3300 W CCM bi-directional totem pole with CoolSiC™ 650 V G2 and XMC™

EVAL_3K3W_TP_PFC_SIC2

About this document

Scope and purpose

This document presents a system solution based on Infineon superjunction (SJ) (CoolMOS™) and wide bandgap (CoolSiC™ G2) power semiconductors, drivers, and a microcontroller (MCU) for a bridgeless totem-pole power factor corrector (PFC) with bi-directional capability. The EVAL_3K3W_TP_PFC_SIC2 board is intended for applications that require the highest efficiency (99.2 percent) and high power density (73 W/in^3), such as high-end servers and telecoms. The bi-directional power flow capability enables this design to be used in battery chargers or battery formation applications. The totem pole implemented in the EVAL_3K3W_TP_PFC_SIC2 board operates in continuous conduction mode (CCM) in both rectifier (PFC) and inverter modes, with full digital control implementation using the Infineon XMC™ 1000 series microcontroller (MCU).

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1 System description

The EVAL_3K3W_TP_PFC_SIC2 board is a system solution enabled by Infineon's power semiconductors, along with drivers and a microcontroller. The evaluation board consists of a bridgeless totem-pole topology – intended for high-end applications with the highest efficiency requirements. The totem-pole topology is simple and offers a reduced part count and complete utilization of the PFC inductor and switches [1]. Therefore, the totem-pole PFC enables high power density at a limited system cost for high-performance systems. The EVAL_3K3W_TP_PFC_SIC2 board also provides reverse power flow (inverter operation for grid-connected applications) due to the inherent bi-directional power flow capability of the totem-pole topology.

The totem-pole topology with CCM operation in PFC applications is feasible using wide bandgap semiconductors [1]. In this case, Infineon's CoolSiC™ G2 MOSFET in TO-247 four-pin package is used to push the efficiency to 99.2 percent (Figure 1). The converter operates exclusively at high-line (176 V_{rms} minimum, 230 V_{rms} nominal) in CCM with 65 kHz switching frequency.

Note: Due to production variations and measurement set-up, efficiency variations up to ±0.2 percent can be seen in Figure 1.

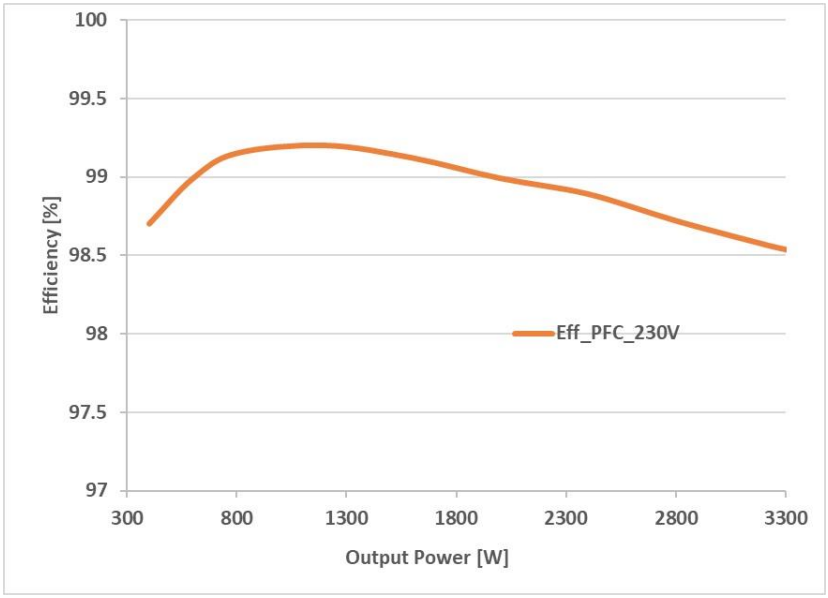

Figure 1 Measured efficiency at 230 V (with applied line filter in the power analyzer) of the 3300 W totem-pole PFC with CoolSiC™ G2 62 mΩ and CoolMOS™ 17 mΩ

The PFC function to achieve bulk voltage regulation while demanding high-quality current from the grid is implemented with an Infineon XMC1404 MCU [2]. For further details on PFC control implementation with XMC™ 1000 family of MCUs, see application notes of other Infineon PSU and PFC evaluation boards with classic boost or dual boost topologies ([3],[4], and [5]).

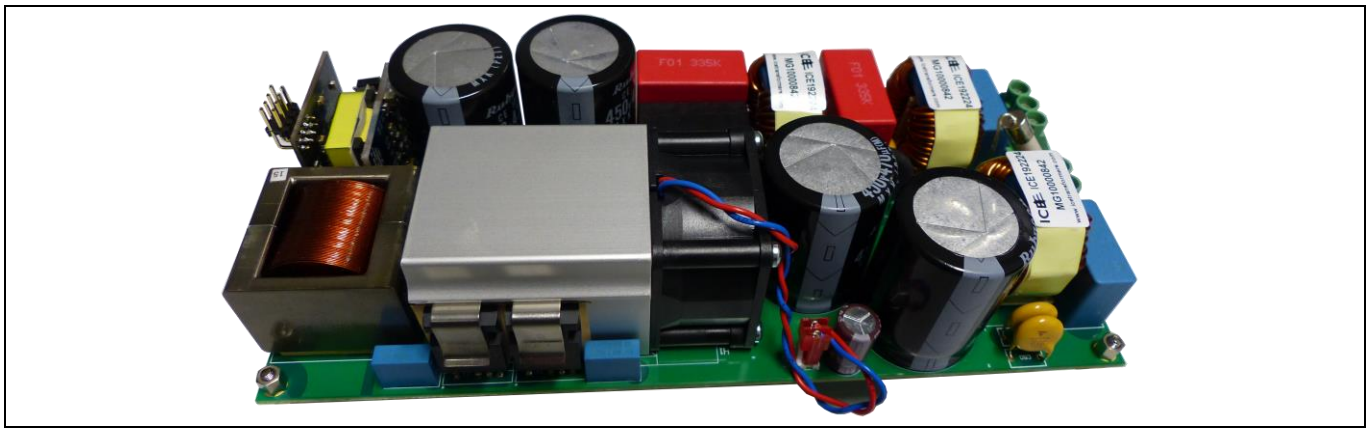

Figure 2 3300 W bridgeless totem-pole PFC with CoolSiC™G2, CoolMOS™, and XMC™ MCU

The 3300 W bridgeless bi-directional (PFC/AC-DC and inverter/AC-DC) totem-pole discussed in this application note is a system solution developed with Infineon power semiconductors, drivers, and controllers. The Infineon devices used to implement the EVAL_3K3W_TP_PFC_SIC2 board are:

- CoolSiC™ 650 V G2 MOSFET (IMZA65R050M2H) 62 mΩ in TO-247 four-pin package, as totem-pole PFC high-frequency switches
- 600 V CoolMOS™ C7 SJ MOSFET (IPW60R017C7) 17 mΩ in TO-247 package, for the totem-pole PFC return path (low-frequency bridge)
- EiceDRIVER™ 2EDF7275F isolated gate drivers
- CoolSET™ ICE5QSAG QR flyback controller and CoolMOS™ 950 V P7 (IPU95R3K7P7) for the bias auxiliary supply (bias board KIT_6W_18V_P7_950V)
- XMC™ XMC1404 MCU for PFC control implementation

A simplified block diagram of the bridgeless topology with the mentioned devices from the Infineon portfolio is shown in Figure 3. The diode bridge in front of the totem-pole PFC converter is meant to be a current path for start-up or surge conditions; it is not part of the current path during the steady-state converter operation. The power flow direction, which will select the converter operation – forward power flow or PFC operation versus reverse power flow or inverter operation – can be selected by a switch connected to the XMC™ MCU as a digital input pin.

Note: The power flow or operation mode is selected before the application starts and the power flow cannot be reverted during operation. Therefore, the EVAL_3K3W_TP_PFC_SIC2 board is able to operate as either PFC or inverter but the current version of the SW does not provide dynamic change of the operation mode.

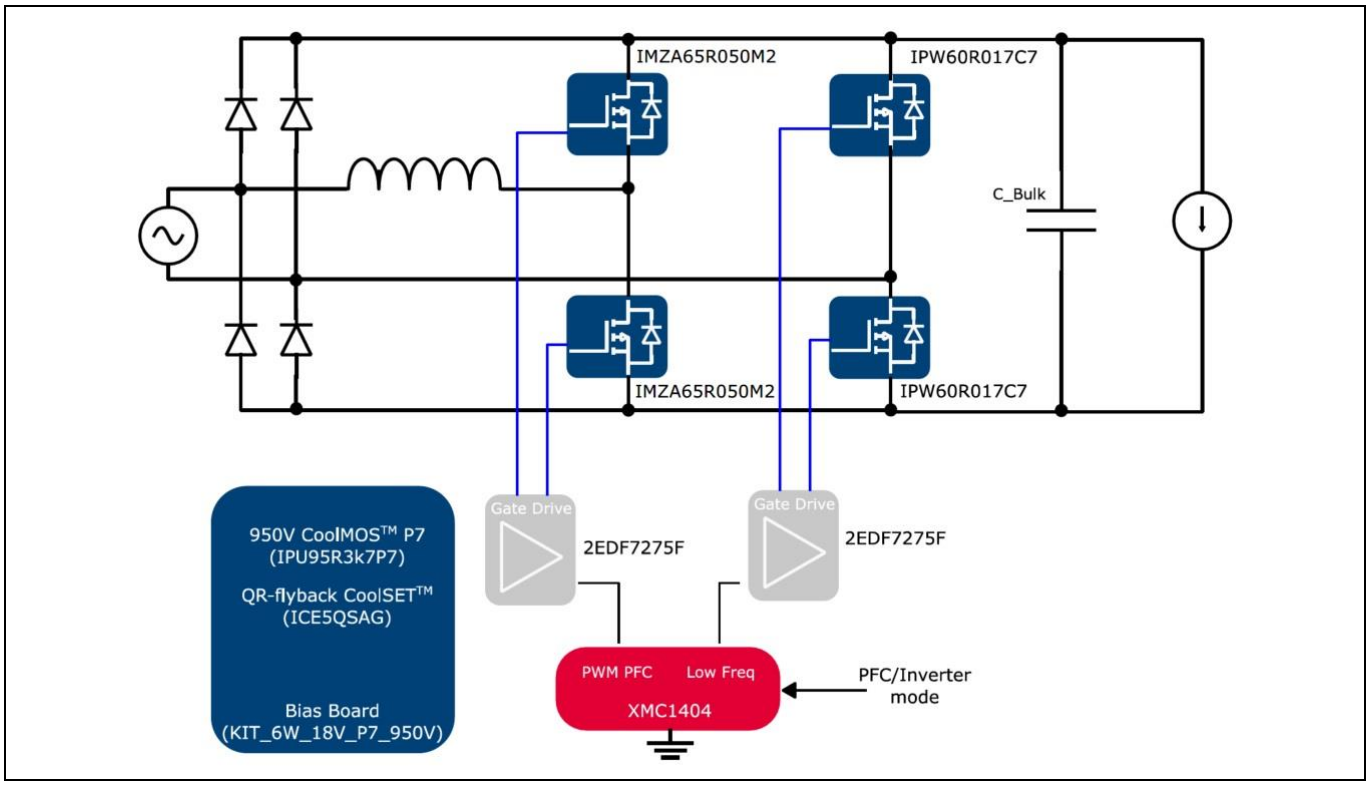

Figure 3 **3300 W bridgeless totem-pole PFC board (EVAL_3K3W_TP_PFC_SIC2) simplified diagram showing the topology and Infineon semiconductors used**

This document describes the EVAL_3K3W_TP_PFC_SIC2 board implementation, specifications, and main test results. This document describes the EVAL_3K3W_TP_PFC_SIC2 board implementation, specifications, and main test results. Visit Infineon's Evaluation Board Finder to easily find the right evaluation board for your needs.

1.1 Board description

Figure 4 shows the placement of the different sections of the EVAL_3K3W_TP_PFC_SIC2 bridgeless totem-pole bi-directional PFC with Infineon 650 V CoolSiC™ G2 silicon carbide MOSFET. The board is 208 mm long, with a width of 89 mm and a height of 40 mm (1U) for a power density of 73 W/in^3.

Inmediately after the AC input connector, a two-stage EMI filter, fuse, and NTC in-rush current limiter is placed together with the input relay. The DC output connector is placed on the same side of the board as the AC connector. Close to the output connector, a single-stage filter (with differential and common mode paths) is placed to guarantee proper aquisition of the output variables in efficiency measurements.

On the other side of the board, two daughter cards are placed: the bias board and the control card. The bias board uses a QR CoolSET™ controller and 950 V P7 CoolMOS™ switch to generate the required voltages for the control card, driving, relay, and fan supply. The control card implements the required current, voltage, and polarity sensing. The full digital control is implemented in the Infineon XMC™ MCU, which is in charge of the proper operation of the bridgeless totem-pole topology.

The rest of the board is occupied by the bridgeless totem-pole itself, which comprises the PFC choke, the bulk capacitor, and a bridge with 650 V CoolSiC™ G2 and 600 V C7 CoolMOS™ MOSFETs. The bulk capacitance is designed to comply with the hold-up time shown in Table 1. The semiconductors in TO-247 package are

mounted on a heatsink with an attached fan, which blows air towards the PFC choke. The choke is designed with high-flux material in an EQ shape to comply with the height requirement, high efficiency performance, and high power density.

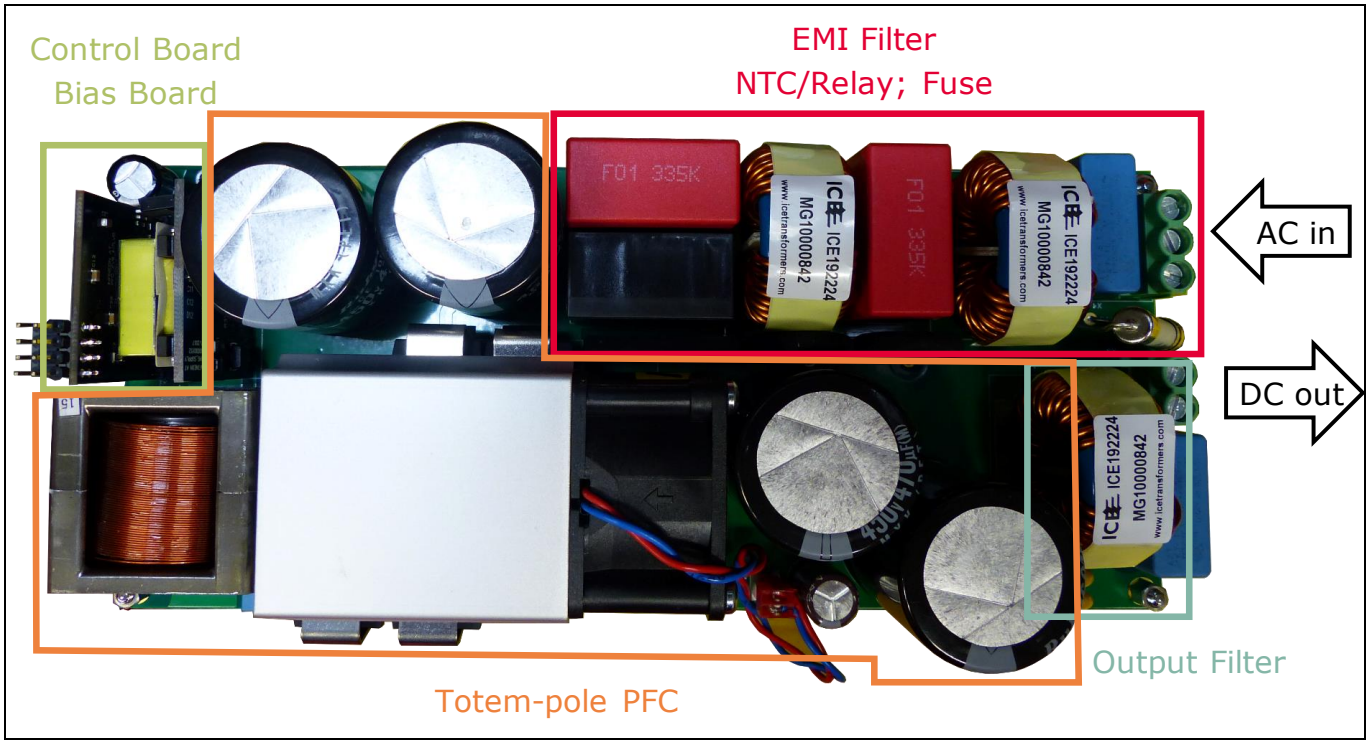

Figure 4 **Placement of sections in the 3300 W bridgeless totem-pole PFC with 650 V CoolSiC™ G2 and 600 V C7 CoolMOS™ MOSFETs and XMC™ MCU**

1.2 Signal conditioning for digital control of totem-pole CCM PFC

The evaluation board EVAL_3K3W_TP_PFC_SIC2 implements CCM average current mode control with duty feed-forward (DFF) for both PFC and inverter operations. It follows a control structure similar to what is implemented for a classic PFC (shown in [2] and [4]) or the dual boost (shown in [5]).

Unlike the classic PFC in which the AC voltage is rectified by the diode bridge, in the bridgeless totem-pole PFC converter the inductor current is both positive and negative. The most simple and cost-effective way to sense this current is to use a shunt resistor in series with the inductor, as shown in Figure 5. In addition, the control reference (GND_iso in Figure 5) in the evaluation board is placed in the AC-line after the shunt resistor. Therefore, the current sense voltage (CS+) is positive and negative according to the positive reference current shown by the red arrow in Figure 5.

Since the ADC of the MCU used for the control implementation (Infineon's XMC1404 [2]) only allows input voltages between zero and the supply voltage (Vcc_XMC in Figure 5), an offset is included with the CS gain to properly use the input spam of the ADC. In this case, the offset is 2.5 V, corresponding to half the supply voltage for the XMC™ controller used. The differential gain (K_i) is adjusted to consider both the inductor average current and the switching frequency ripple, since this signal is used for CCM average current control and peak current limitation [2].

In the totem-pole operation, for both PFC and inverter power flow, the return path transistors (HS_SR and LS_SR in Figure 5) are switched at the AC zero crossing according to the AC polarity: HS_SR for the positive AC

and LS_SR for the negative AC cycle. The polarity of the input voltage is set according to the control reference GND_iso. Since the control reference is in one of the AC input rails, the polarity detection is significantly simplified and the internal ESD diode protection of XMC™ is used to transform the input capacitor voltage into a digital signal.

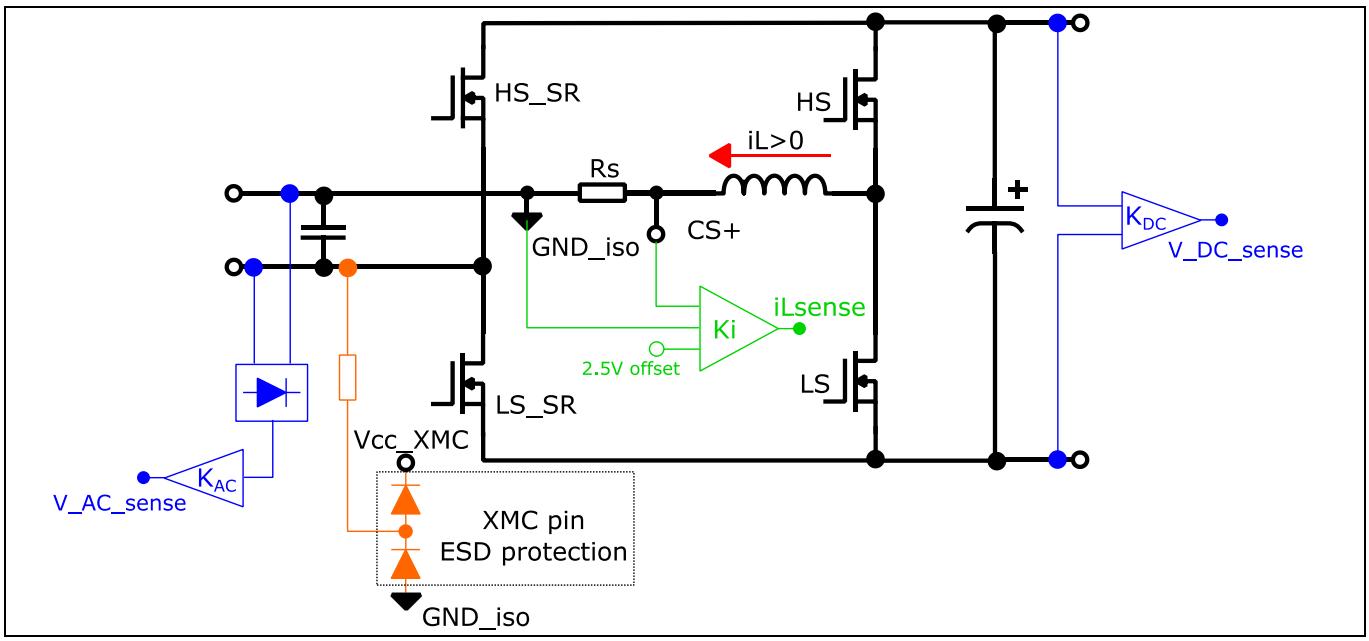

Figure 5 Block diagram of the sensing circuitry required for bi-directional totem-pole control with XMC™ and control reference in the AC rail in series with the PFC choke

Due to the control reference location, the bulk voltage sense requires a differential amplifier with gain K_{DC}, as shown in Figure 5. For AC voltage sensing, the control reference location allows simple sensing. In this case, the voltage has been rectified (positive ADC input is required) and adapted to the ADC input range with a differential gain K_{AC}.

Since the AC voltage is used for the current reference generation in the selected average current mode structure (Figure 6), the current reference is a full wave rectified sinusoidal sequence. However, the current sense after the ADC is a sinusoidal sequence with an offset at half of the ADC spam. Therefore, the ADC result from the CS first requires the offset to be removed and then rectified according to the AC polarity signal and the operation mode: the current in inverter mode is 180 degrees out of phase with the AC voltage, while the current in PFC mode is in phase with the AC voltage. These two steps, together with the extra gain, are implemented through software in the XMC™ MCU.

The current loop controller and structure is kept the same for inverter operation. However, since the bulk voltage is controlled by a DC-DC converter in DC-AC operation, the V_{loop_output} signal is substituted with a value sent by the DC-DC stage, which is the target power to deliver into the grid.

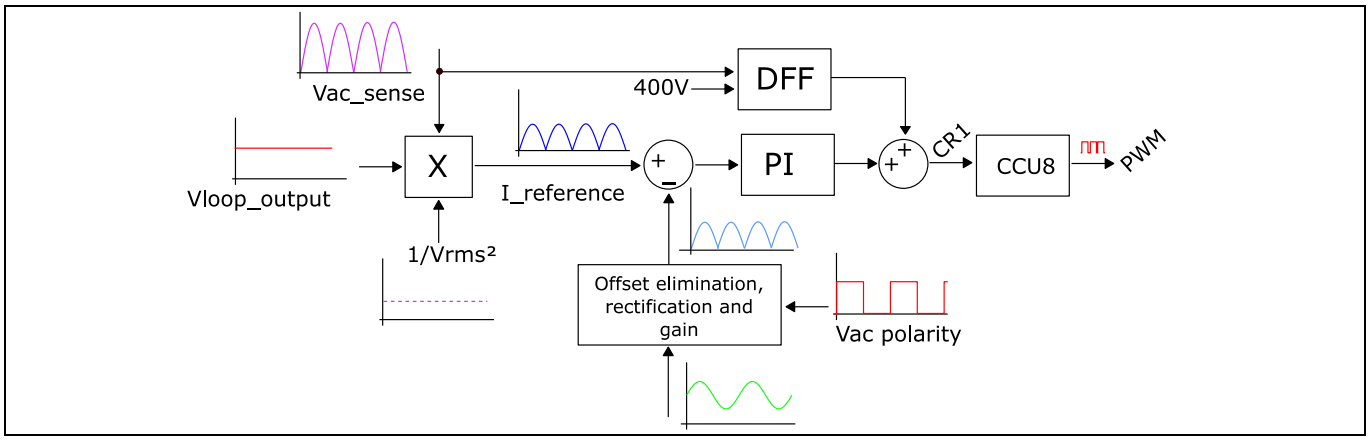

Figure 6 Current loop structure with duty feed-forward and the required current manipulation

1.3 Graphical user interface (GUI)

The XMC™ MCU includes a serial communication interface (UART) and a specific protocol that allows communication from a computer to the MCU. The user interface for Windows (Figure 7) has been developed to communicate with the controller using XMC™ Link (UART to USB conversion).

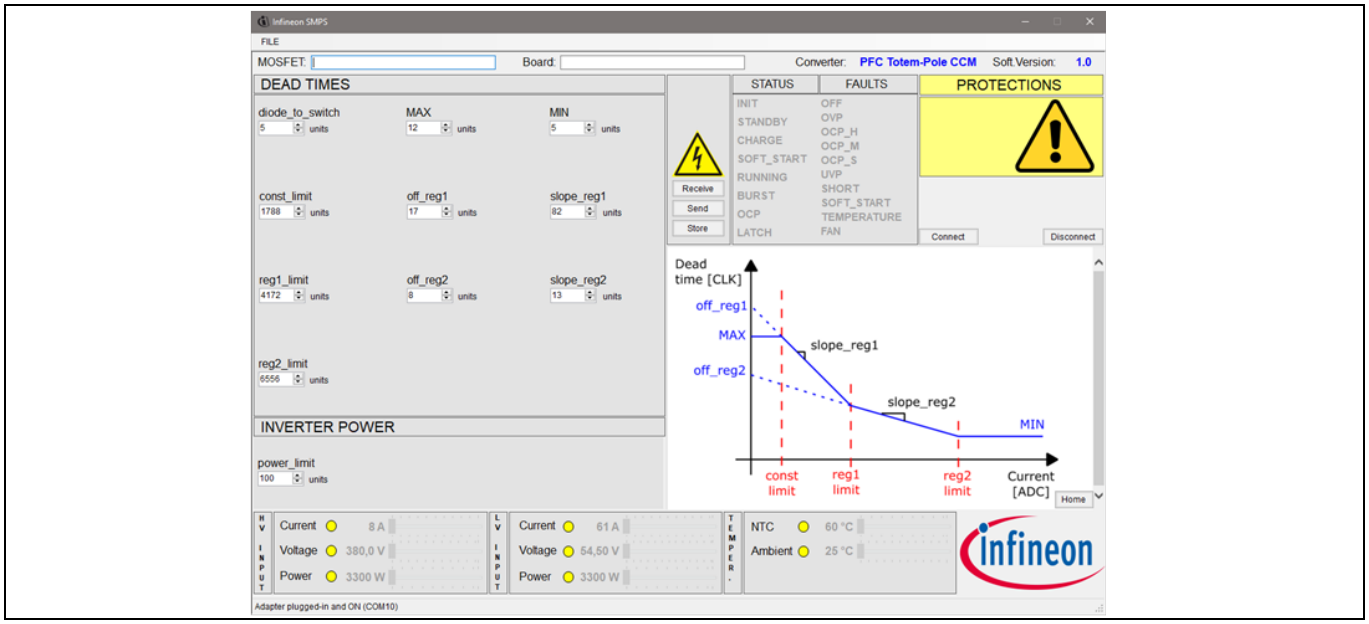

Figure 7 GUI for dead-time optimization and power target in inverter operation in the EVAL_3K3W_TP_PFC_SIC2 board

Two main sets of parameters can be updated in the controller using the GUI:

- Dead-time between low-side and high-side CoolSiC™ switches in the totem-pole topology. The dead-time can be modified in the controller following two linear regions with minimum and maximum limitations (Figure 7).
- Power command, which sets the current level in inverter operation. This emulates the command sent by the DC-DC stage in the final application. Figure 8 shows the relationship between the power command in the GUI and the output power for different AC voltages.

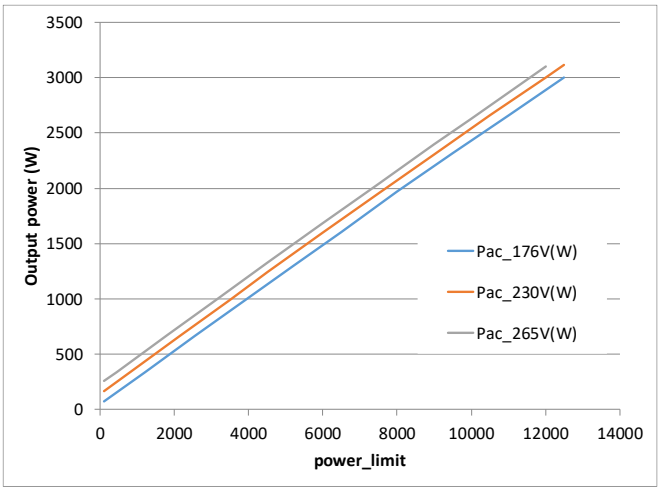

Figure 8 Measured output power (AC) according to the power_limit parameter from the GUI

The GUI shown in Figure 7 is intended for the development of the totem-pole platform, and the other functions displayed are not available.

2 PFC (AC-DC operation) specification and test results

This chapter discusses the specifications, performance, and behavior of the 3300 W bridgeless totem pole with average current mode control in CCM for PFC operation. Table 1 shows the demonstrator performance and specifications under several steady-state and dynamic conditions. The converter operates at 65 kHz switching frequency and only for high-line AC input (176 V minimum RMS voltage). The results have been obtained with CoolSiC™ 650 V 62 mΩ G2 devices in TO-247 four-pin package and 600 V CoolMOS™ 17 mΩ devices in TO-247 as low-frequency switches.

Table 1 Summary of specifications and test conditions for the 3300 W bi-directional totem-pole board in PFC mode

Test		Conditions	Specification	
Efficiency test		230 V_{rms}, 50 Hz/60 Hz	η_{pk} = 99.2 percent at 1650 W (50 percent load)	
Current THD		230 V_{rms}, 50 Hz/60 Hz	THDi less than 10 percent from 10 percent load	
Power factor		230 V_{rms}, 50 Hz/60 Hz	PF more than 0.95 from 20 percent load	
Rated DC voltage			400 V	
Steady-state Vout ripple		230 V_{rms}, 50 Hz/60 Hz, 100 percent load	$\lvert\Delta V_{out}\rvert$ less than 20 $V_{pk\text{-}pk}$	
In-rush current		230 V_{rms}, 50 Hz/60 Hz, measured on the first AC cycle	I_{in_peak} less than 30 A	
Power line disturbance	AC lost (hold-up time)	230 V_{rms}, 50 Hz, 10 ms at 100 percent load, 20 ms at 50 percent load	V_{out_min} = 300 V (UVP)	No damage: * PFC soft-start if bulk voltage is under 300 V * PFC soft-start if AC is out of range for a certain time
	Voltage sag	200 V_{rms}, 50 Hz/60 Hz, different sag conditions, 100 percent load		
Brown-out	AC voltage		174 V on; 168 V off	
Load transient		7.4 A (90 percent) ↔ 0.8 A (10 percent), 0.2 A/µs	V_{out_min} = 300 V (UVP) V_{out_max} = 450 V (OVP)	
OCP			Peak current limit 40 A	
			AVG current limit 28 A	

2.1 Performance and steady-state waveforms

The performance of the EVAL_3K3W_TP_PFC_SIC2 board in PFC mode has been tested using a programmable AC source and electronic load. The measurements given in this section comply with the specifications presented in Table 1.

Figure 9 shows the efficiency measurements for PFC operation at different AC voltages. The efficiency results are the same regardless of the AC frequency (50 Hz/60 Hz) and do not include the fan consumption.

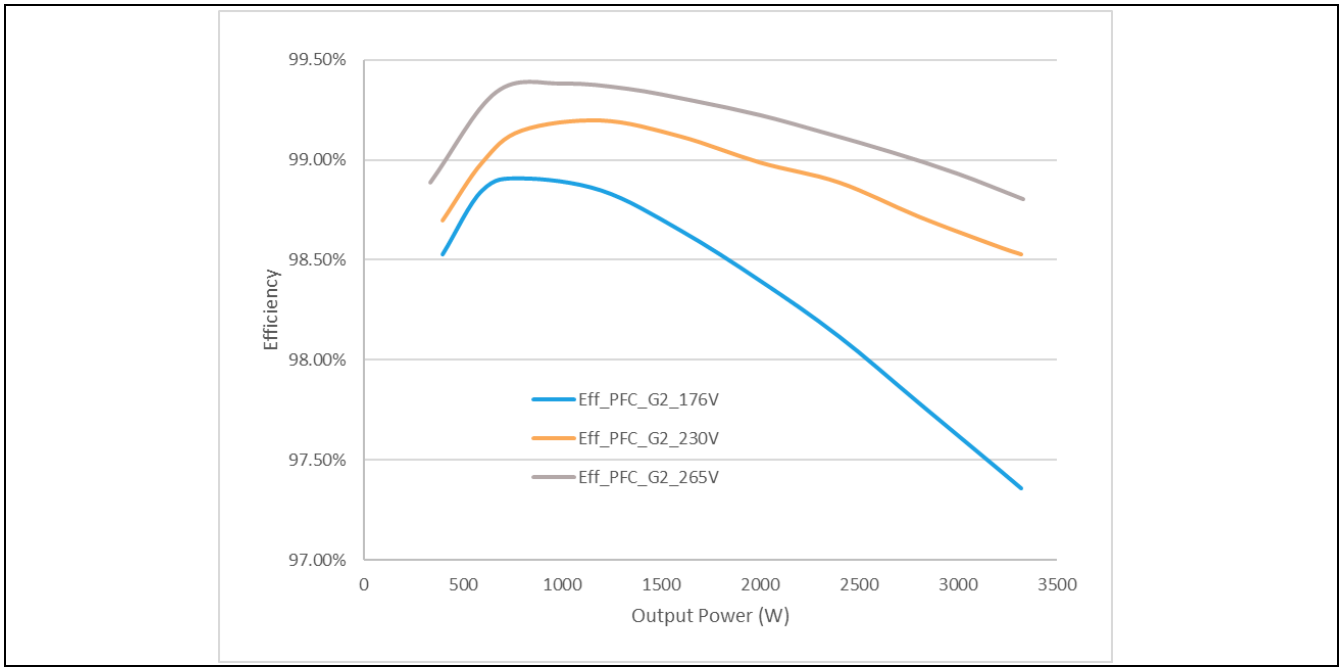

Figure 9 Measured efficiency (with applied line filter in the power analyzer) at different RMS voltages (50/60 Hz) for PFC operation

Figure 10 shows the total harmonic distortion (THD) and power factor measured for different AC voltages at 50 Hz and 60 Hz for PFC operation. As shown, the results for THD and power factor have small differences; within the measurement accuracy of the equipment used.

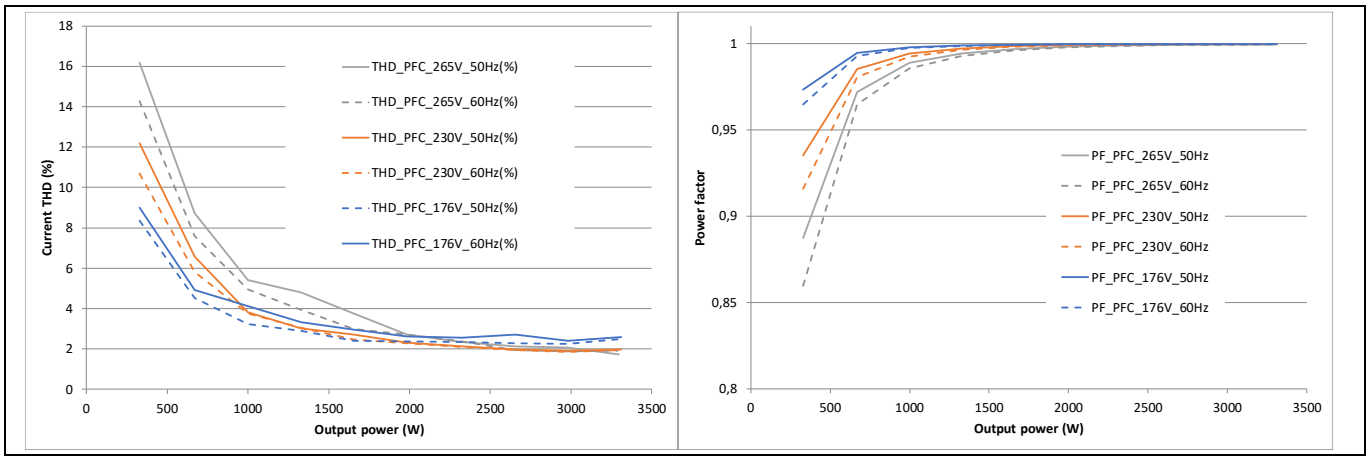

Figure 10 Measured THD and power factor at different RMS voltages for 50 Hz and 60 Hz in PFC operation

Figure 11 and Figure 12 show the PFC operations for different AC voltages in amplitude, frequency, and power levels.

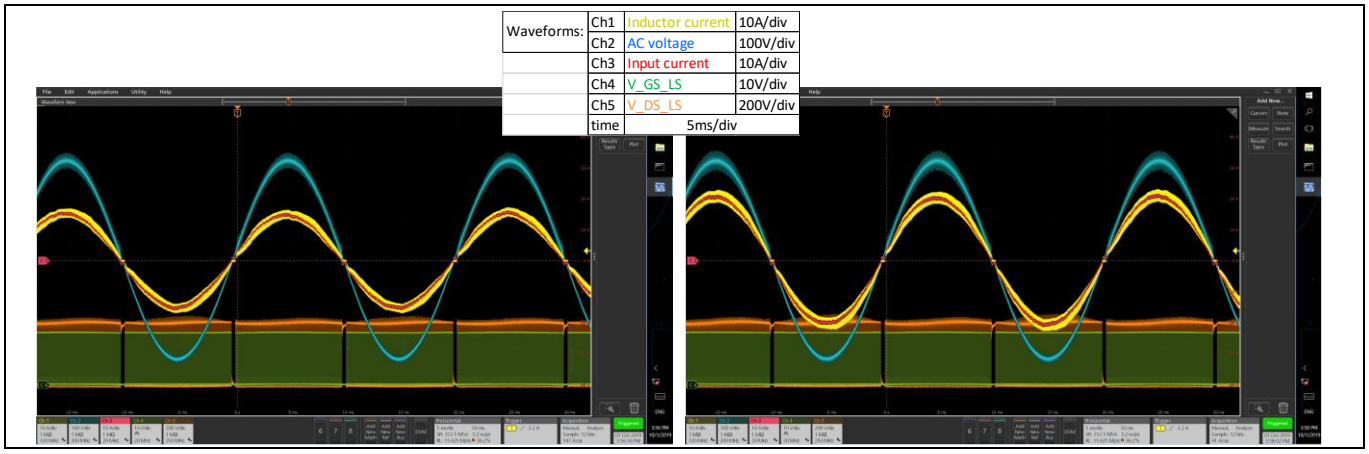

Figure 11 **Steady-state waveforms at 230 V, 50 Hz AC voltage, 50 percent load (left) and 100 percent load (right)**

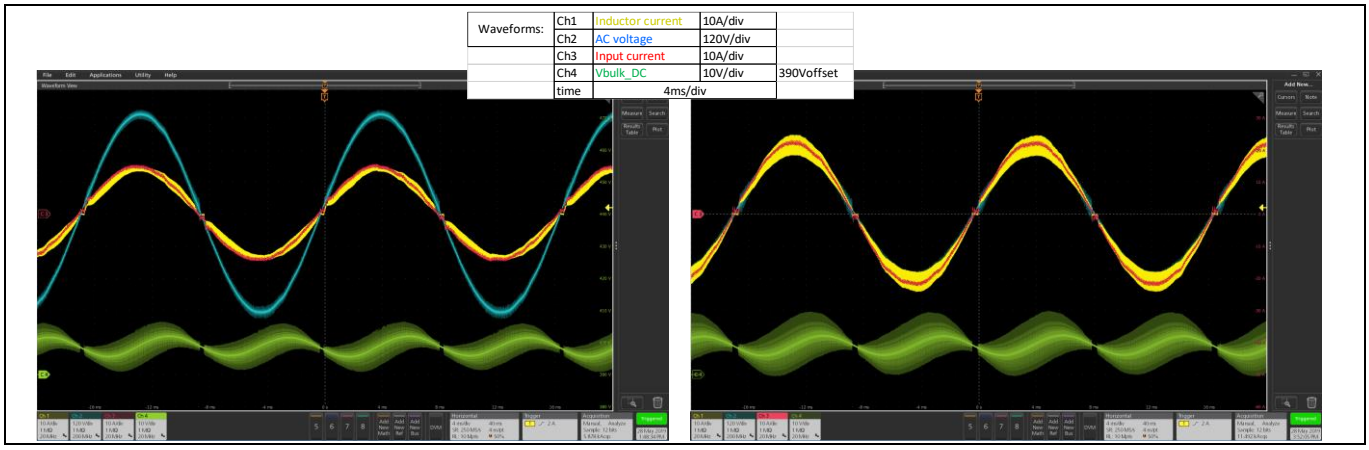

Figure 12 **Steady-state waveforms at 265 V (left) and 176 V (right) for 60 Hz AC voltage and 80 percent load (2.7 kW)**

2.2 Power line disturbance

Two main line disturbance conditions can occur when connected to the grid. On one side, the AC can be lost during a certain time (line cycle drop-out (LCDO)); on the other side, the AC voltage can suddenly decrease to an abnormal value (voltage sag). This section shows the test conditions for both disturbances and the performance of the board when the conditions are applied. For these PFC operation tests, a programmable AC source and a high-voltage electronic load have been used.

2.2.1 Line cycle drop-out

The 3300 W totem-pole CCM PFC operates exclusively in high-line. Therefore, the ACLCDO capability is tested from 230 to 0 V. Different timing, related to the specified hold-up time and the line frequency, is applied as shown in Table 2. The test results (Figure 13 and Figure 14) show that the output voltage is within the specified dynamic variation regardless of the start angle of the voltage drop-out. In case the drop-out is longer than specified, the output voltage under-voltage (300 V) can be triggered, causing a turn-off and restart of the unit.

Table 2 Applied voltage cycles for LCDO test at different loads with 50 Hz AC input voltage

		1st to 10th time (100 ms period)	
Applied voltage	230 V AC	0 V AC	230 V AC
Timing at different load conditions	50 percent load	20 percent (20 ms)	80 percent (80 ms)
	100 percent load	10 percent (10 ms)	90 percent (90 ms)

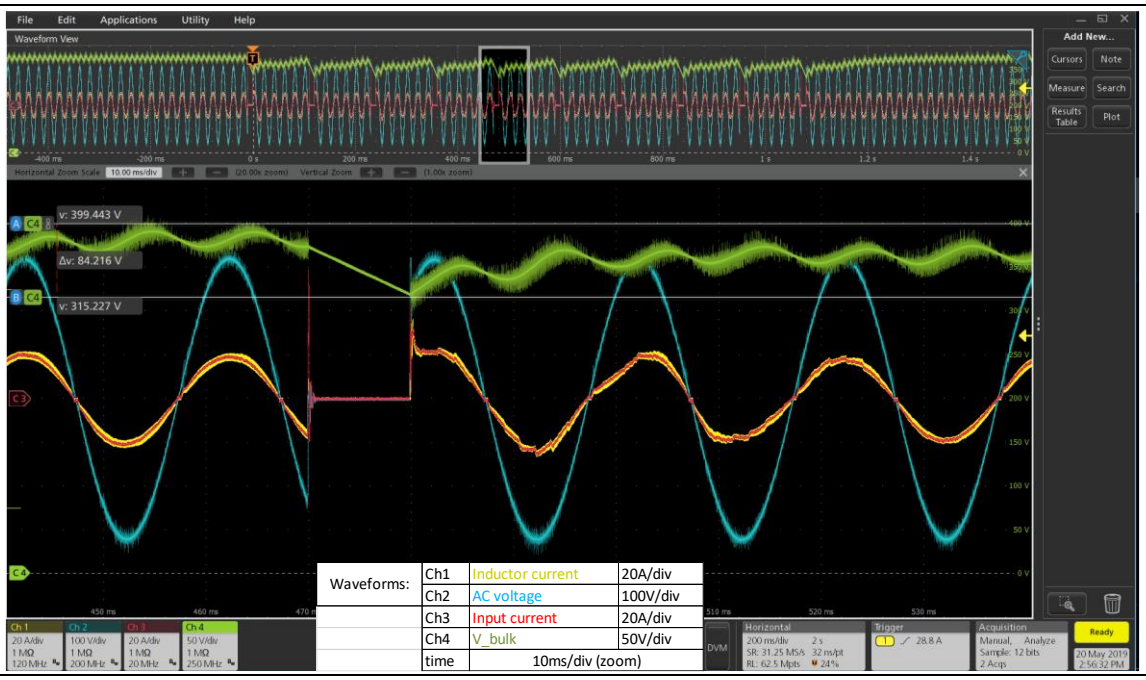

Figure 13 Details of the fifth repetition in a 10 ms LCDO test at 230 V AC, 50 Hz and 100 percent load with starting angle of 45 degree

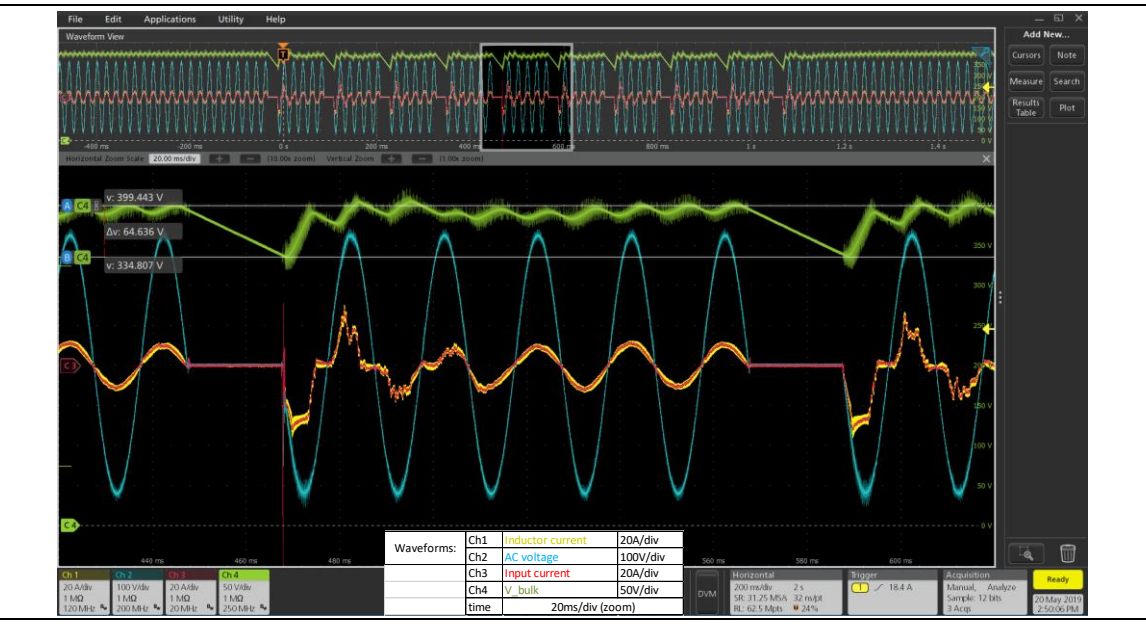

Figure 14 Details of the fifth and sixth repetition in a 20 ms LCDO test at 230 V AC, 50 Hz and 50 percent load with a starting angle of 0 degree

2.2.2 Voltage sag

For high-line, two different voltage sag conditions are considered and tested, shown in Table 3.

Table 3 Voltage sag conditions for high-line applied to the EVAL_3K3W_TP_PFC_SIC2 board

		1st to 10th time	
	Steady AC input	**Voltage sag (time)**	**Period**
AC input	200 V AC	130 V AC (0.5 s)	5 s
	200 V AC	150 V AC (2 s)	20 s

Figure 15 shows the totem-pole PFC behavior with 130 V voltage sag during 500 ms. As shown with the V_{DS} waveform, the output voltage cannot be regulated to 400 V in this condition since the inductor average current is limited to 28 A. Not only is the average current limitation applied in the evaluation board for both power flow modes but also the peak current limitation, which is set to 40 A (Figure 16).

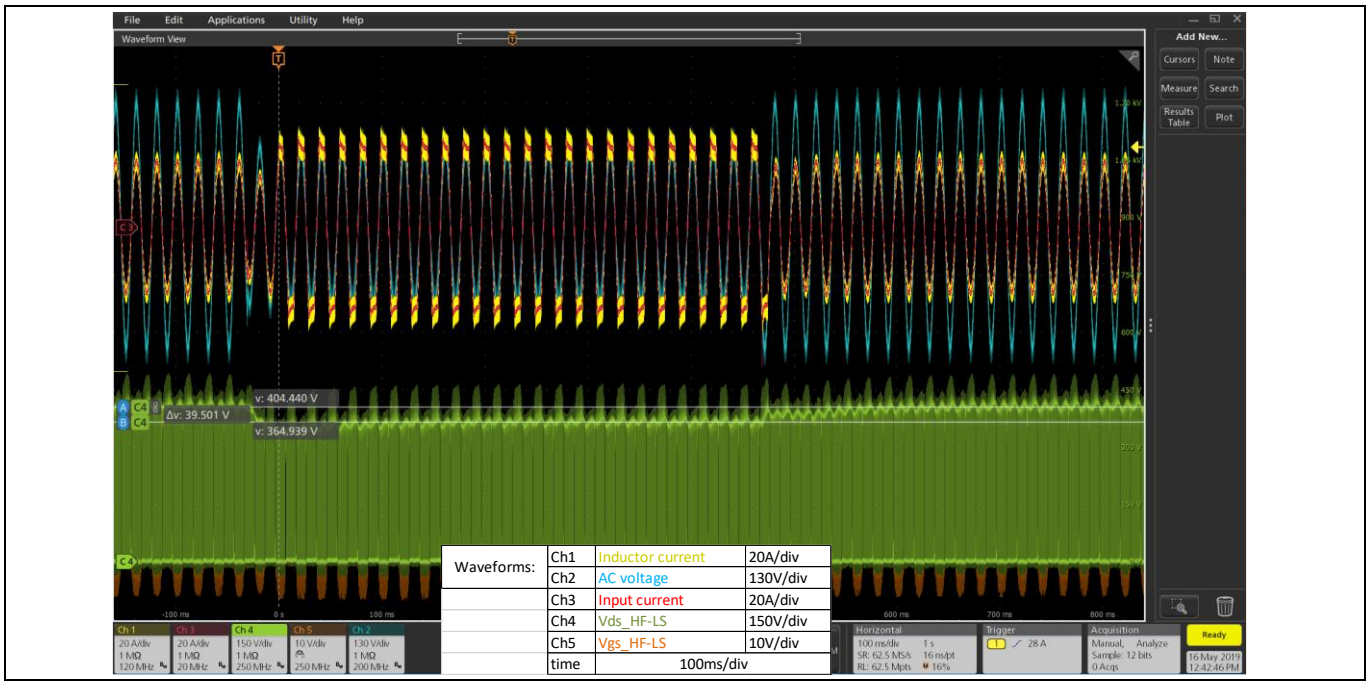

Figure 15 Main waveforms during a 500 ms and 130 V_{rms} voltage sag at full load

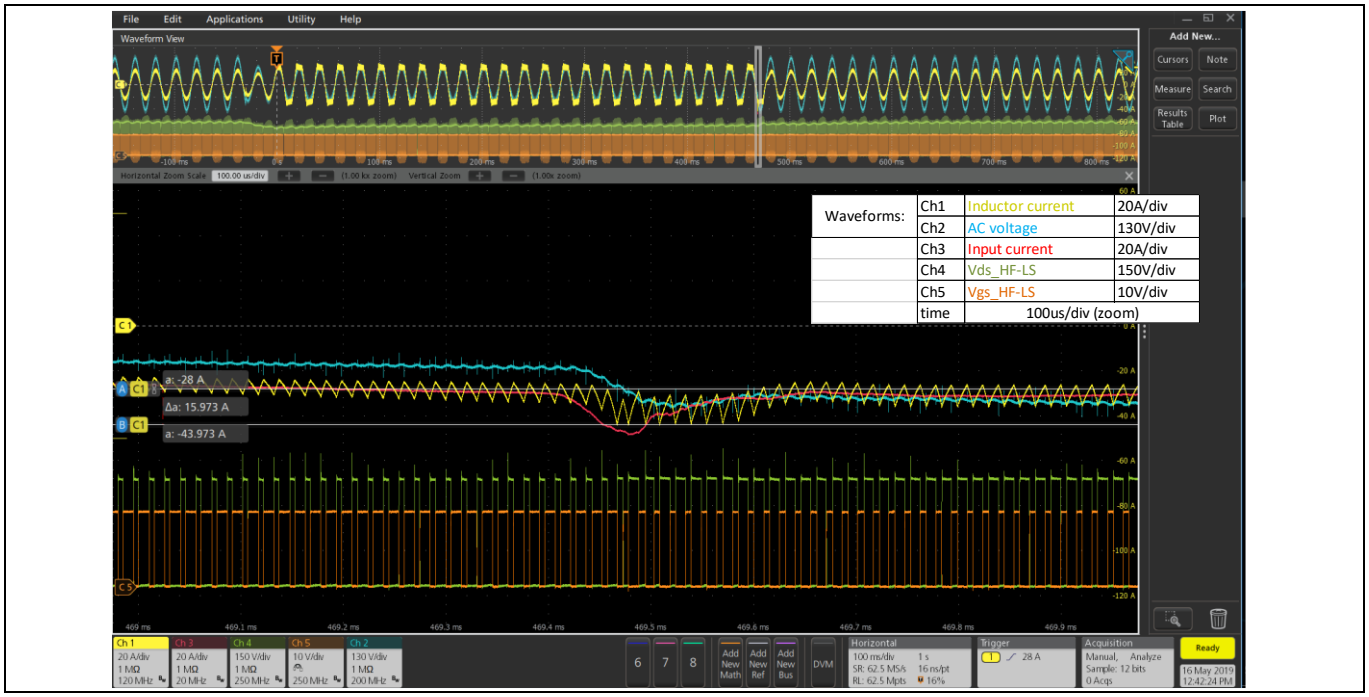

Figure 16 Peak current limitation when returning to the nominal voltage after 130 V voltage sag in PFC mode

However, if the voltage is under the nominal range for longer than specified in the table, the PFC turns off and restarts with a soft-start after an idle time. Figure 17 shows this behavior when a voltage sag of 130 V is applied for longer than 500 ms (750 ms) at full load.

Note: The electronic load used during the test is configured to demand current only when the applied voltage is over 300 V, which is the under-voltage setting of the bridgeless PFC.

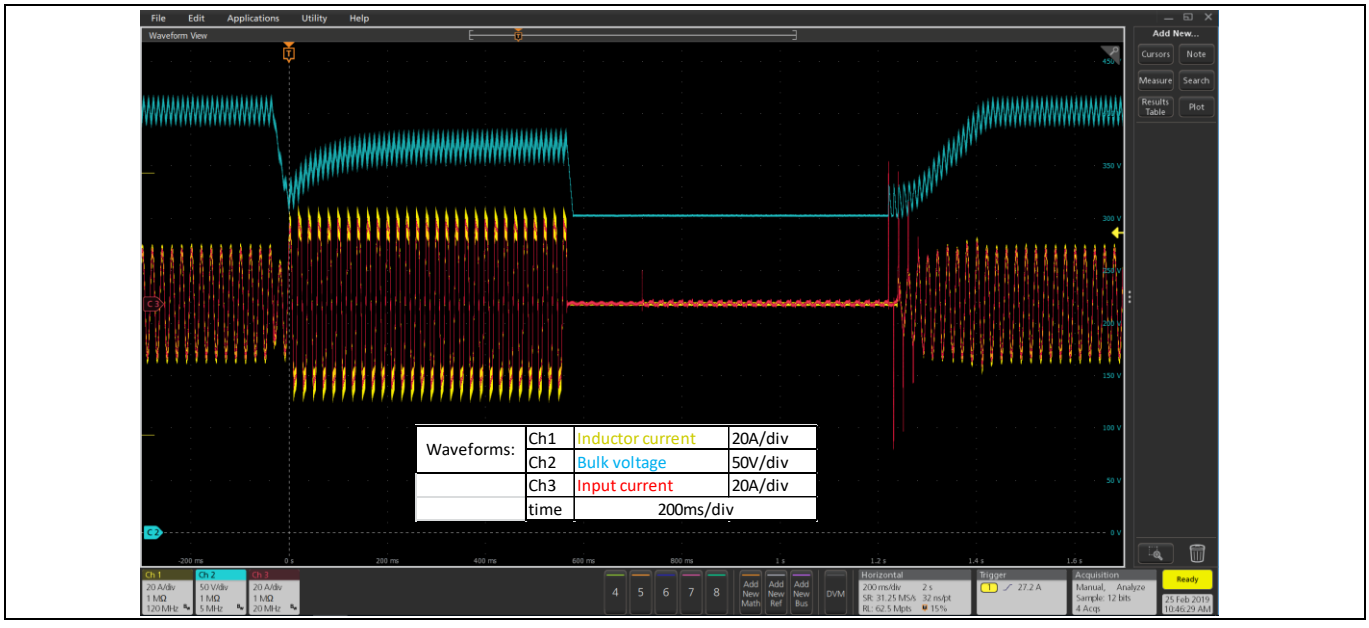

Figure 17 PFC resumes operation after 130 V_{rms} voltage sag applied for 750 ms at full load

A similar behavior is seen when 150 V is applied for 2 seconds (Figure 18). The average inductor current, i.e. input current, is limited to 28 A (Figure 18). In this case, the demanded current is lower, causing the average current limitation to occur for a shorter time. Therefore, the bulk voltage decreases less than that of 130 V.

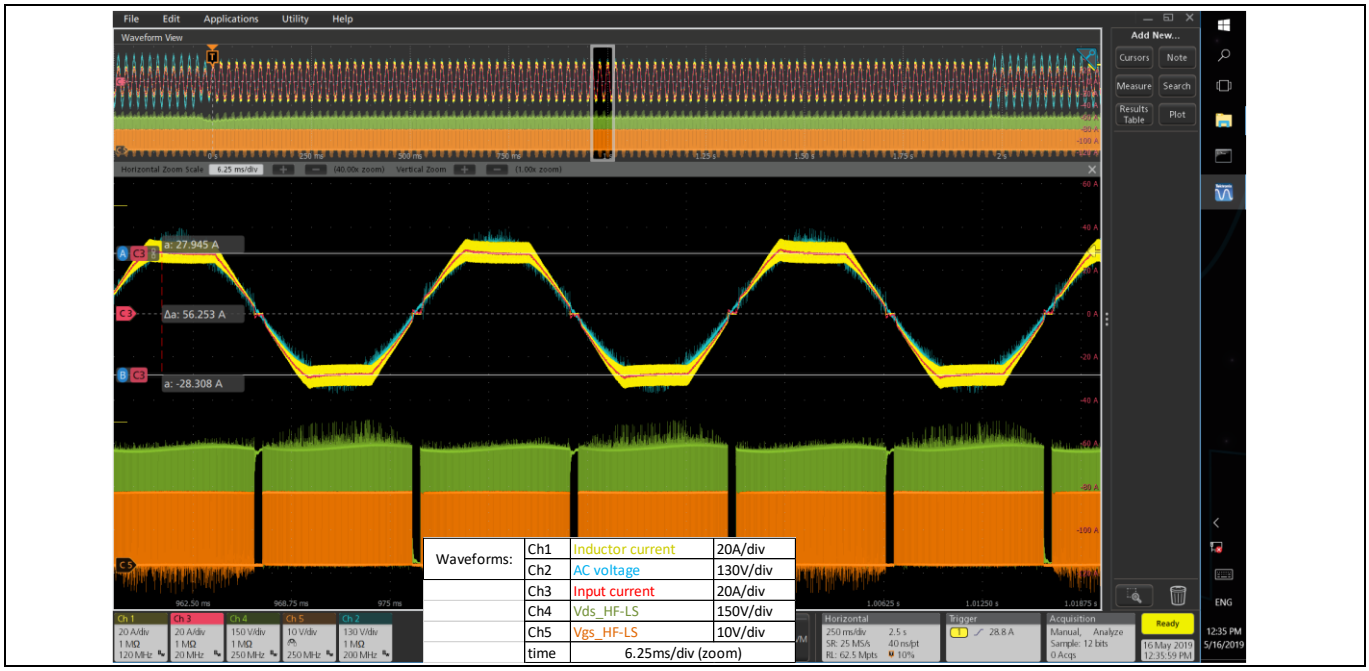

Figure 18 Detail of the voltage sag operation at 150 V for 2 s

2.3 Output voltage dynamic behavior

In addition to the power line disturbance, two other dynamic perturbances can affect the performance of the power supply shown: load and input voltage variation.

2.3.1 Load-transient response in PFC mode

As specified in Table 1, 10 percent load (0.8 A) to 90 percent load (7.4 A) steps (and vice versa) with 0.2 A/µs slope are considered in PFC mode. Figure 19 and Figure 20 show the EVAL_3K3W_TP_PFC_SIC2 board behavior under these load steps. The implemented voltage loop has a 35 Hz crossover frequency. In this SW version of the totem-pole control, neither extra gain nor non-linear current variation have been implemented.

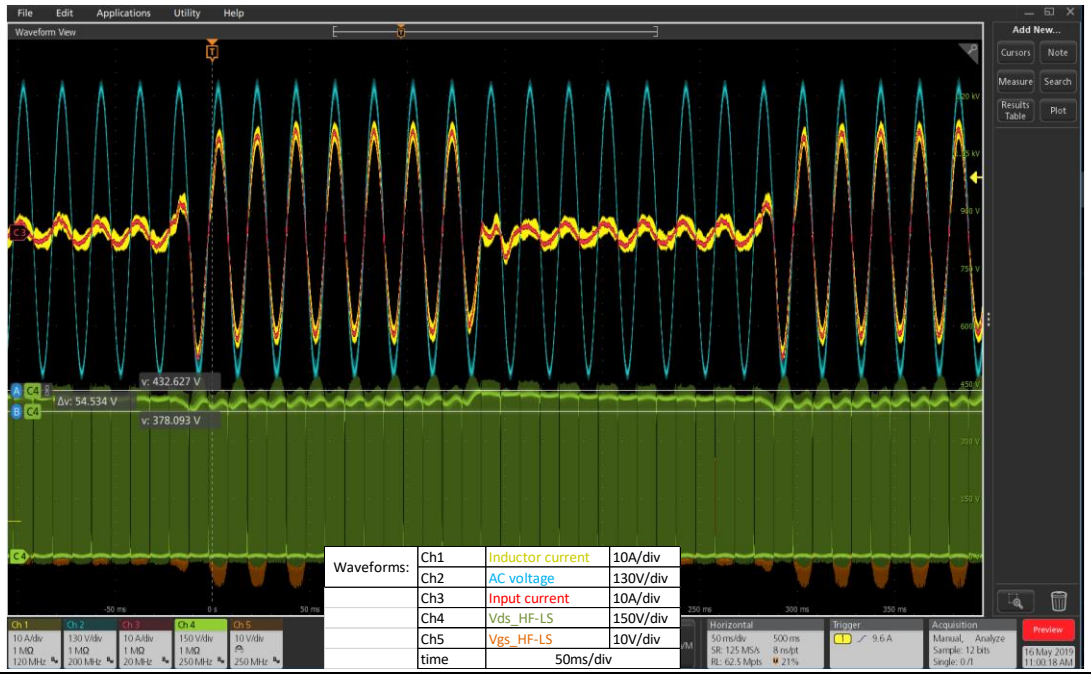

Figure 19 3.3 kW SiC totem-pole CCM PFC response for 10 percent to 90 percent load steps every 150 ms with 0.2 A/µs current slope

The output voltage dynamic range for the specified load variation is within 375 V and 430 V. When the load is removed (Figure 20), the overshoot reaches 440 V, which is under the over-voltage setting (450 V) and the converter manages to reduce the voltage without PWM interruption. The converter also regulates the output voltage under no-load conditions by making the average inductor current close to zero. This is possible since negative inductor current is allowed in a totem-pole configuration with complementary PWM signals, i.e. if the MOSFET in diode function is not turned off when the inductor current gets close to zero to emulate the diode behavior.

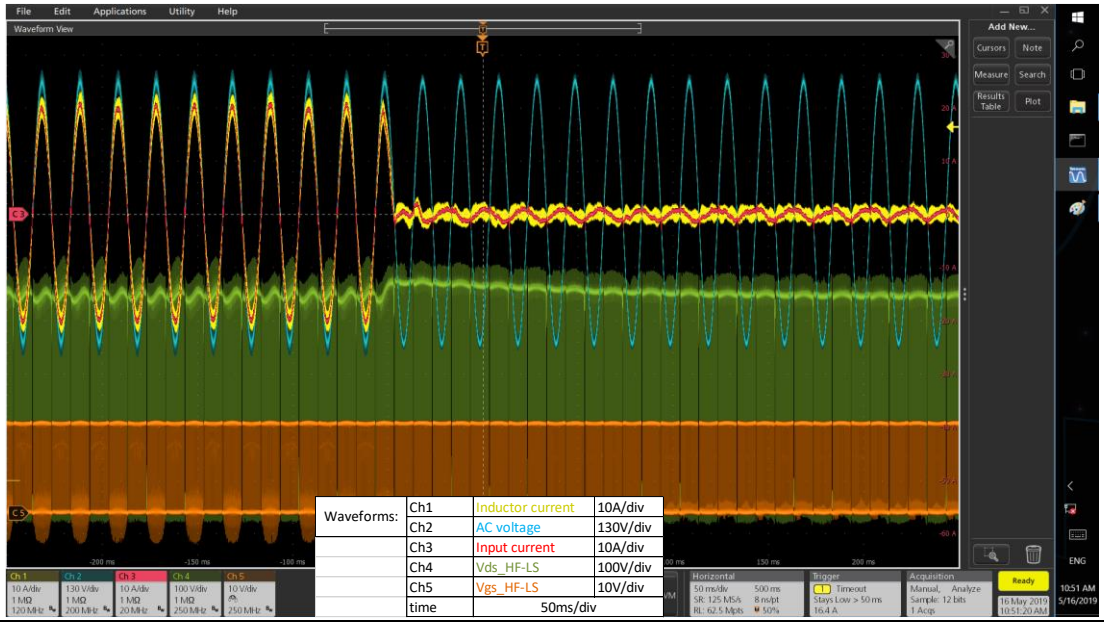

Figure 20 3.3 kW SiC totem-pole CCM PFC response at full load to no-load step with 0.2 A/µs current slope

2.3.2 AC voltage variation in PFC mode

Input voltage variations, as shown in Section 2.2, can modify the bulk voltage. This can also occur when the input voltage varies even within the normal operation range, as shown in Figure 21. In this condition, the bulk voltage lies in the range of 330 to 430 V, as shown in the test result.

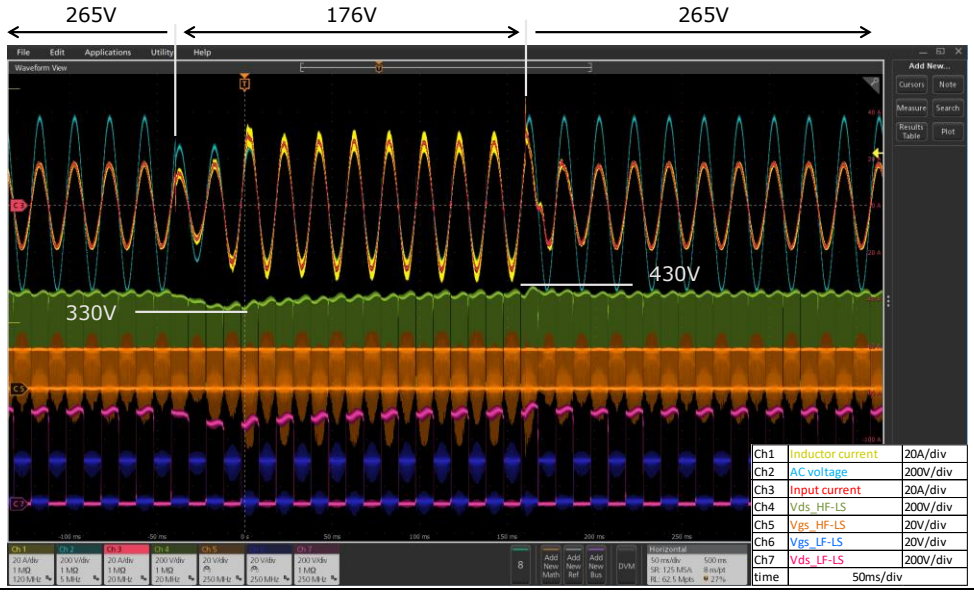

Figure 21 Maximum (265 V_{rms}) to minimum (176 V_{rms}) line voltage variation at full-load operation

As discussed in Section 2.2.2, a sudden increase in the input voltage leads to an immediate increase in the inductor current until the voltage loop and the line feed-forward reduce the current demand. Figure 22 shows this effect when the AC voltage changes from 176 to 265 V. The sudden change of the inductor current leads to peak current limitation, which is set to 40 A for both positive and negative AC.

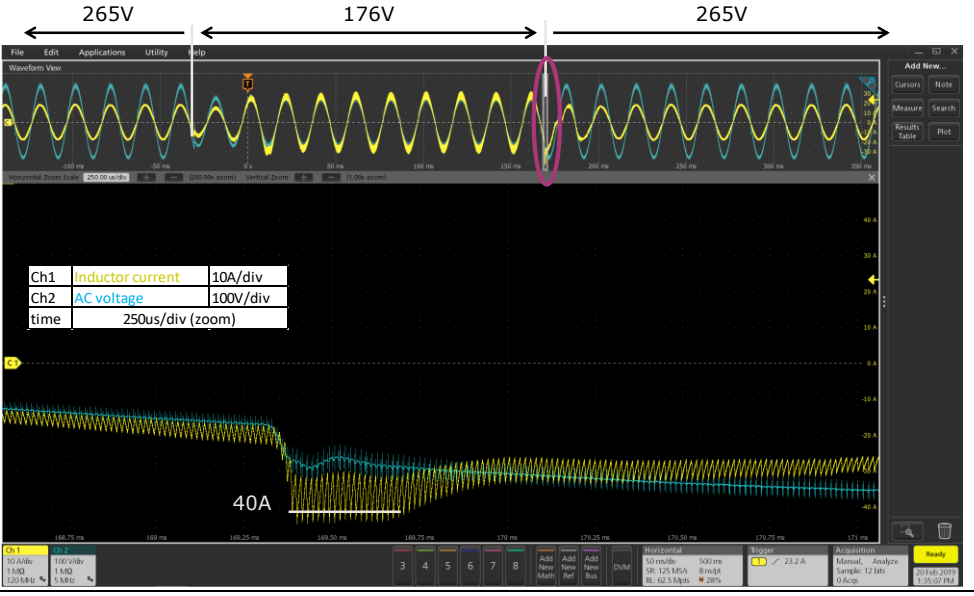

Figure 22 Detail of the inductor peak current cycle-by-cycle limitation when the input voltage changes from 176 to 265 V

2.4 In-rush current and PFC start-up

Figure 23 shows the start-up of the bridgeless totem pole in PFC mode for full-load operation. The test has been performed with a programmable AC source and high-voltage electronic load. The load is configured with a 350 V threshold to start the sinking current. This threshold emulates the DC-DC converter behavior, which would be the load for the PFC (Figure 24).

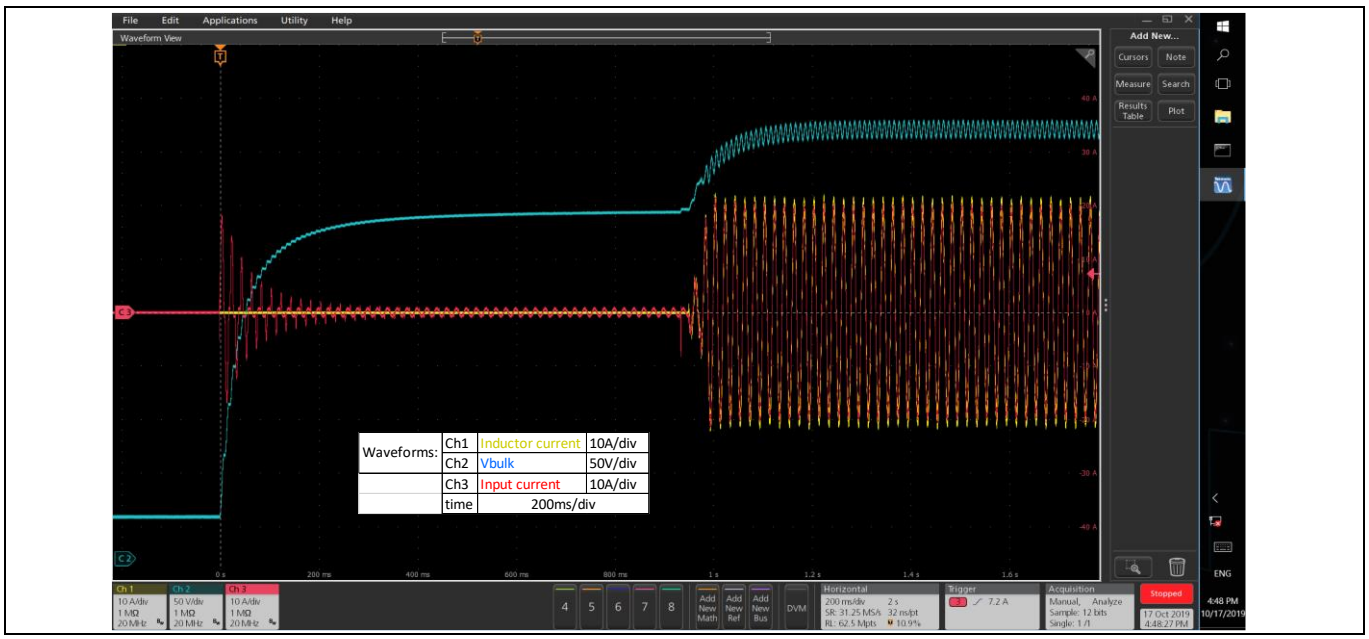

Figure 23 EVAL_3K3W_TP_PFC_SIC2 start-up at full load for 230 V, 50 Hz input voltage

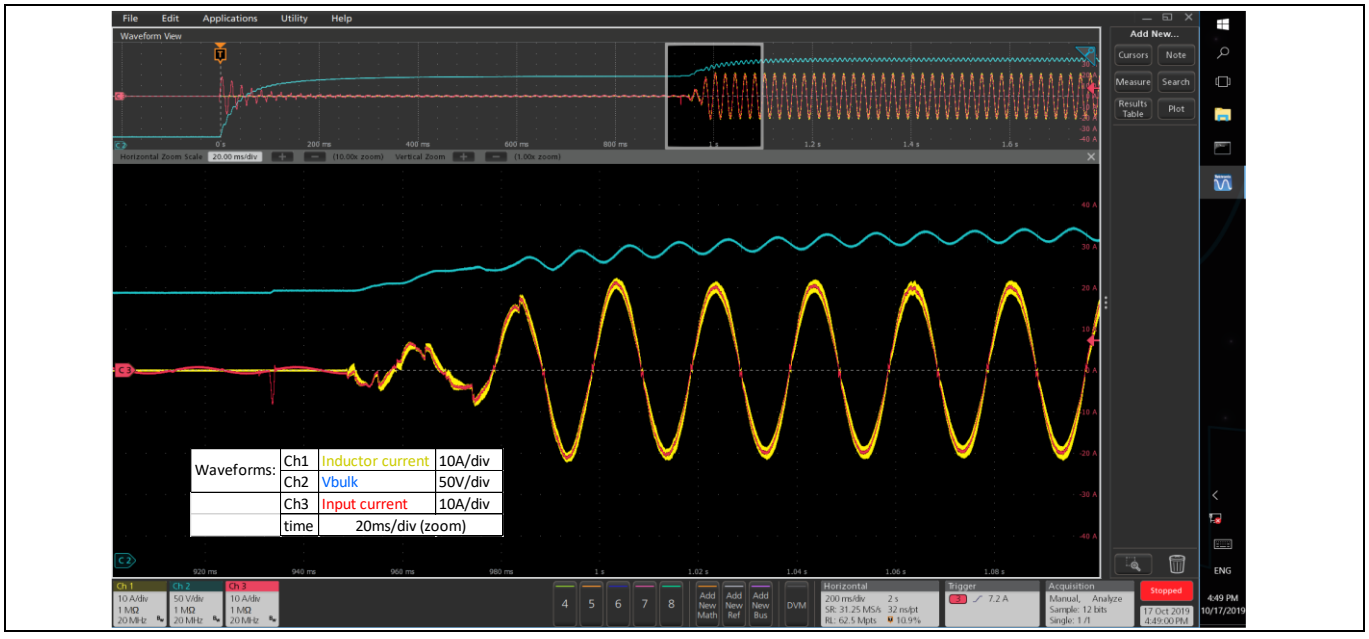

Figure 24 Details of the bulk voltage soft-start from AC peak voltage to steady-state voltage after the relay is closed (230 V/50 Hz)

The in-rush current when connecting to the AC source is limited with an NTC. This resistor is short-circuited by a parallel relay before start-up if the input and output voltage conditions to start the bridgeless PFC are met. The in-rush current is measured at the first AC cycle and it is independent of the output load. Figure 25 shows the in-rush current at full-load start-up. According to the measurement, the in-rush current is significantly under the specified 30 A in Table 1.

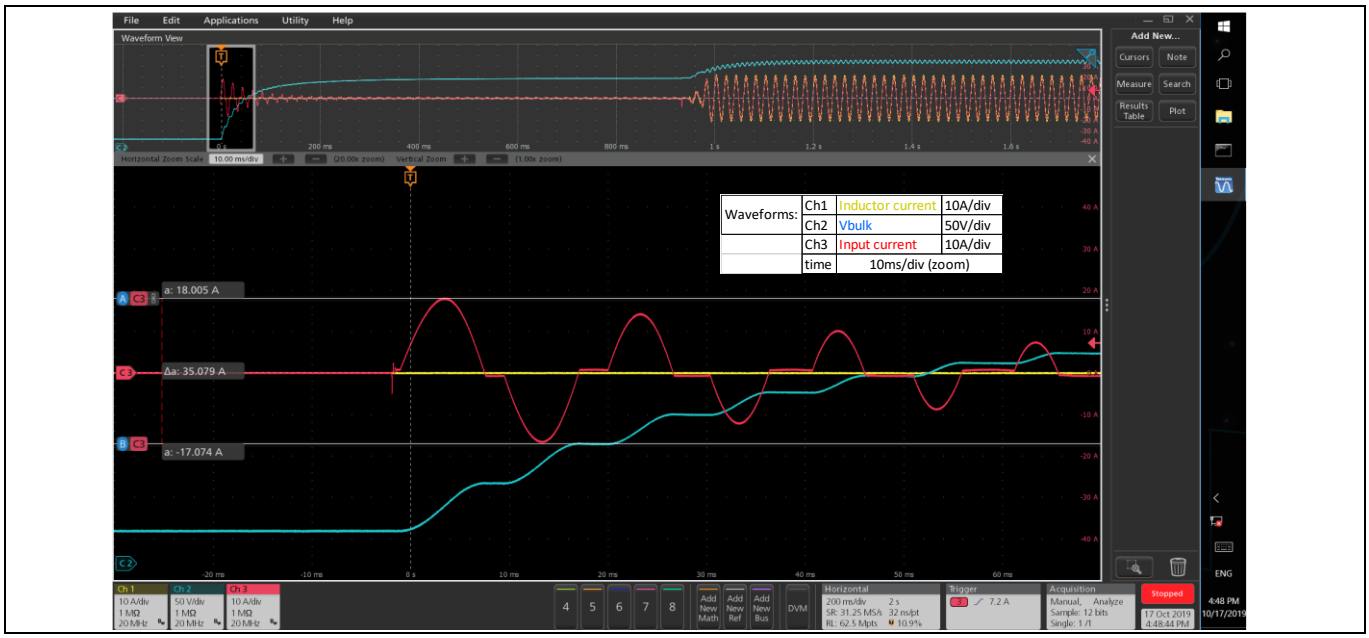

Figure 25 In-rush current of EVAL_3K3W_TP_PFC_SIC2 at full-load start-up

3 Inverter (DC-AC operation) specification and test results

The bridgeless totem-pole topology offers inherent bi-directional power flow capability, which can be explored in EVAL_3K3W_TP_PFC_SIC2. The inverter operation mode can be selected before the application starts by choosing the “INV” option in the available switch (SW1) on the main board.

Note: The power flow or operation mode is selected before the application starts and the power flow cannot be reverted during operation in this version of the SW. Therefore, EVAL_3K3W_TP_PFC_SIC2 can operate as either a PFC or an inverter but the SW is not ready for a dynamic change of the operation mode.

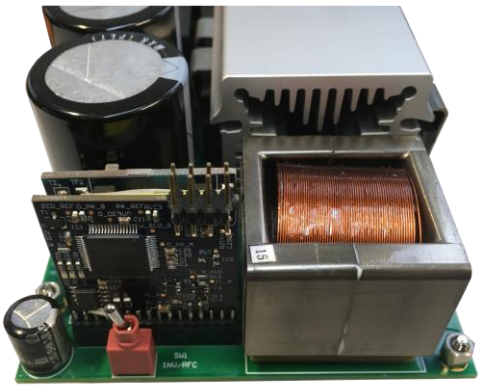

Figure 26 Switch to select the operation mode (PFC or inverter) in EVAL_3K3W_TP_PFC_SIC2

The inverter operates at 65 kHz switching frequency for high-line AC input (176 V minimum RMS voltage), as in the rectifier operation. The specifications in inverter operation regarding efficiency, THD, PF, and AC voltage ranges, and OCP are the same as those shown in Table 1. The specifications that are different for the inverter operation are shown in Table 4.

Table 4 Summary of specifications and test conditions for the 3300 W bi-directional totem-pole board in inverter mode

Test		Conditions	Specification
Rated DC voltage			400 V
AC voltage		Relay off after 100 ms	174 V on; 168 V off
DC voltage			Low range: 390 V on, 350 V off/latching
			High range: 410 V on, 450 V off/latching
Load transient			Soft change between received power commands
Power line disturbance	AC lost	230 Vrms, 50 Hz, 2 ms, load independent	Inverter resumes operation with soft-start after AC returns to range
	Voltage sag	100 ms under 170 V, load independent	Inverter off and restarts after a defined time with soft-start when AC returns to range

The EVAL_3K3W_TP_PFC_SIC2 board can be tested in inverter mode using the board EVAL_3K3W_BIDI_PSFB [6] as the voltage supplier for the inverter. This board is a bi-directional ZVS phase-shift full-bridge converter that can be used together with the presented bi-directional bridgeless PFC to build a full system solution using Infineon components. This set-up enables the usage of the high–frequency isolation transformer present in the DC-DC stage to properly interface a voltage source to a grid emulator equipment – and it can be used to test the bi-directional capability of the bi-directional totem-pole.

Note: *Since the DC-DC board has been designed as standalone, changes in the control loop are implemented to operate with the SiC bridgeless totem pole as a load.*

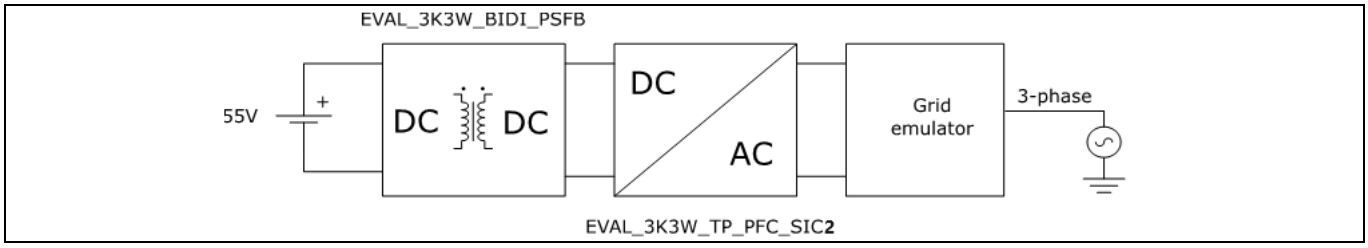

Figure 27 **EVAL_3K3W_BIDI_PSFB and EVAL_3K3W_TP_PFC_SIC2 set-up for the inverter test connected to a grid emulator**

3.1 Steady-state waveforms

The totem-pole bi-directional converter operating in inverter mode with Infineon CoolSiC™ G2 can be tested in steady-state up to 3 kW output power. The power limitation is necessary because of the thermal limitation of EVAL-3K3W_BIDI_PSFB operating in boost mode [6].

The inductor current of the bridgeless totem-pole topology in the inverter operation is 180 degree out of phase compared to the PFC operation. Therefore, current is actually injected into the AC grid. This main difference is shown in Figure 28, which shows the main waveforms of EVAL_3K3W_TP_PFC_SIC2 in rectifier and inverter operations for the same power level at 50 percent load.

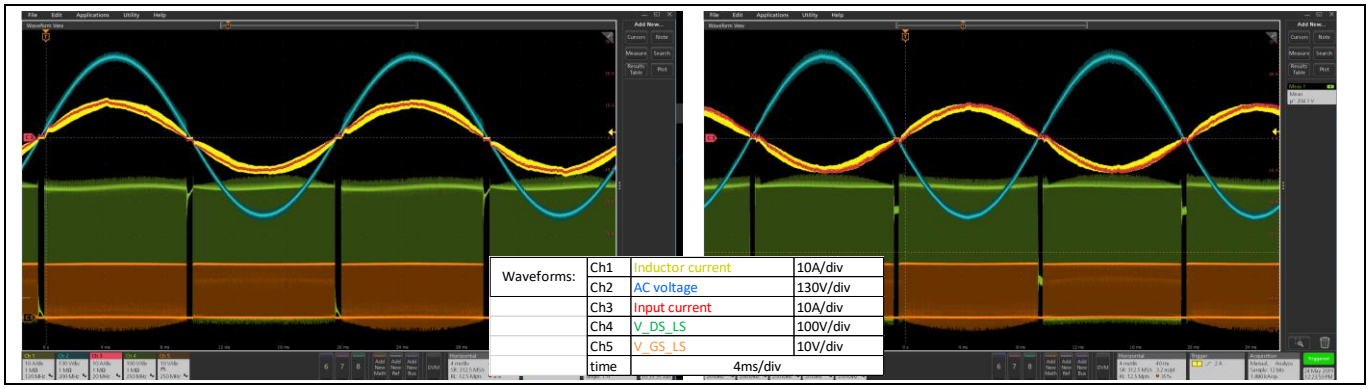

Figure 28 **Steady-state waveforms at 230 V 50 Hz for 50 percent load (1.65 kW) in PFC (left) and inverter (right) modes**

3.2 Inverter mode load change

In the inverter mode, the EVAL_3K3W_TP_PFC_SIC2 board behaves as a current source connected between two voltage sources: the bulk voltage and the AC grid. In this case, the power to inject into the grid is set by the DC-

DC stage, which also regulates the bulk voltage (input voltage for the inverter). Therefore, the DC-DC stage would send a power command to the DC-AC converter, which in the presented tests has been substituted by a power command sent from the computer using a GUI (Section 1.3).

When a new power command is received, the power is modified following a ramp as shown in Figure 29, where a power change from 300 W to 2500 W is received. A similar behavior would be observed in case of a power command reduction.

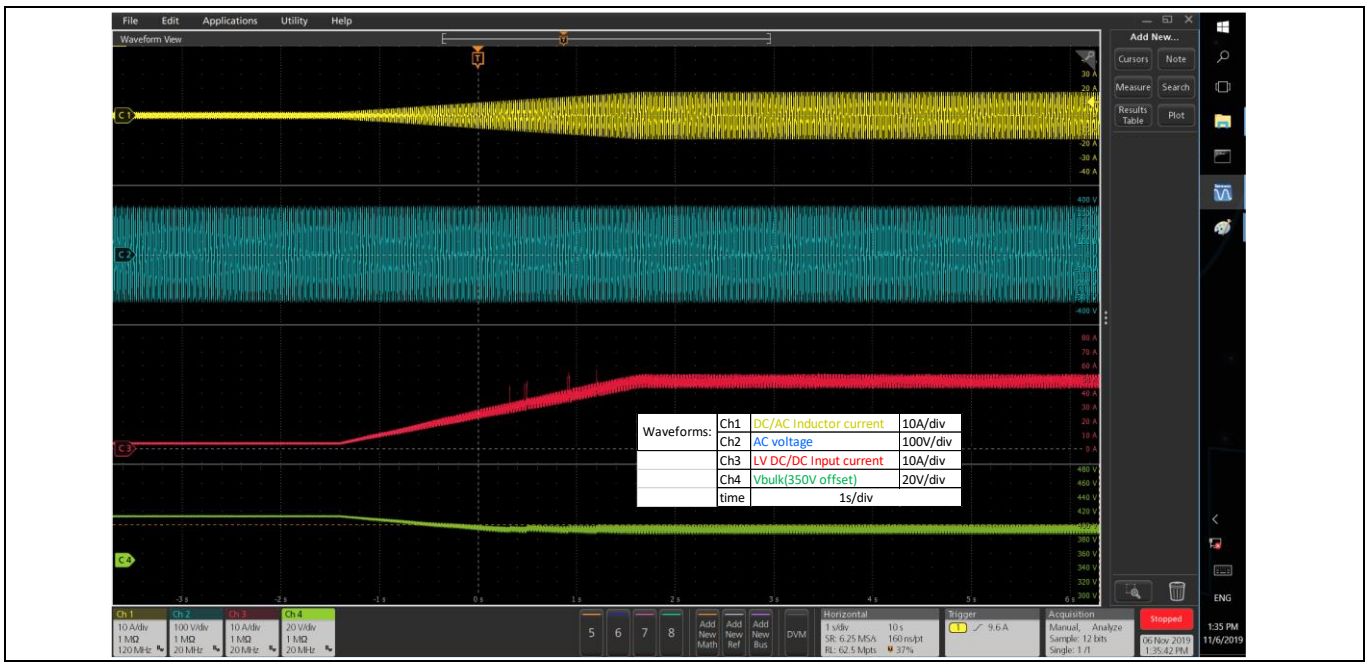

Figure 29 Load increase (300 W to 2.5 kW) in inverter mode; 230 V, 50 Hz AC voltage

3.3 Power line disturbance and AC voltage variation

3.3.1 Inverter mode LCDO

For the inverter operation, the hold-up time does not apply since the DC-DC stage is controlling the bulk voltage, i.e. the supply voltage to the DC-AC stage. Therefore, when an AC voltage loss is detected (AC close to zero for more than 2 ms) the inverter prepares for a soft-start operation when the voltage returns. This behavior, independent of the injected power, is shown in Figure 30 for a 20 ms line drop-out to 0 V, or in Figure 31 when the AC reaches 0 V for 50 ms.

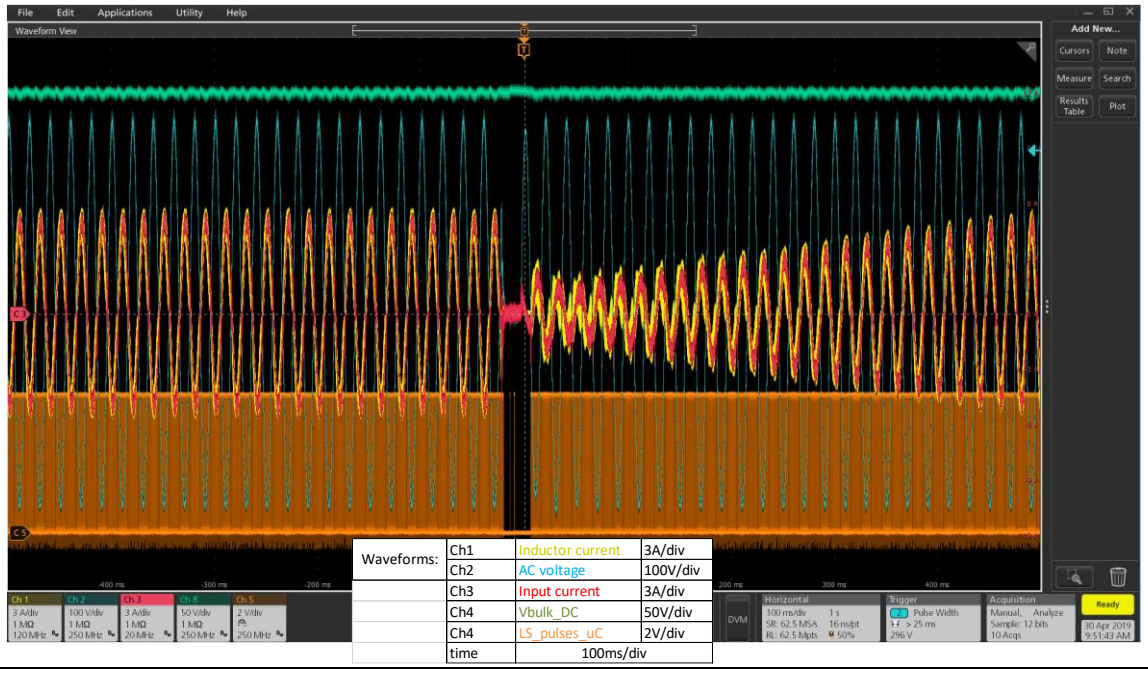

Figure 30 Inverter behavior under AC-line drop-out of 20 ms for 800 W power

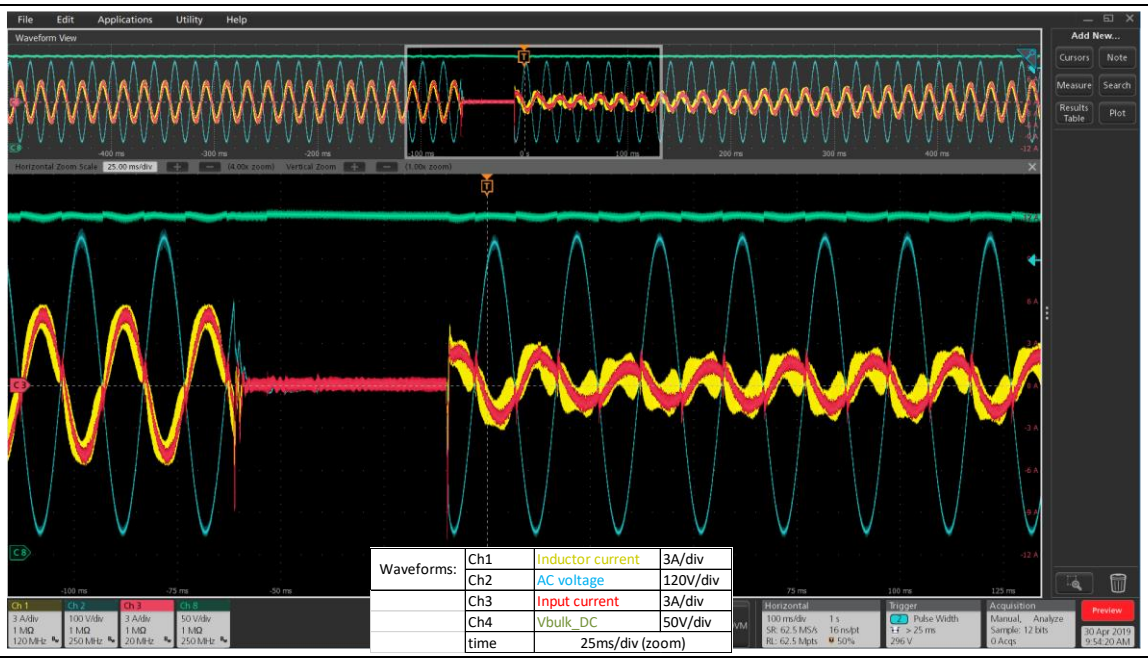

Figure 31 Details of the inverter behavior under an AC-line drop-out of 50 ms for 800 W power

3.3.2 Voltage sag and AC voltage variation

The behavior shown previously occurs when the AC voltage drops to zero. In case the AC voltage is under the AC voltage limit specified in Table 4, the inverter stops the operation and opens the NTC relay. After a defined time, the inverter resumes operation with a soft-start after closing the relay, given that the AC voltage has returned to

the nominal range. Figure 32 shows a voltage sag from 230 V to 115 V for 200 ms with 2.5 kW injected into the grid emulator, where the sequence shown can be recognized.

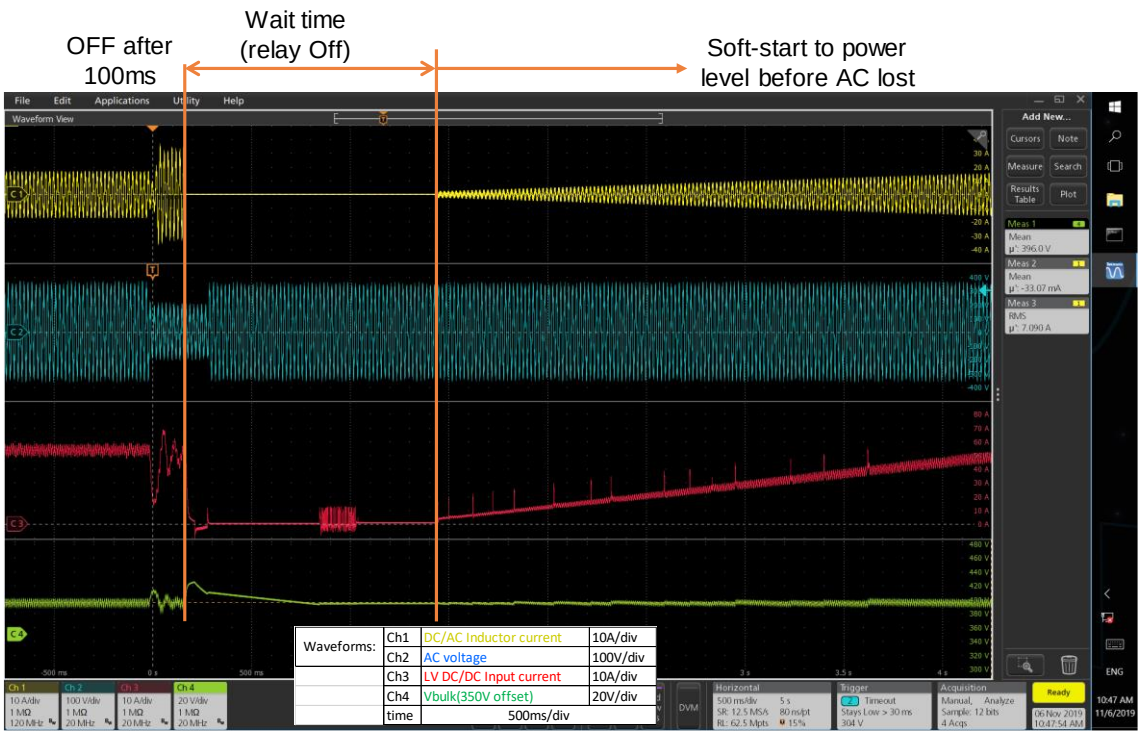

Figure 32 115 V/200 ms voltage sag from 230 V at 2.5 kW inverter operation

In case the AC voltage is out of range for a time shorter than 100 ms, the inverter momentarily demands a higher current when the AC voltage returns to the range. This increase in the current, together with the slow voltage loop of the DC-DC supplying the bulk voltage, produces an over-current in the DC-DC low-voltage side. This over-current can trigger over-current protection (OCP) in the DC-DC stage. Figure 33 (left) shows a successful voltage sag of 100 ms from 230 V to 115 V with a 380 W output power. However, when the power is increased to 880 W, the increase in the AC current during the transition transfers into an increase in the low-voltage current and DC-DC OCP (68 A) is triggered. After that, the DC-DC converter stops and bulk voltage reaches down to 350 V, and thus the DC-AC totem-pole latches operation.

Figure 33 115 V voltage sag from 230 V applied during 100 ms at 380 W (left) and 880 W (right)

The same behavior can be expected even with variations within the normal AC range. Figure 34 shows two examples of 265 to 176 V steps in the AC voltage for different power levels. When the power increases, OCP in the DC-DC stage can also be triggered, as shown in Figure 33.

Figure 34 265 to 176 V AC voltage variation for 960 W (left) and 1200 W (right) in the inverter operation

4 Thermal measurements

The board shown in this document, EVAL_3K3W_TP_PFC_SIC2, is not provided with an enclosure. The implemented thermal concept uses a low-power fan attached to the main heatsink, in which the power semiconductors dissipate their generated losses. The PFC choke is behind the heatsink and also receives the airflow from the implemented fan.

As shown in Figure 35, especially for AC voltages in the lower part of the range, the hotspot of the board is the PFC choke. As introduced above, the PFC choke is implemented with a high-flux EQ core and helical flat wire. The obtained form factor of this design enables high efficiency and increased power density while keeping the height requirement. The main disadvantage is the heat dissipation since there are only two small contacts to dissipate the winding heat through the PCB and the enclosed core limits the airflow from the implemented fan. Therefore, a more powerful fan in an enclosed environment might be required in the final application.

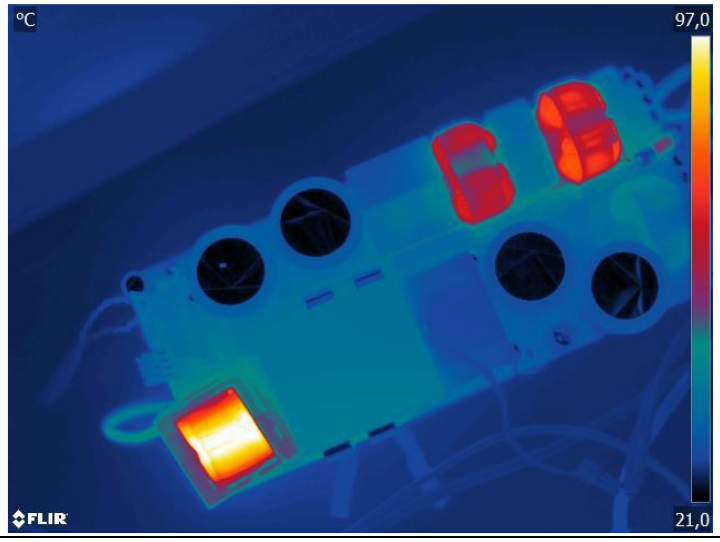

Figure 35 Thermal capture at room temperature of EVAL_3K3W_TP_PFC_SIC2 at nominal input (230 V) and full-load (3.3 kW) conditions for the PFC operation

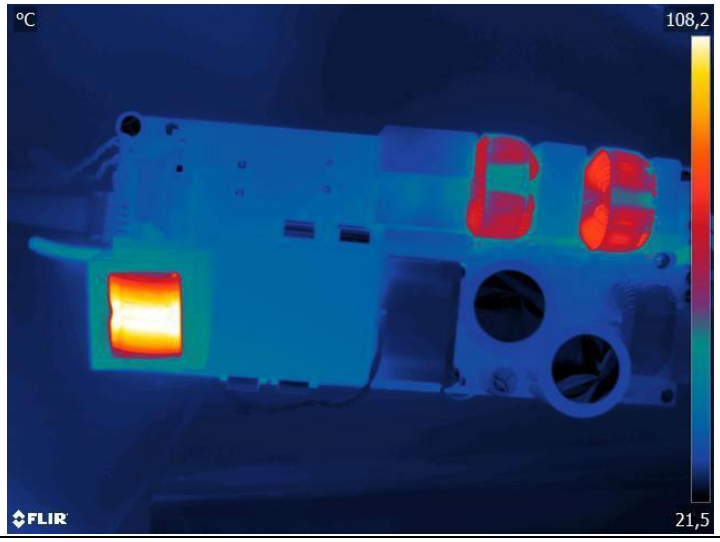

Figure 36 Thermal capture at room temperature of EVAL_3K3W_TP_PFC_SIC2 at minimum AC voltage (176 V) and full-load (3 kW) conditions for the inverter operation

5 Summary

This document introduces an Infineon system solution for bridgeless totem-pole PFC achieving a peak efficiency of 99.2 percent with a 1U form factor and a power density of 73 W/in^3. The totem-pole PFC topology is enabled using Infineon 650 V CoolSiC™ G2 silicon carbide MOSFETs. The combination of the wide bandgap switches and 600 V CoolMOS™ C7 enables high performance in a compact form factor, as shown in this application note. The bridgeless topology implements full digital control with an XMC™ 1000 series Infineon microcontroller.

The EVAL_3K3W_TP_PFC_SIC2 board has been tested using a programmable AC source and electronic load to demonstrate the power line disturbance behavior or dynamic load conditions in PFC operation.

Digital control enables the utilization of the inherent bi-directional power flow capability of the bridgeless totem-pole topology of EVAL_3k3W_TP_PFC_SIC2. The power flow has to be selected before starting the board using an incorporated switch in the main board. The bi-directional solution is not prepared for dynamic change in the power flow.

The performance of the board in PFC operation complies with the power line disturbance and hold-up time. In case of the inverter operation, the dynamic load and power line disturbance behavior has been adapted by introducing soft transitions. The interaction with the DC-DC converter and the influence of AC variations in inverter operation is also discussed in the application note.

6 Schematics

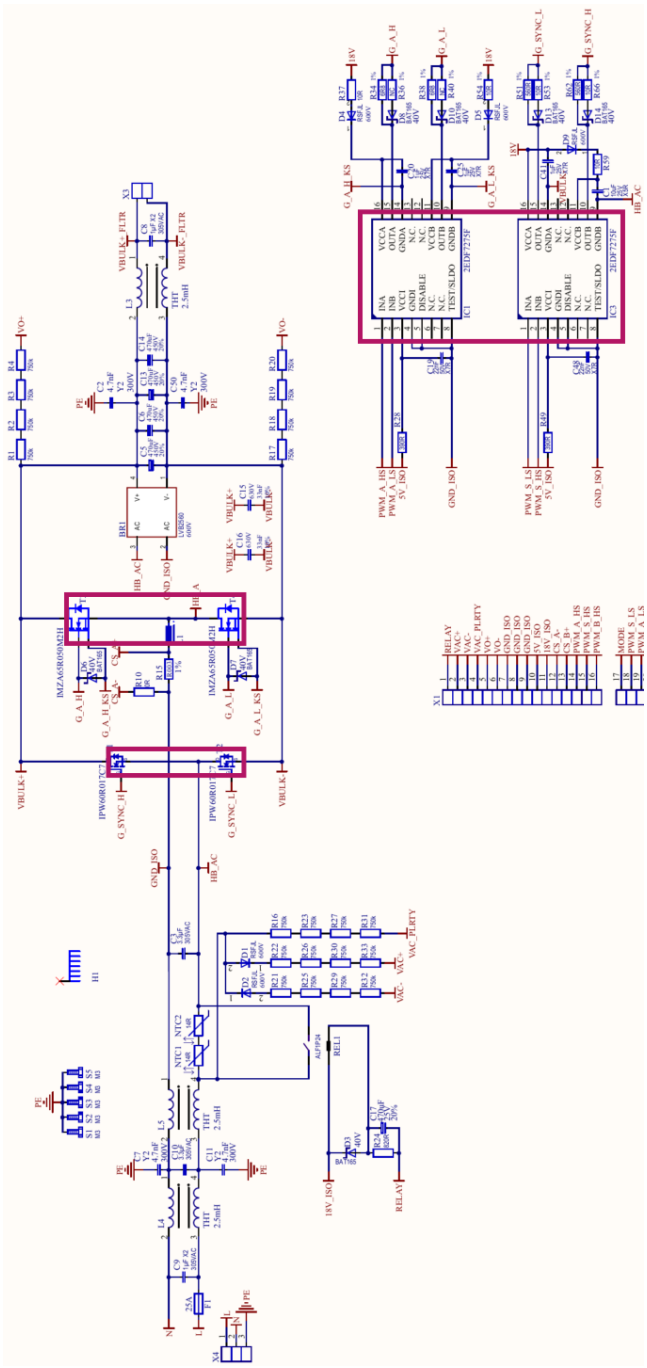

Figure 37 EVAL_3K3W_TP_PFC_SIC2 main board schematic (Infineon devices highlighted)

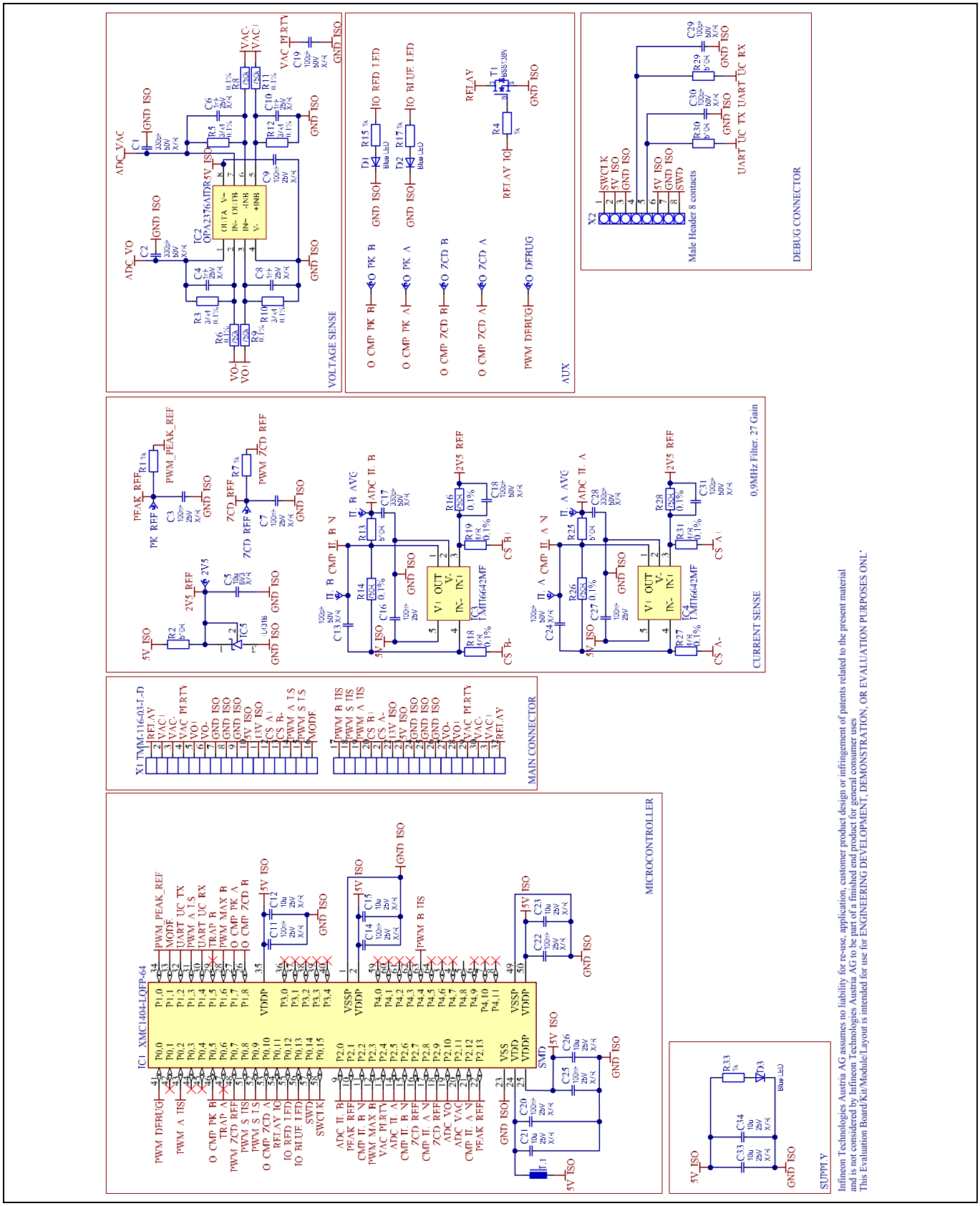

Figure 38 Control card schematic in EVAL_3K3W_TP_PFC_SIC2 with XMC1404

7 Bill of materials (BoM)

Table 5 Main board components in EVAL_3K3W_TP_PFC_SIC2

Designator	Value	Tolerance	Voltage	Description
T1, T2	**IPW60R017C7**		**600 V**	**MOSFET**
T3, T4	**IMZA65R050M2**		**650 V**	**N-channel MOSFET**
IC1, IC3	**2EDF7275F**			**Integrated circuit**
BR1	LVB2560		600 V	Bridge diode
C1	10 µF	X5R	25 V	Ceramic capacitor
C2, C7, C11, C50	4.7 nF	Y2	300 V	Ceramic capacitor
C3, C10	3.3 µF	10 percent	305 V AC	Foil capacitor
C4, C12, C20, C41	1 µF	X7R	25 V	Ceramic capacitor
C5, C6, C13, C14	470 µF	20 percent	450 V	Polarized capacitor
C8, C9	1 µF X2	20 percent	305 V AC	Foil capacitor
C15, C16	33 nF	5 percent	630 V	Foil capacitor
C17	470 µF	20 percent	25 V	Polarized capacitor
C19, C48	22 nF	X7R	50 V	Ceramic capacitor
C25	1 µF	X7R	25 V	Ceramic capacitor
D1, D2, D4, D5, D9	RSFJL		600 V	Diode
D3, D6, D7, D8, D10, D13, D14	BAT165		40 V	Schottky diode
F1	25 A			Fuse
H1	LAM4K05024		24 V	Heatsink
IC2	L78L05ACUTR			Integrated circuit
L1	500 µH			Inductor
L3, L4, L5	2.5 mH			Inductor
NTC1, NTC2	14 R	25 percent		NTC resistor
R1, R2, R3, R4, R16, R17, R18, R19, R20, R21, R22, R23, R25, R26, R27, R29, R30, R31, R32, R33	750 k	1 percent		Resistor
R5, R6	2k7	1 percent		Resistor
R10	0 R	1 percent		Resistor
R15	R003	1 percent		Resistor
R24	820 R	1 percent		Resistor
R28, R49	390 R	1 percent		Resistor
R34, R38	6R8	1 percent		Resistor
R37, R54, R59	10 R	1 percent		Resistor
R50	0 R	1 percent		Resistor
R51, R62	560 R	1 percent		Resistor
R53, R66	10 R	1 percent		Resistor

Designator	Value	Tolerance	Voltage	Description
REL1	ALF1P24		24 V	Relais
SW1	2AS1T2A1M2RES			Toggle switch
X1	SQW-116-01-L-D			Pin header 2 x 16
X2				Female header, 2 contacts
X3	MKDS 5/3-6,35 – 1714955			AC connector
X4	MKDS 5/3-6,35 – 1714968			DC connector

Table 6 Control board components in EVAL_3K3W_TP_PFC_SIC2

Designator	Value	Tolerance	Voltage	Description
IC1	**XMC1404-LQFP-64**			**Integrated circuit**
T1	**BSS138N**			**MOSFET**
C1, C2, C17, C28	330 pF	X7R	50 V	Ceramic capacitor
C3, C7, C9, C11, C14, C16, C20, C22, C25, C27	100 nF	X7R	25 V	Ceramic capacitor
C4, C6, C8, C10	1 nF	X7R	25 V	Ceramic capacitor
C5	10 µF	X7R	6V3	Ceramic capacitor
C12, C15, C21, C23, C26, C33, C34	10 µF	X7R	25 V	Ceramic capacitor
C13, C18, C19, C24, C29, C30, C31	100 pF	X7R	50 V	Ceramic capacitor
D1, D2, D3	Blue LED			LED diode
IC2	OPA2376AIDR			Integrated circuit
IC3, IC4	LMH6642MF			Integrated circuit
IC5	TL431B	0.50 percent		Integrated circuit
L1	Ferrite bead 60 Ω at 100 MHz			Inductor
R1, R4, R7, R15, R17, R33	1 k	1 percent		Resistor
R2, R13, R25, R29, R30	510 R	1 percent		Resistor
R3, R5, R10, R12	37k4	0.10 percent		Resistor
R6, R8, R9, R11	750 k	0.10 percent		Resistor
R14, R16, R26, R28	750 R	0.10 percent		Resistor
R18, R19, R27, R31	47 R	0.10 percent		Resistor
X1	TMM-116-03-L-D			Pin header 2 x 16 contacts

8 References

[1] Q. Huang and A. Q. Huang, “Review of GaN totem-pole bridgeless PFC”, *CPSS Transactions on Power Electronics and Applications*, vol. 2, no. 3, pp. 187–196, Sept. 2017

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[3] Infineon Technologies AG: *Application Note – 800 W Platinum® server power supply. Using 600 V CoolMOS™ C7 and digital control with XMC™*; Available online

[4] Infineon Technologies AG: *Application Note – PFC demoboard - system solution. High power density 800 W 130 kHz Platinum server design*; Available online

[5] Infineon Technologies AG: *Application Note – High-efficiency 3 kW bridgeless dual-boost PFC demo board. 90 kHz digital control design based on 650 V CoolMOS™ C7 in TO-247 4-pin*; Available online

[6] Infineon Technologies AG: *Application Note – 3300 W 54 V bi-directional phase-shift full-bridge with 600 V CoolMOS™ CFD7 and XMC™, EVAL_3K3W_BIDI_PSFB*; Available online

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Document revision	Date	Description of changes
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