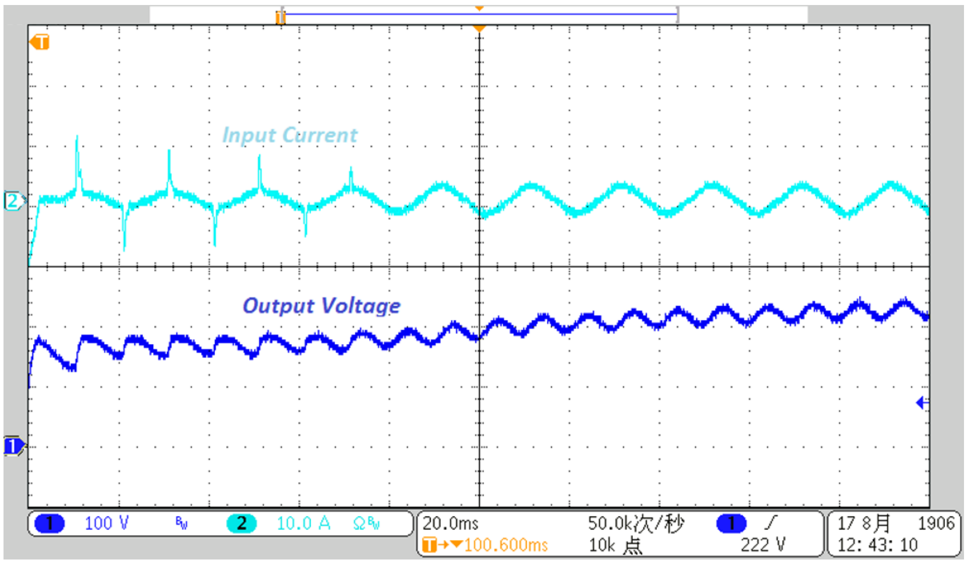

Figure 11. Startup Behavior for 230-V AC 50-Hz Line Voltage Input

Figure 12 plots the converters line input current in bright blue and the output voltage in dark blue. The initially constant switching input current varies with the line frequency of 50 Hz. Within the depicted period of 1 s, the converter is disabled at 580 ms. After the converter is disabled, the current is turned off instantaneously and the output voltage on the bulk capacitor is discharged continuously by constant current drawn by the electronic load. The converter shutdown is smooth as expected.

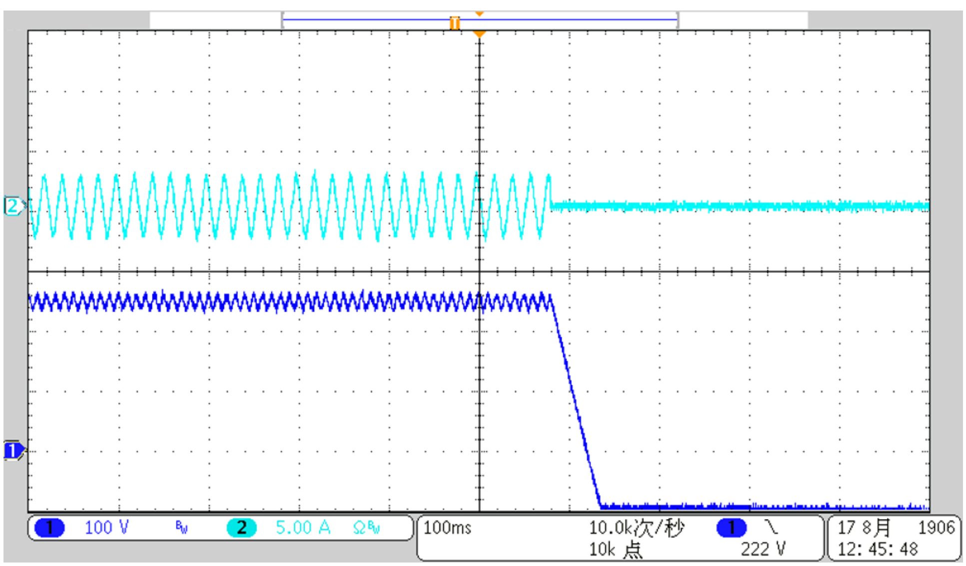

Figure 12. Shutdown Behavior for 230-V AC 50-Hz Input Voltage

Figure 13 depicts the converters initial startup at a line frequency of 60 Hz over a period of 200 ms. The input current (bright blue) initially increases rapidly and then settles into CCM and charges the bulk capacitor. Charging current and therefore the output voltage (dark blue) increase vary around the line frequency of 60 Hz. The line frequency of 60 Hz does not alter the startup behavior. The converter starts up as expected.

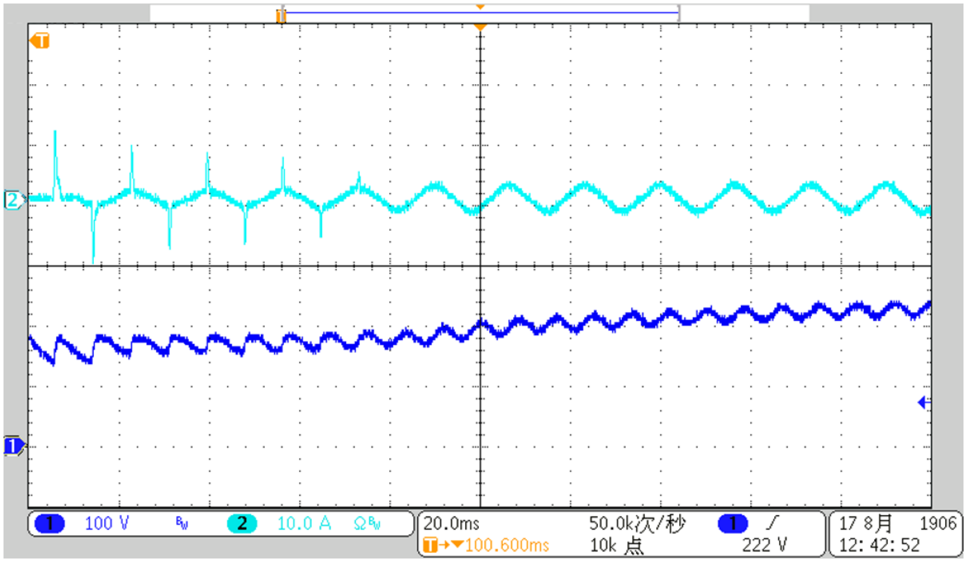

Figure 13. Startup Behavior for 230-V AC 60-Hz Input Voltage

Figure 14 shows the converters shutdown behavior for a test with a line frequency of 60 Hz over a period of 1 s. The initially constant switching input current (bright blue) varies with the line frequency 60 Hz. Within the depicted period of 1 s, the converter is disabled after 600 ms. Then the current is turned off instantaneously and the output voltage (dark blue) on the bulk capacitor is discharged continuously by constant current drawn by the electronic load. As expected the converter shutdown is swift and smooth independently of line frequency.

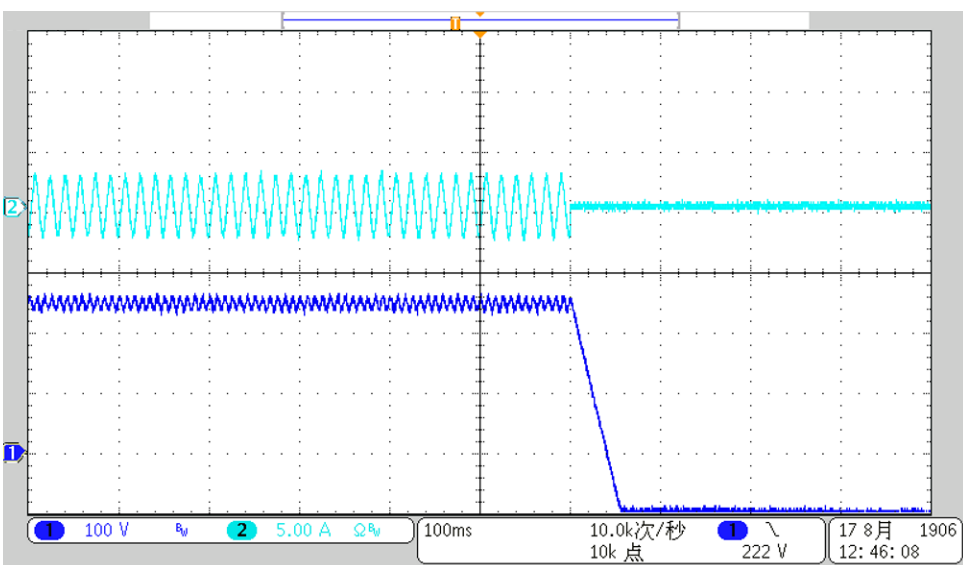

Figure 14. Shutdown Behavior for 230-V AC 60-Hz Input Voltage

4.5.2 Full Load Input Voltage and Current Waveform

Figure 15 shows input voltage (dark blue) and input current (dark blue) waveform at 230-V AC in full-load condition. As expected due to the measured high power factor and low distortion, the current matches to the input voltage very closely and are in phase.

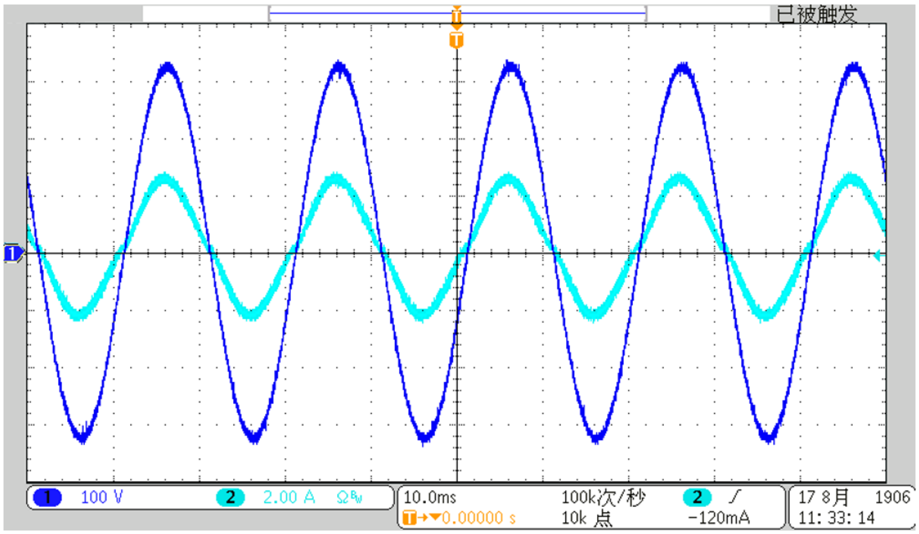

Figure 15. Input Voltage and Current for Full Load With 230-V AC Input

4.5.3 Output Voltage Ripple

This section describes the observed ripple at the 390-V DC output of the AC/DC power converter at both line and switching frequency for two different line frequencies.

Figure 16 shows the output voltage at the converter's 390-V DC output during a 40-ms period for line frequency of 50 Hz. The expected less than 5% peak-to-peak ripple relates to the trade-off between solution cost, size, and performance. The line frequency output voltage ripple is proportional to the bulk capacitance. In order to optimize cost and solution size of this TI Design, a very small bulk capacitor capacitance of merely 150 μF is used. Consequently, the line frequency ripple is non-negligible. This trade-off should be very acceptable for relevant applications; the 50-Hz low frequency ripple will be suppressed very effectively, even by slow regulation loops. For more stringent line frequency ripple requirements, a larger value of the bulk capacitor could be used.

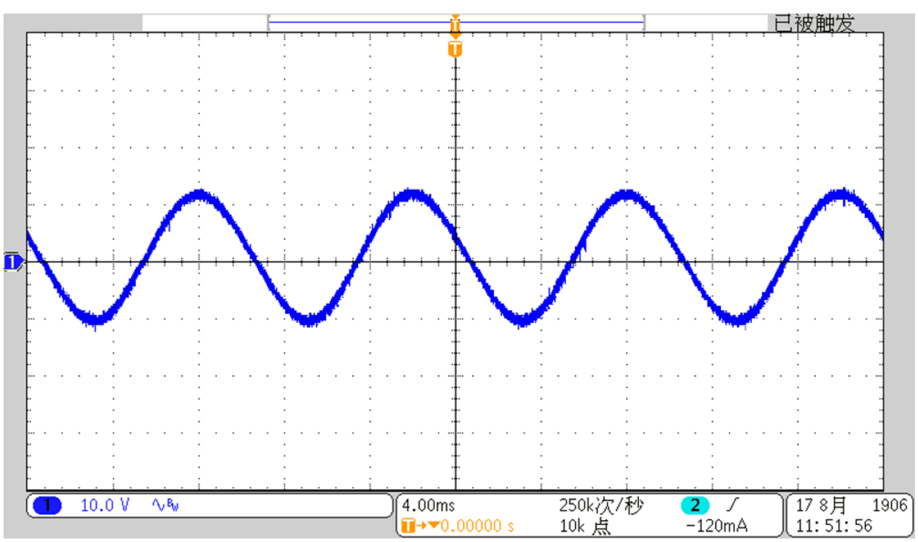

Figure 16. 50-Hz Line Frequency Output Voltage Ripple

Figure 17 shows the expected less than 5% peak-to-peak ripple observed at the converter's 390-V DC output for a line frequency of 60 Hz during 40 ms. Again, this ripple can be traded off with the bulk capacitor size.

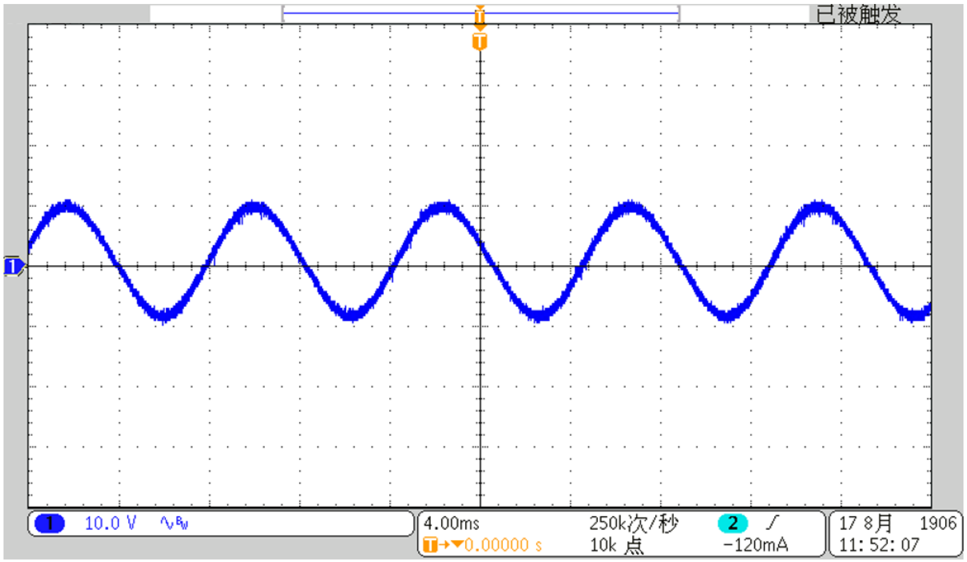

Figure 17. 60-Hz Line Frequency Output Voltage Ripple

Figure 18 shows the expected less than 1% peak-to-peak switching ripple at the converter's 390-V DC output during a period of 40 µs for line frequency of 50 Hz.

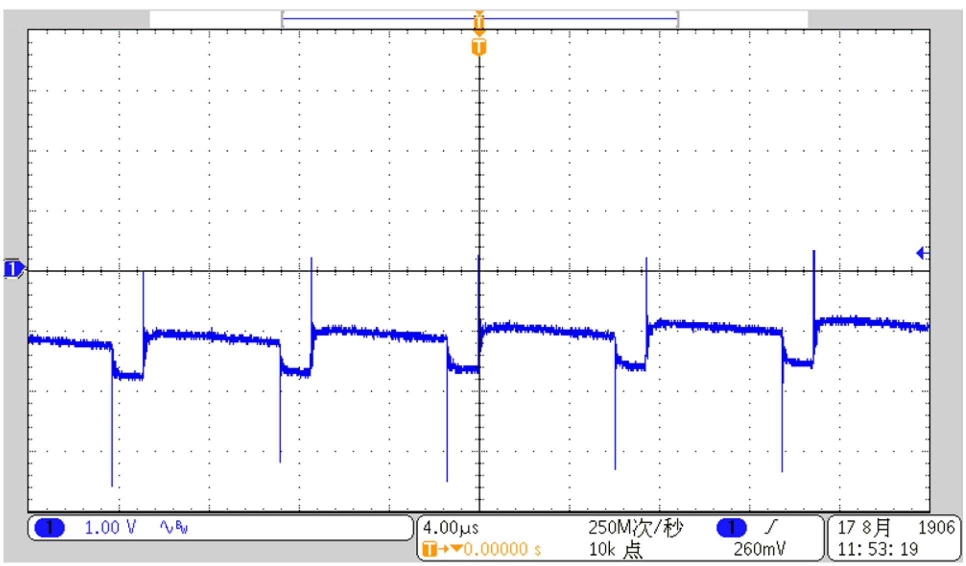

Figure 18. Output Voltage Ripple at Switching Frequency for 50-Hz Line Frequency

Figure 19 shows the expected less than 1% peak-to-peak switching ripple during a 40-µs period at the converter's 390-V DC output for line frequency of 60 Hz.

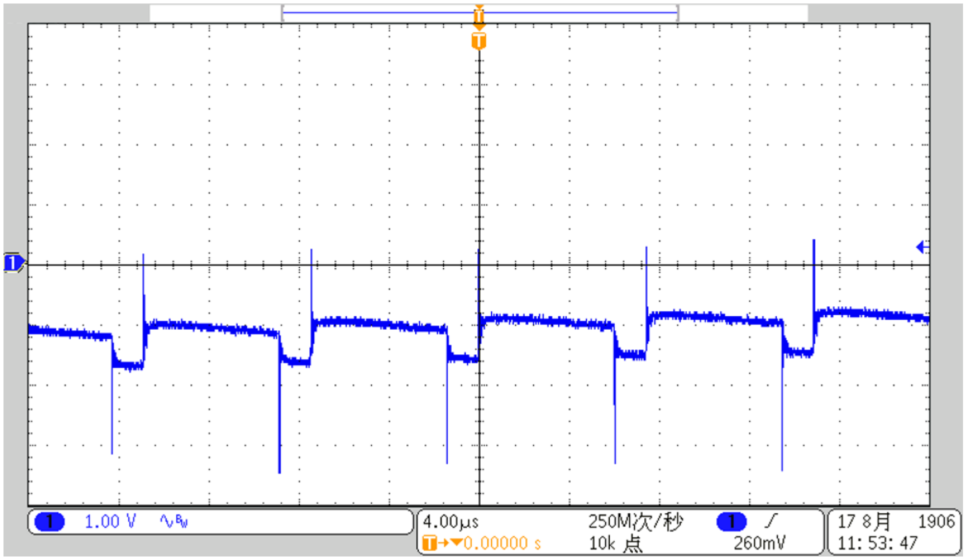

Figure 19. Output Voltage Ripple at Switching Frequency for 60-Hz Line Frequency

4.5.4 PFC Choke Current, Gate, and Switching Node Waveforms

In this subsection, the reliability of the converter is investigated by consideration of typical PFC choke current, gate voltage, and switching node voltage transients.

Figure 20 shows the PFC choke current (bright blue) and output waveform (dark blue) of gate driver at the line frequency scale. The small ripple of the current of PFC choke indicates that operates always in CCM. Therefore, the total harmonic distortion is low and consequently the inductors current ripple and power consumption is low as well.

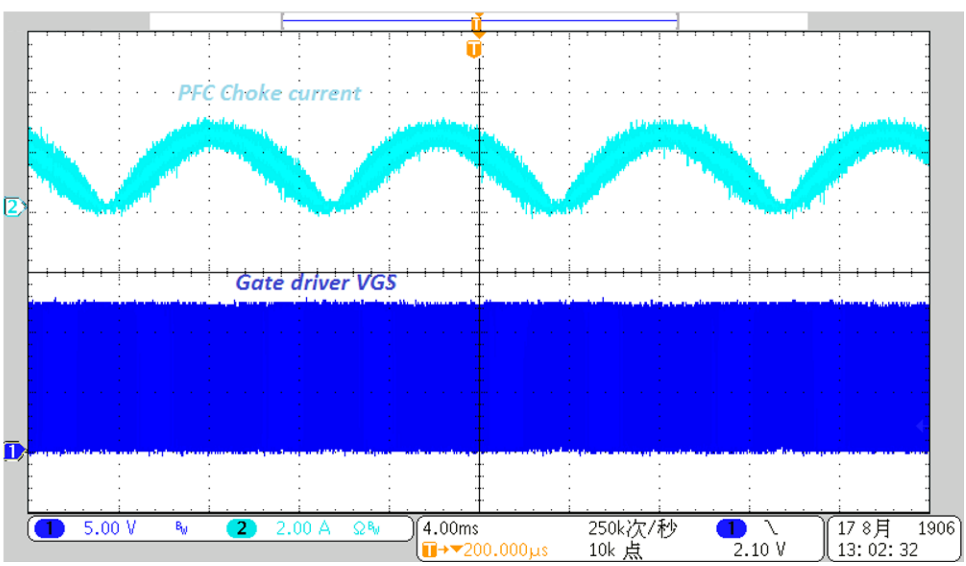

Figure 20. Choke Current and VGS Waveform at Line Frequency Scale

Figure 21 plots the PFC choke current (bright blue) and output waveform of gate driver respectively MOSFET gate voltage VGS (dark blue) and drain voltage VDS (magenta) at the switching frequency scale. The smooth switching waveforms proof step yet well damped dynamic settling, which yields rapid turnon and turnoff and a high efficiency. The absence of any ringing or overshoot minimizes noise emissions, filtering requirements, and cost.

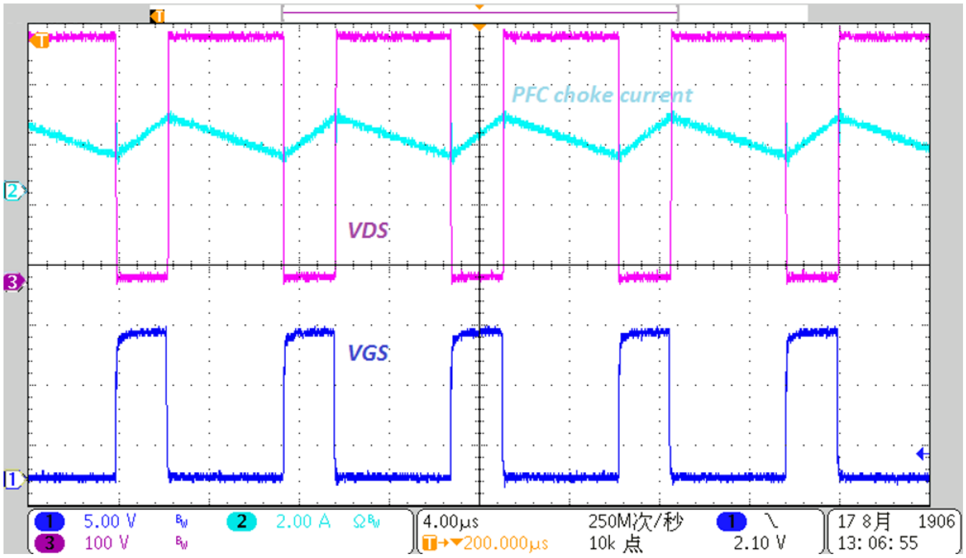

Figure 21. Choke Current, VGS, and VDS at Switching Frequency Scale

Figure 22 zooms into the gate voltage VGS (dark blue) and the drain voltage VDS (magenta), when the MOSFET turns on under full-load condition with a 230-V AC line voltage. The rapid yet smooth turnon can be observed.

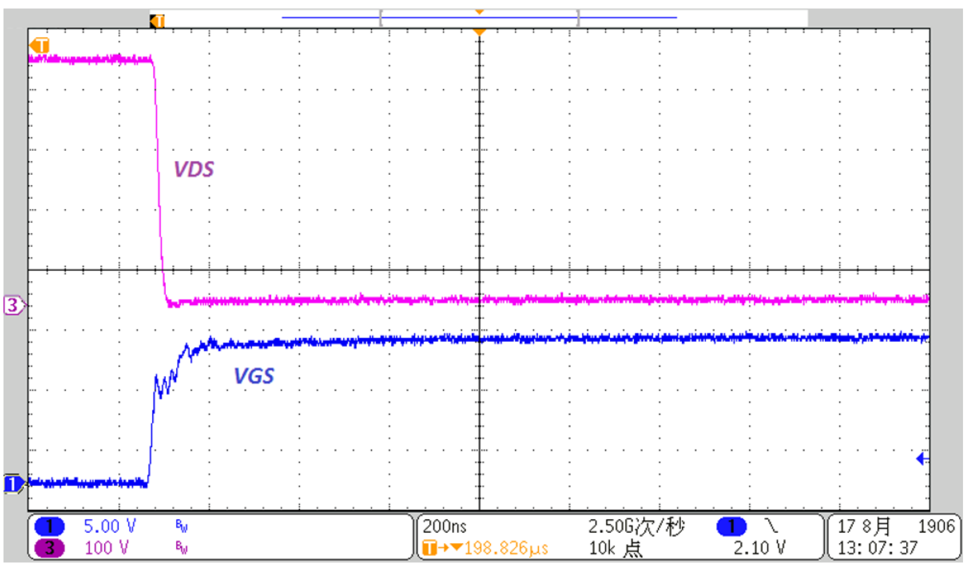

Figure 22. VGS and VDS MOSFET Turnon Waveforms

Figure 23 zooms the gate voltage VGS (dark blue) and drain voltage VDS (magenta), when the MOSFET turns off under full-load condition with a 230-V AC line voltage. The turnoff is rapid and smooth.

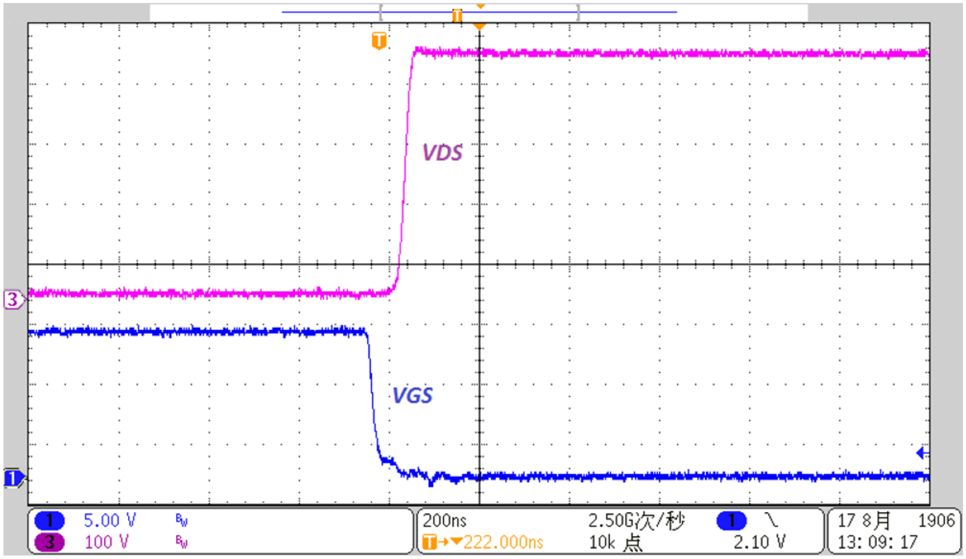

Figure 23. VGS and VDS MOSFET Turnoff Waveforms

4.5.5 Transient Abrupt Load Change Step Response Behavior

Another very helpful criterion for the assessment the nature of the dynamic behavior of a power converter is its response to abrupt load changes. This behavior was consequently tested and included in this report as well. The load step response was tested with a periodically abruptly changing electronic load.

Figure 24 shows the step load current (bright blue) steps from 0 to 0.9 A and vice versa from 0.9 to 0 A for a line voltage input level of 230-V AC. Due to the instantons load step, the output voltage (dark blue) drops more than 5%, then the UCC28180 Enhanced Dynamic Response (EDR) rapidly increases the current and suppresses the output voltage drop.

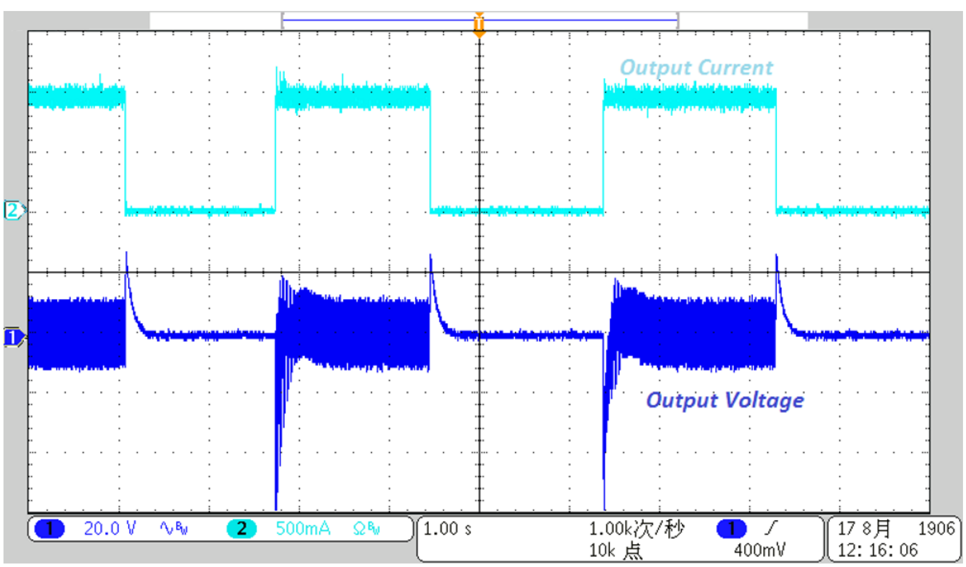

Figure 24. Load Transient Under 230-V Input

4.6 Thermal Measurements

Sound thermal management is a trade-off between cooling effort and cost for any power converter. To better understand the temperature of power components and realistic operating temperature, the thermal images were plotted at room temperature (25°C) with a closed enclosure, no airflow, and at different load conditions for different input voltage and load levels. The converter was run for 30 minutes after a load change before a thermal image was captured. This period ensured settled operation temperature.

Figure 25 indicates the temperature distribution across the AC/DC power converters at a 220-W load and an input voltage of 90-V AC.

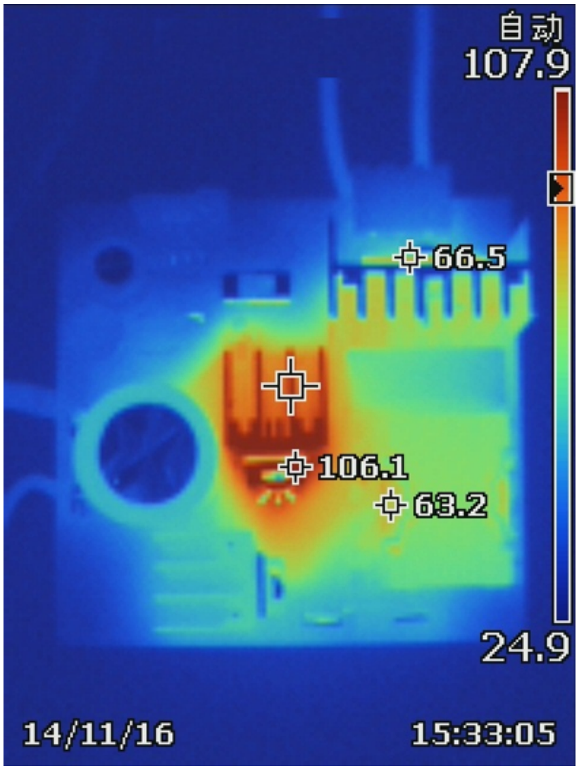

Figure 25. Top-Side Thermal Image of Converter PCB for 90-V AC Input and 180-W Load

Table 13 summarizes the temperature of the converters components from Figure 25.

Table 13. Summary of Component Temperature for 90-V AC Input and 180-W Load

PARAMETER	VALUE
Input voltage	90 V
Output power	180 W
Ambient temperature	25°C
Main switch	106.1°C
PFC choke coil	63.2°C
Bridge diode	66.5°C

With exception of the main switch the temperature is well below 70°C. At the main switch the 106°C temperature is with the highest. This result is expected, as low line input voltages represent the worst case for the power dissipation in the main switch. Given the typical high maximum switch junction temperatures, the margin for ambient temperature increases is more than sufficient.

Moreover a more similar component temperature can be achieved by balancing the cooling body's heat dissipation capabilities closer to the low line heat dissipation. Anyway, if the main switch is placed on the border of the PCB and the housing is used as cooling body, then the component temperature will decrease significantly and automatically be more balanced.

Figure 26 shows the temperature distribution across the converters at a 220-W load and an input line voltage of 115-V AC.

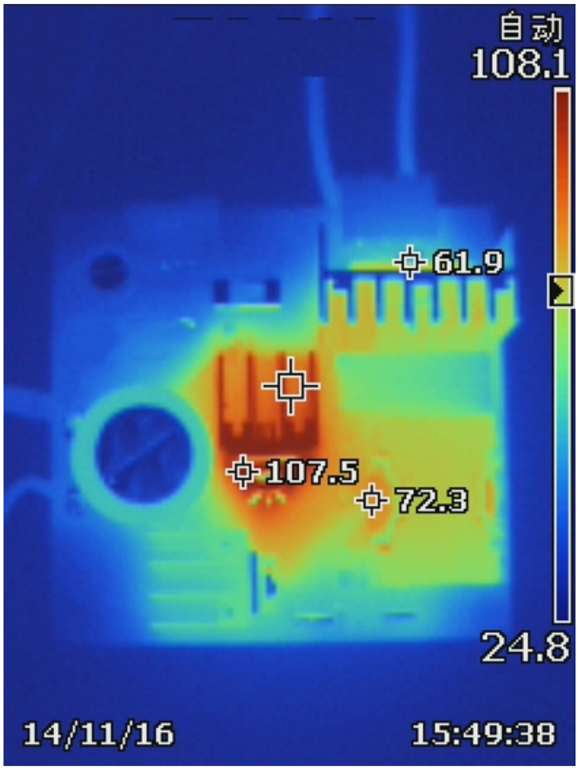

Figure 26. Top-Side Thermal Image of Converter PCB at 115-V AC Input and 220-W Load

Table 14 summarizes the temperature of the converters components from Figure 26. The temperatures are, as expected, very similar to the prior test result for the same reasons.

Table 14. Summary of Component Temperature for 115-V AC Input and 220-W Load

PARAMETER	VALUE
Input voltage	115 V
Output power	220 W
Ambient temperature	25°C
Main switching	107.5°C
PFC choke coil	72.5°C
Bridge diode	61.9°C

Figure 27 depicts the temperature distribution across the converter at a 350-W load and an input voltage of 230-V AC.

Figure 27. Top-Side Thermal Image of Converter PCB at 230-V AC Input and 350-W Load

Table 15 summarizes the temperature of the converters components from Figure 27. The temperature in this condition for all components is very low—even the switching transistor is below 70°C—and the component temperature is very well balanced.

Table 15. Summary of Component Temperature for 230-V AC Input and 220-W Load

PARAMETER	VALUE
Input voltage	230 V
Output power	350 W
Ambient temperature	25°C
Main switching	66.1°C
PFC choke coil	57.9°C
Bridge diode	57.5°C

5 Design Files

5.1 Schematics

To download the schematics, see the design files at TIDA-00776.

5.2 Bill of Materials

To download the bill of materials (BOM), see the design files at TIDA-00776.

5.3 PCB Plots

To download the layer plots, see the design files at TIDA-00776.

5.4 Altium Project

To download the Altium project files, see the design files at TIDA-00776.

5.5 Gerber Files

To download the Gerber files, see the design files at TIDA-00776.

5.6 Assembly Drawings

To download the assembly drawings, see the design files at TIDA-00776.

6 Related Documentation

1. Texas Instruments, *Using the UCC28180EVM-573, 360-W Power Factor Correction Module*, UCC28180EVM-573 User's Guide (SLUUAT3)
2. Texas Instruments, *UCC28180 Programmable Frequency, Continuous Conduction Mode (CCM), Boost Power Factor Correction (PFC) Controller*, UCC28180 Datasheet (SLUSBQ5)
3. Texas Instruments, *3W Non-ISO Bias Power Supply with up to 80% Efficiency, 15dB Margin EMI Performance Reference Design* , TIDA-00940 User's Guide (TIDUBM8)
4. Texas Instruments, *5V 1A, Low EMI, 94% Efficiency DC/DC Module in Dual Layer TO-220 Form Factor Reference Design*, TIDA-00946 User's Guide (TIDUBX3)
5. Texas Instruments, *3.3V 1A, Low EMI, 92% Efficiency DC/DC Module in Dual Layer TO-220 Form Factor Reference Design*, TIDA-00947 User's Guide (TIDUBX5)
6. Texas Instruments, *5V 1A, Low EMI, 94% Efficiency DC/DC Module in Single Layer TO-247 Form Factor Reference Design*, TIDA-00948 User's Guide(TIDUBX4)
7. Texas Instruments, *3.3V 1A, Low EMI, 92% Efficiency DC/DC Module in Single Layer TO-247 Form Factor Reference Design*, TIDA-00949 User's Guide (TIDUBX6)

6.1 Trademarks

7 About the Authors

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Revision A History

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

Changes from Original (December 2016) to A Revision	Page
• Changed language and images to fit current style guide	1

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