250W PFC-LLC Adapter Reference Design

Abridged version

Technical Manual

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Please refer to the Reference Design Kit Important Notice on page 18

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1. Scope and Purpose

This document provides a comprehensive functional description and design guide with the 250W AC/DC charger reference design (part number: GS-EVM-CHG-250WPFCLLC-GS1). This adapter reference design uses 650V Gallium Nitride (GaN) transistors from GaN Systems (**GS-065-011-2-L**). This manual describes the system operation and covers technical aspects essential to the design process. Test results and waveforms are also included.

2. Introduction

The 250W GaN-based charger reference design provides a cased turn-key solution with the following key features:

- High-frequency PFC and LLC controller with GaN FET
- High power density 16W/in^3 (256cc)
- High efficiency above 96%
- Cost-effective topologies with Boost PFC+ Half-Bridge LLC
- Low Total Harmonic Distortion (THD)
- Passes EN55023 Class B for conduction and radiation electromagnetic interference (EMI)
- Meets IEC 62368-1 touch temperature requirement
- Comprehensive system protections such as TSD, OLP, OVP, OCP, and OPP

2.1 System Block Diagram

The block diagram of the 250W adapter is shown in Figure 1. This adapter has a two-stage power conditioning system, including a boost AC/DC PFC stage and an isolated DC/DC half-bridge LLC stage.

1. **Boost PFC stage**: A boost architecture regulates the AC grid voltage to a 400V DC bus voltage. Also, this boost converter is responsible for PFC. The PFC controller of this converter provides hybrid continuous/discontinuous current mode (CCM/DCM) with a digital average current control scheme. In particular, CCM is provided for heavy loads to benefit from the reduced peak current, and DCM is provided for light loads to reduce the

switching frequency (i.e., improve the efficiency). Two parallel GaN Systems' GS-065-011-2-L transistors (650V, 150mΩ) are utilized in this converter. Having parallel GaN transistors improves the thermal and electrical performance of the converter.

2. **Half-bridge LLC stage**: The second stage isolated LLC converter steps down the 400V DC bus voltage to 19V. The LLC converter is capable of providing soft switching (ZVS). Besides, the LLC converter features quasi-sinusoidal currents, which leads to reduced EMI. This converter utilizes GaN Systems' GS-065-011-2-L transistors (650V, 150mΩ) for the half-bridge devices and SRs in the transformer's secondary. The controller of the LLC converter employs current mode control. The duty cycle of this converter is set to 0.5, and the variable switching frequency provides the output voltage regulation.

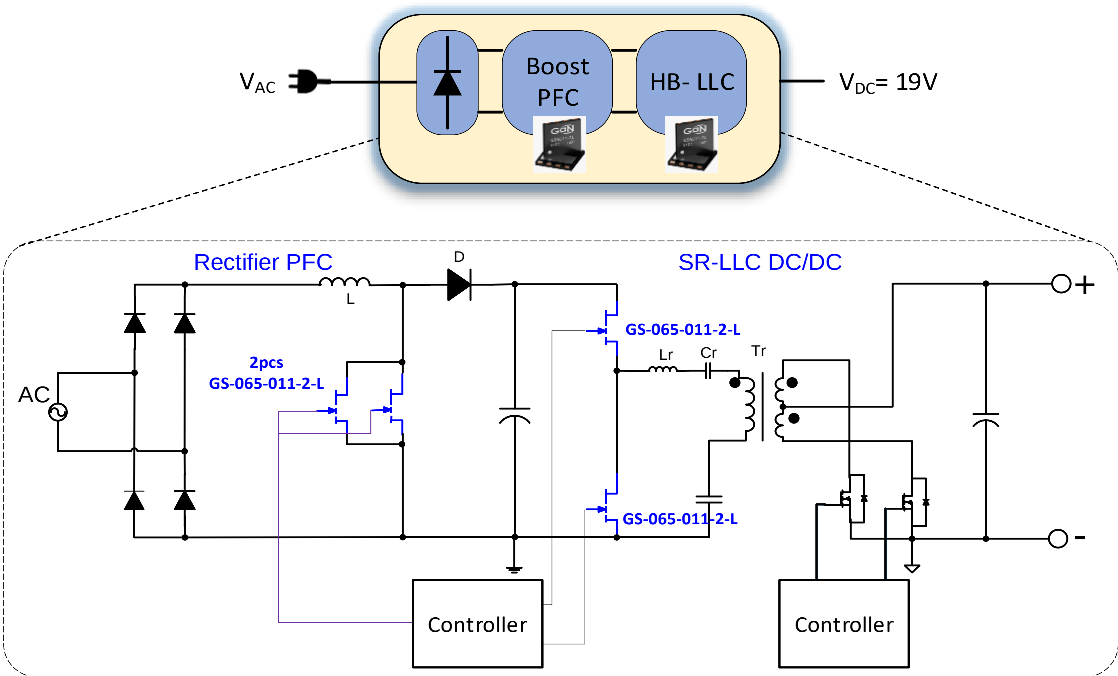


Figure 1. Simplified system block diagram for the GS-EVM-CHG-250WPFCLLC-GS1 reference design.

2.2 System Specifications

Table 1 summarizes the key specifications for this 250W GaN-based charger reference design.

Table 1. Key parameters and performance of GS-EVM-CHG-250WPFCLLC-GS1 reference design

Parameter	Value
Input AC Voltage (V_{in})	90-264 V_{rms}
Input Frequency Range	50/60 Hz
Max. Output Power	250W
Output Voltage and Current	19V, 13.2A
Full-load Efficiency	>95%
Output voltage ripple	<500mV
Standby Power	<150mW
Cased Power Density	16 W/in^3 (256 cc)
Operating temperature	0~40°C
Performance	**Specification**
Input socket	Three pins
Average Efficiency	CoC V5 Tier2
Heat dissipation	Natural convection
Board Dimension with Case	171mmX68mmX22mm (6.7inchX2.7inchX0.9inch)
Surface temperature rise	<53 °C
Touch Temperature @19V/13.2A	IEC 62368-1
EMI Standard	EN55032 CE & RE Class B
System Protections	TSD, OLP, OVP, OCP, SCP, Open Loop

2.3 Reference Design Board

The PCBA photos of the 250W adapter reference design are shown in Figure 2. According to this figure, the surface mount devices (SMD) are placed on the bottom layer, and through-hole components are placed on the top layer. The PCB of this adapter is based on a 4-layer 2Oz FR4 design. The Key components placements are highlighted in Figure 2. As a general rule, in the PCB design of adapters, it is essential to keep a clearance distance between the significant heat sources (e.g., magnetic components and bridge diodes on the top layer) and the GaN devices on the bottom layer. This provides minimum heat effect applied from other sources to GaN transistor junction temperature. The key magnetic components (e.g., PFC inductor and LLC transformer) are implemented using low-profile magnetic cores suitable for high frequency and high-power density.

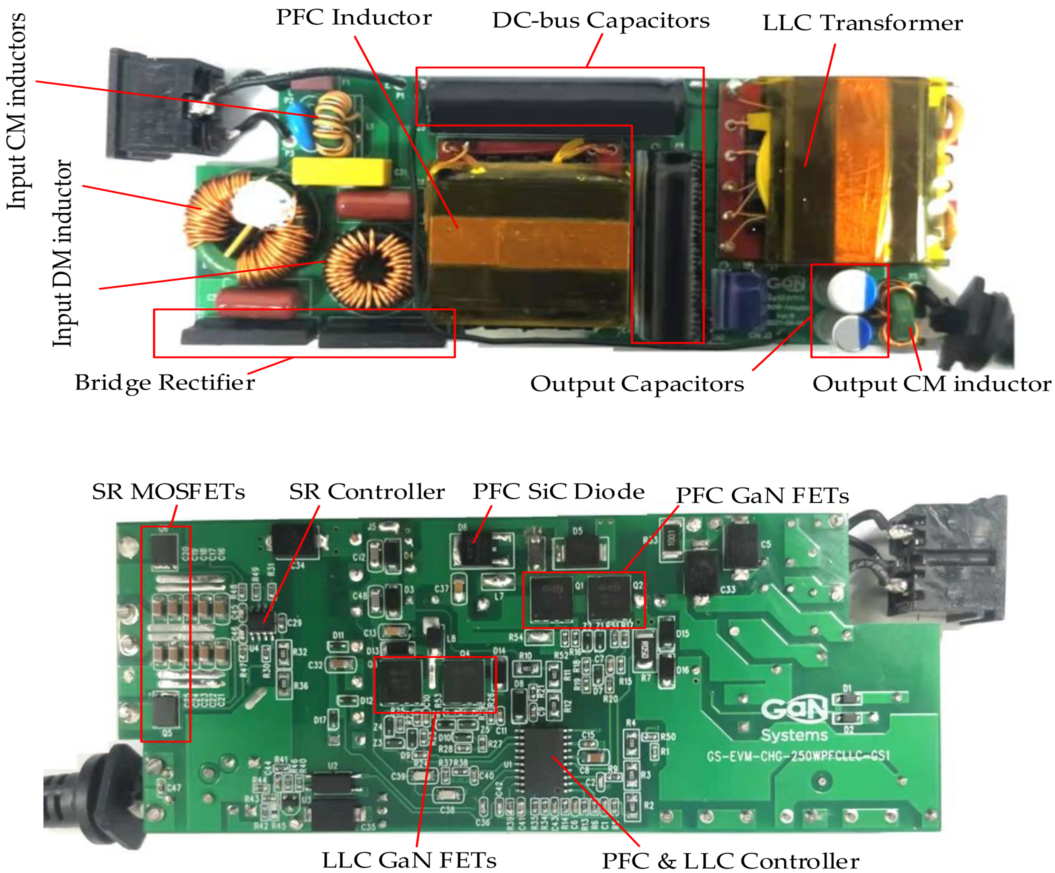


Figure 2. PCBA photos for the GS-EVM-CHG-250WPFCLLC-GS1 reference design.

3. GaN Value Proposition

Table 2 summarizes key Figures of Merit (FOM) between the GaN transistor and Si Super Junction (SJ) MOSFET. As can be seen, a GaN transistor has much lower FOMs compared to Si SJ MOSFETs. The combined advantages of GaN transistors: low gate charge, low parasitic capacitor, and low on-state resistance in the converter lead to a more efficient system. In particular, lower switching energy and parasitic capacitance of GaN transistors provide higher efficiency with hard-switching of the boost PFC and hard-switching turn-off of the LLC stage. Moreover, the zero-reverse recovery and optimized packaging of GaN power stage enable less EMI noise. In addition to significantly improved efficiencies, the lower switching energy of GaN transistors provides fewer thermal challenges, which is a critical advantage, especially for adapter applications.

Table 2. GaN vs Si MOSFET parameters for both PFC and LLC stage of 250W adapter reference design

Manufacturer	**GaN Systems**	**Si SJ MOSFET**			**GaN benefit**
Part Number	GS-065-011-2-L	#1	#2	#3	
Technology	GaN	Si Super Junction MOSFET			
On resistance R_{dson} (mOhm) Typ. Tj=25C	150	159	300	300	Almost same or 2x smaller typical R_{dson}
Total gate charge Q_g (nC)	2.2	24	13	16.4	Lower gate driver loss
Gate to drain charge Q_{gd} (nC)	0.7	8	4	6	Lower switching loss
Reverse recovery charge Q_{rr} (nC)	0	2900	740	1000	Lower switching turn-on loss for PFC stage; no hard commutation failure for LLC

Moreover, there are several values for GaN at the LLC stage in the 250W adapter. The LLC converters should not continuously operate at the resonant frequency due to the regulatory requirements. Therefore, it is essential to highlight GaN advantages for various situations (e.g., when the switching frequency is below/above the resonant frequency). Figure 3 demonstrates multiple operating points of the LLC converter. GaN offers the following advantages for the LLC stage:

1. The peak efficiency is achieved when the switching frequency is equal to the resonant frequency (**f_{sw}= f_r**) (i.e., the peak efficiency is reached).
   - Considering the same switching frequency and same dead time (t_{dead}), GaN transistors provide higher magnetizing inductance (L_m) or equivalently lower magnetizing current on the primary side of the LLC transformer. Consequently, lower reverse conduction loss is observed during the deadtime. As a result, GaN transistors provide higher efficiency compared to Si/SiC devices.
   - If the same dead time (t_{dead}) and same magnetizing inductance (L_m) are considered, higher switching frequencies can be achieved, which results in increased power density.
   - If the same switching frequency and same magnetizing inductance (L_m) are considered, a significantly shorter dead time is required with GaN transistors to achieve ZVS. In particular, shorter dead time means lower reverse conduction loss for the transistor. Therefore, higher efficiency is achieved with GaN.

2. When the switching frequency is greater than the resonant frequency (**f_{sw}> f_r**), the LLC converter operates in step-down mode. In this mode, the switching frequency is increasing. As a result, the turn-off high switching losses become dominant. This is where GaN helps by offering the lowest turn-off losses.

3. When the switching frequency is less than the resonant frequency (**f_{sw}< f_r**), the LLC converter operates in step-up mode, in this mode, there is a significant primary circulating current, as mentioned earlier, GaN enables the utilization of a larger magnetizing inductance (L_m) with ZVS, or equivalently, lower magnetizing current. This reduces the circulating conduction loss on the primary side and improves efficiency.

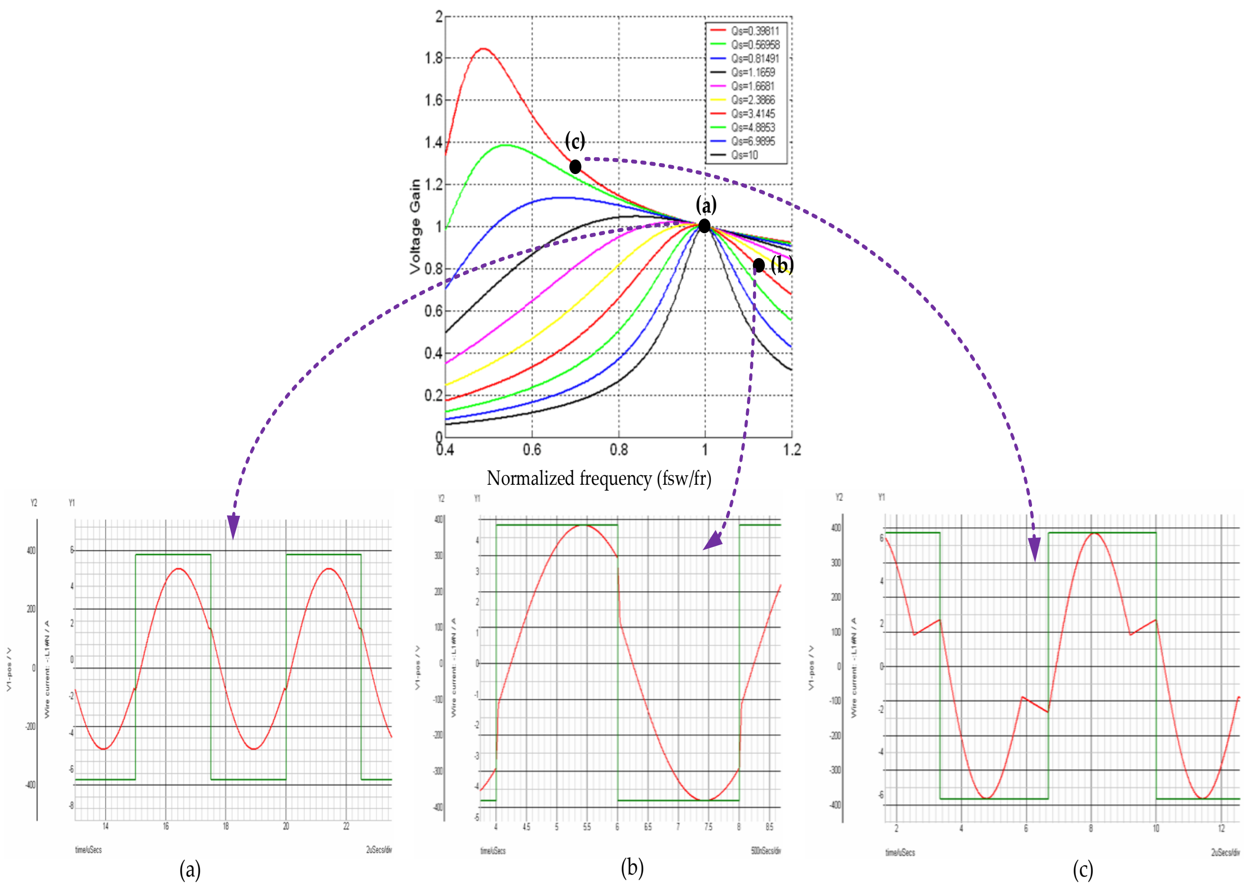


Figure 3. LLC operation for various switching frequencies: (a) f_{sw}= f_r, (b) f_{sw}> f_r, and (c) f_{sw}< f_r.

4. Test Results

In this section, some test results of the charger reference design are presented. For more information and results, please contact us.

4.1 Test Equipment

- Oscilloscope: Tektronix MDO3054
- AC power source: Chroma 6530
- Electronic load: Chroma 6312A
- Power meter: HIOKI PW3335
- Multi-meter: UNI-T UT61E

4.2 Efficiency

For the efficiency test, the output voltage is directly measured by the multimeter from the output port on the PCBA board, and the output current is measured via the E-load. In addition, the input power is measured with the power analyzer. To ensure accurate efficiency measurements, the input voltage is directly measured from the AC input port on the PCBA when the output voltage is equal to 19V. The efficiency values are measured for various load and input voltages, shown in Figure 4.

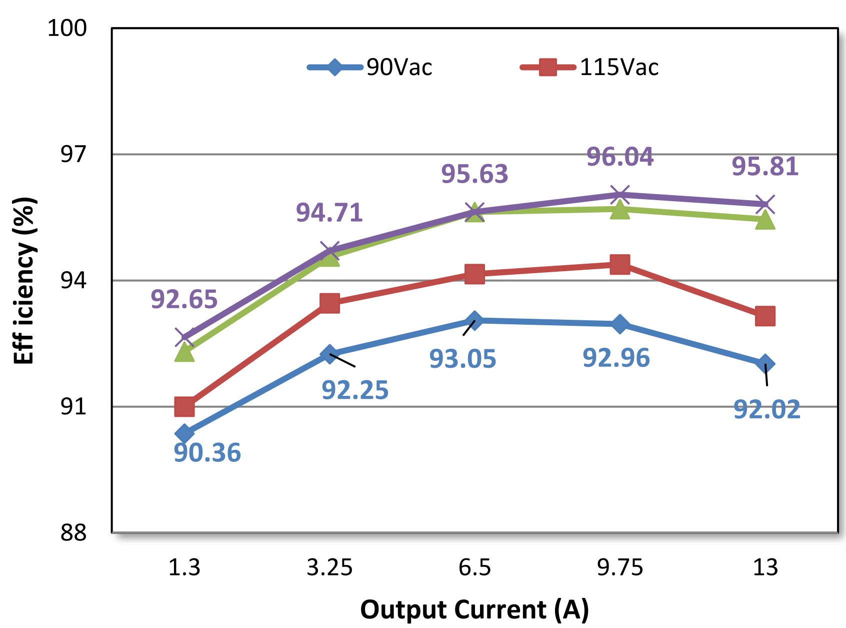


Figure 4. The 250W adapter efficiency curve at 5V, 9V, 12V, 15V, and 20V.

4.3 Standby Power

In Figure 5, the no-load standby power is measured from 90V to 264V, and the maximum standby power of 100mW occurs at the 264V input, which meets the CoC V5 2019/1782 standard requirement with standby power less than 150mW, as shown in Figure 5.

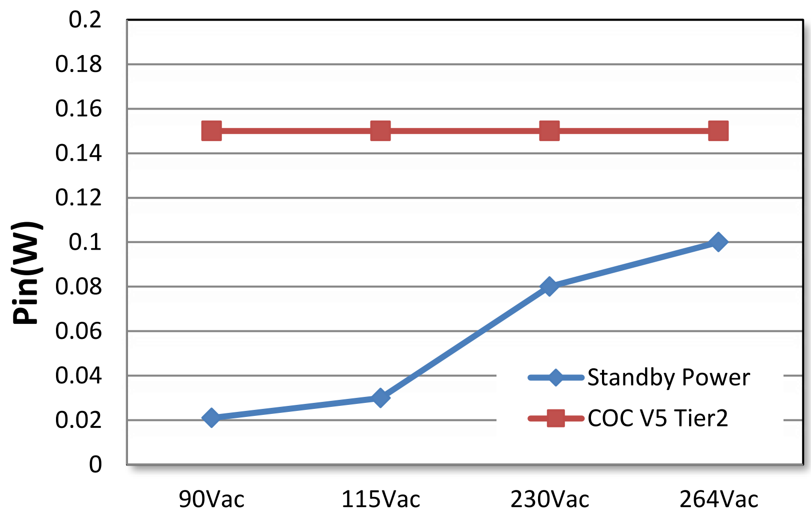
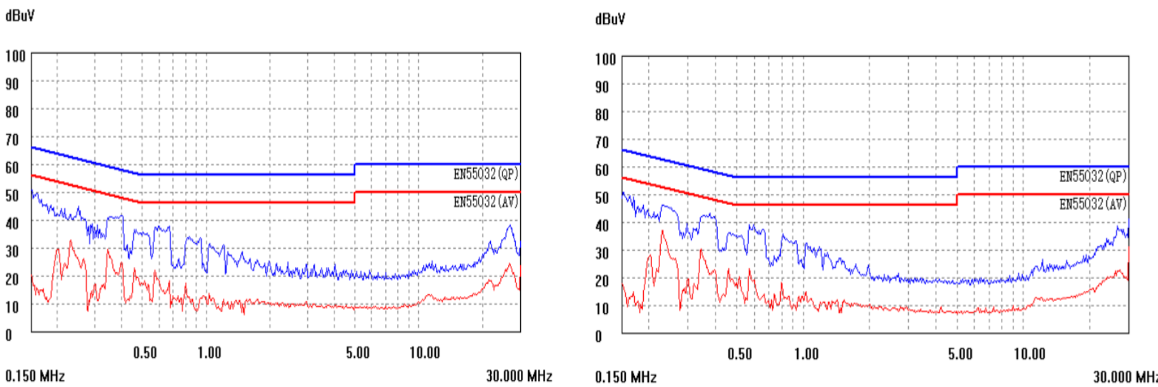


Figure 5. No load standby power from 90V to 264V.

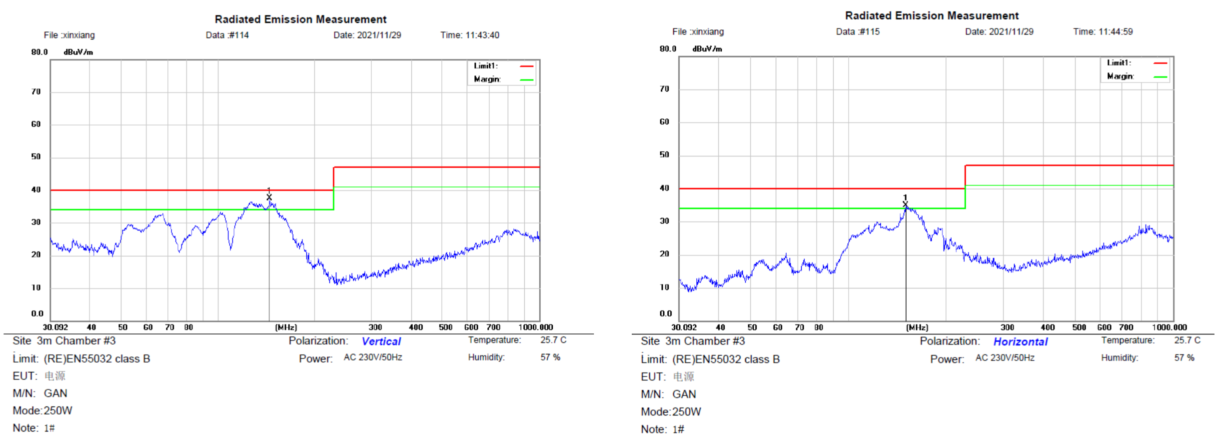
4.4 Electromagnetic Interference (EMI)

The charger reference design board is measured based on EN55032 CE Class B standard for EMI conduction and EN55032 RE Class B standard for EMI radiation. The test results show that this adapter passes the EMI conduction and EMI radiation tests with at least 10dB margin and 3dB margin, respectively. Figure 6 shows the conduction EMI results at 230V under full load conditions (20V/5A). Moreover, Figure 7 demonstrates the radiation EMI results at 230V under full load conditions (20V/5A).



(a) (b)

Figure 6. Conduction EMI performance at (a) 230 Vac full load Line, and (b) 230 Vac full load neutral.



(a) (b)

Figure 7. Radiation EMI performance at (a) 230 Vac full load vertical, and (b) 230 Vac Full load horizontal.

4.5 Thermal performance

The decreased size of the adapters (i.e., the direct outcome of the ultra-fast switching capability) will bring thermal challenges. Besides, the new standards (e.g., IEC 62368-1) require that the adapter case touch temperature not exceed 77 °C at an ambient temperature of 25 °C. This temperature requirement is more stringent than the former standards (e.g., IEC 60950). The maximum allowable heat dissipation within the adapter enclosure must be limited to follow the case temperature limits. In addition, if the heat inside the adapter is not appropriately managed, it can impact the reliability and electrical characteristics of the critical components. These emphasize the importance of a proper thermal design and optimization for power adapters. Therefore, thermal stack-up layers are crucial parts of the adapter design. Moreover, for EMI purposes, it is essential to have copper shielding around the adapter. After running the setup for an hour, and at an ambient temperature of 25 °C, the following measurements are obtained:

Temperature rise	Topside 	Bottom side 
115 Vac	ΔT=51.8°C	ΔT=49.8°C
230Vac	ΔT=44.7°C	ΔT=45.9°C

Figure 8 shows the adapter's surface temperature at an ambient temperature of 25°C. According to the IEC 62368-1 standard, the surface touch temperature at an ambient temperature of 25°C should not exceed 77°C. Accordingly, the thermal images of the 250W adapter show that the surface temperature meets the standard requirements.

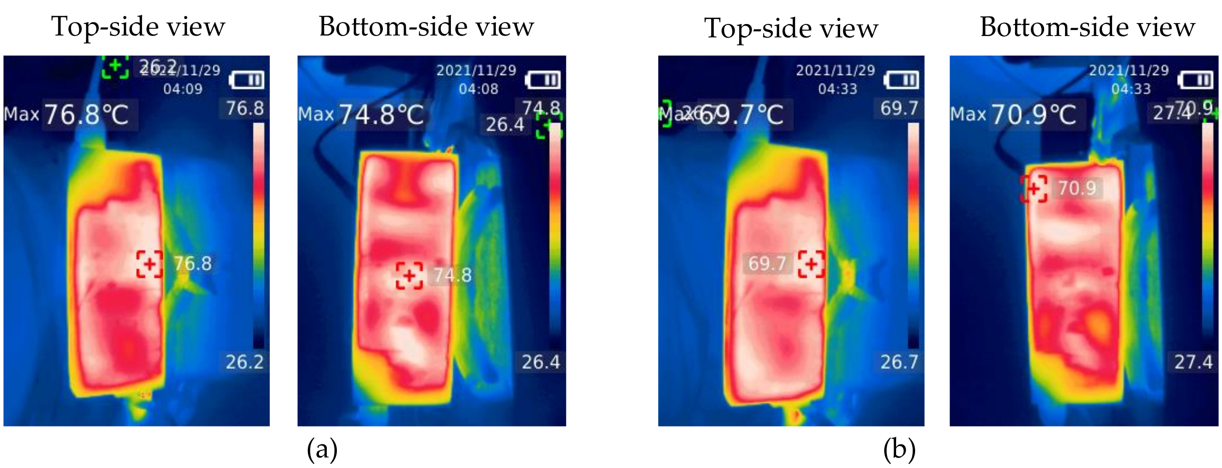
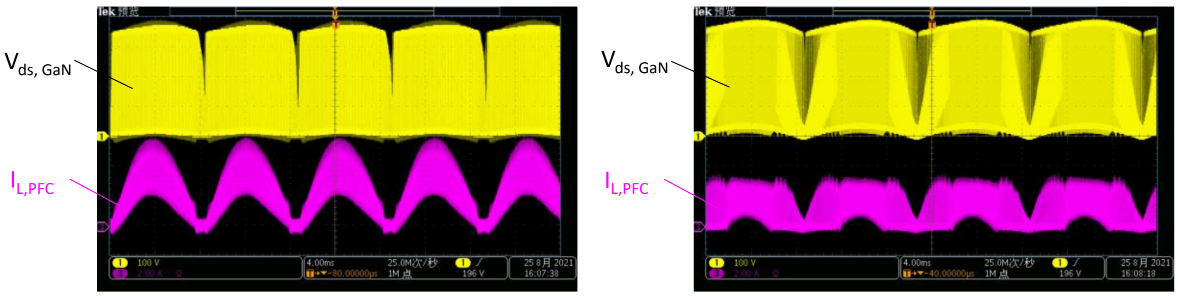


Figure 8. Adapter surface temperature after 1-hour continuous run at full-load and an ambient temperature of 25°C (a) at 115Vac and (b) 230 Vac.

4.6 Electrical Waveforms

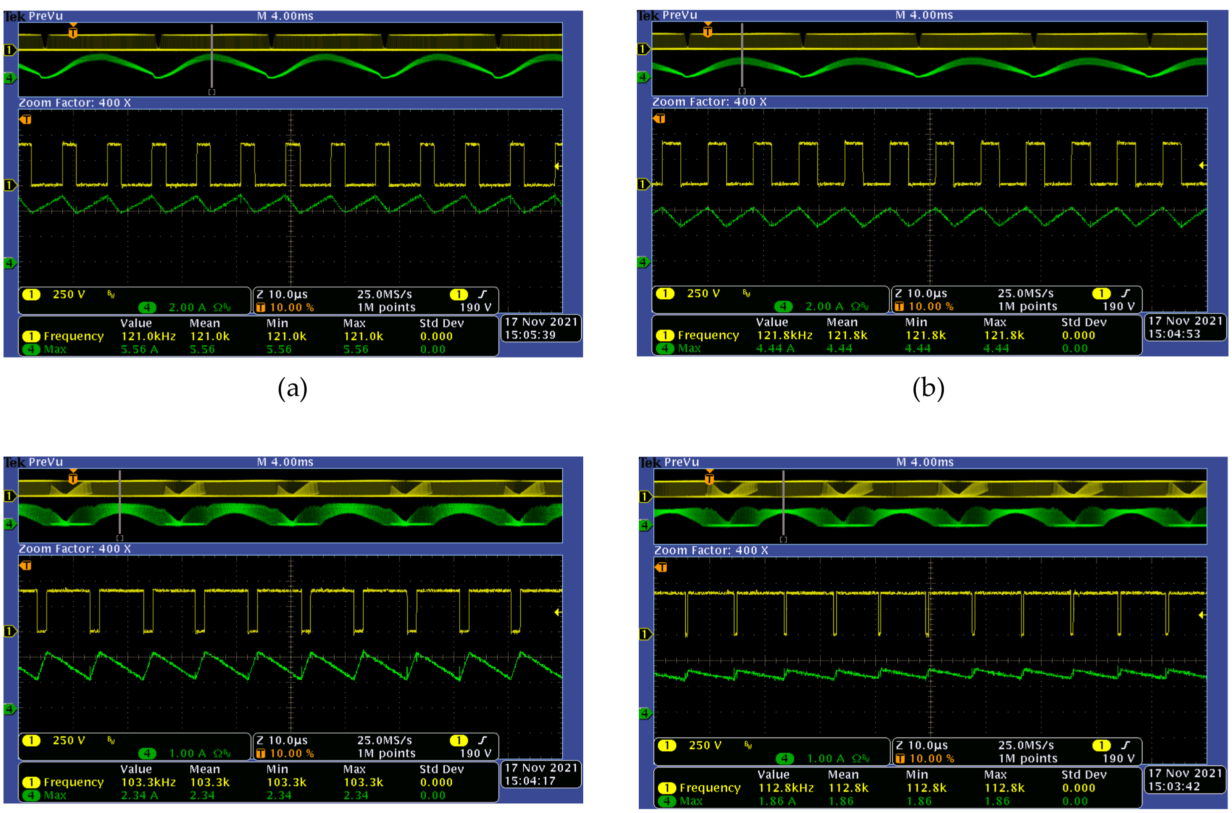
Figure 9(a) shows the key waveforms of the full-load steady-state waveforms at different input AC voltages. In particular, CCM is appropriate for heavy loads as it offers a lower peak current. Therefore, as the load decreases, the controller changes the mode of the circuit to the mixed CCM/DCM waveform shown in Figure 9(b). Various experimental waveforms of the 250w adapter reference design are demonstrated in this section in more detail.

1. Boost PFC Results:



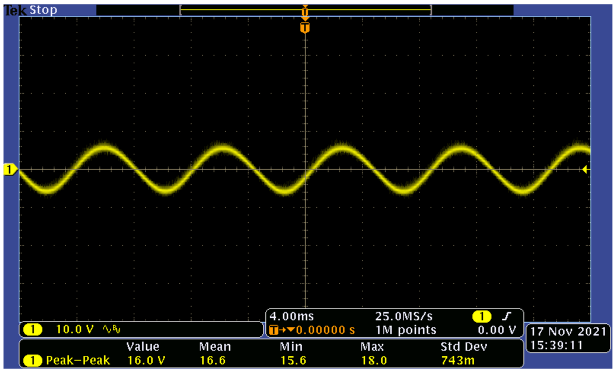
(a) (b)

Figure 9. PFC steady-state waveforms over full range of input voltage including: (a) CCM PFC at 110Vac input and 19V/13A output, and (b) mixed mode PFC (CCM&DCM) at 230Vac and 19V/13A.

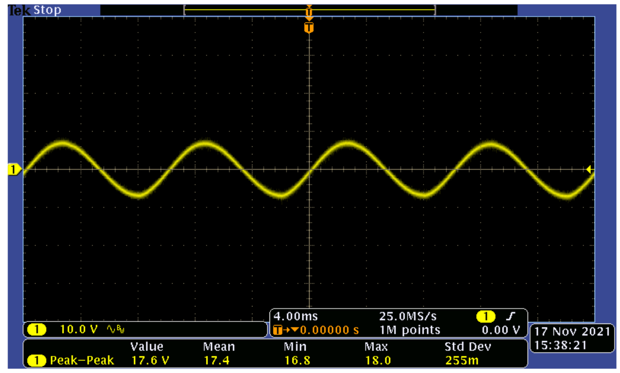


(a) (b) (c) (d)

Figure 10. PFC stage voltage and current waveform at full load: (a) 90 Vac, (b) 115 Vac, (c) 230 Vac, and (d) 264 Vac.



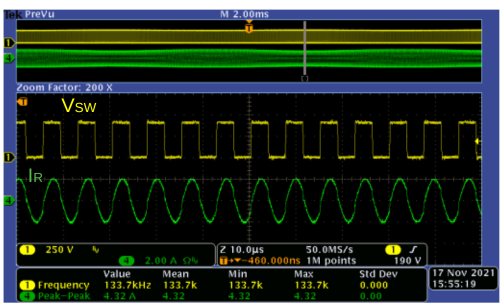
(a)



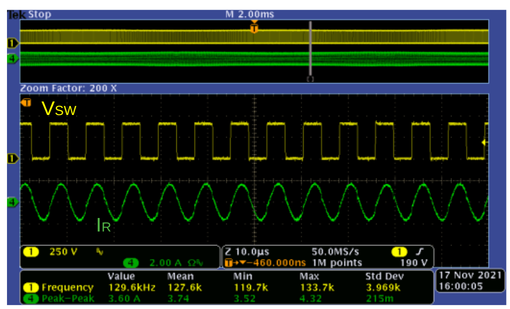
(b)

Figure 11. DC-bus voltage ripple: (a) 90 Vac and 60 Hz, and (b) 264 Vac and 50 Hz.

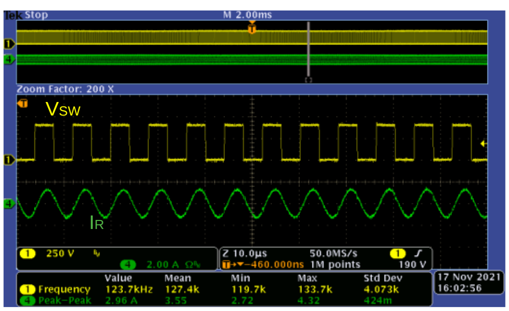
2. Half-Bridge LLC Results:



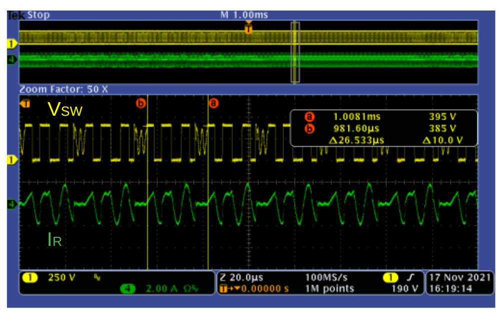
(a)



(b)



(c)



(d)

Figure 12. LLC stage voltage and current waveform at: (a) full load, (b) 75% load, (c) 50% load in normal mode, (d) 50% load in skip mode.

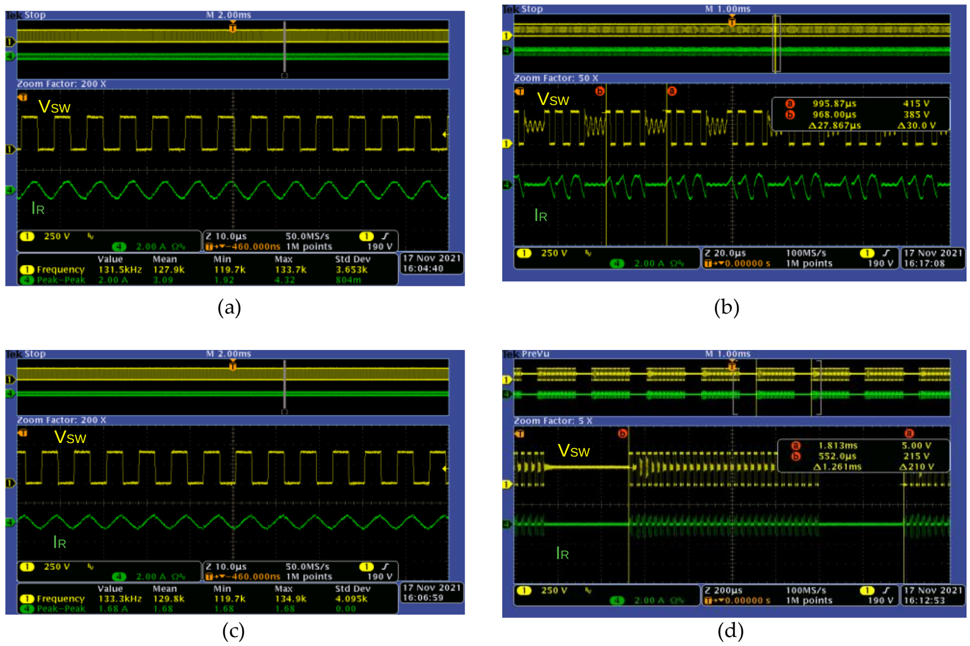


Figure 13. LLC stage voltage and current waveform at: (a) 25% load in normal mode, (b) 25% load in skip mode, (c) 10% load in normal mode, and (d) 10% load in burst mode.

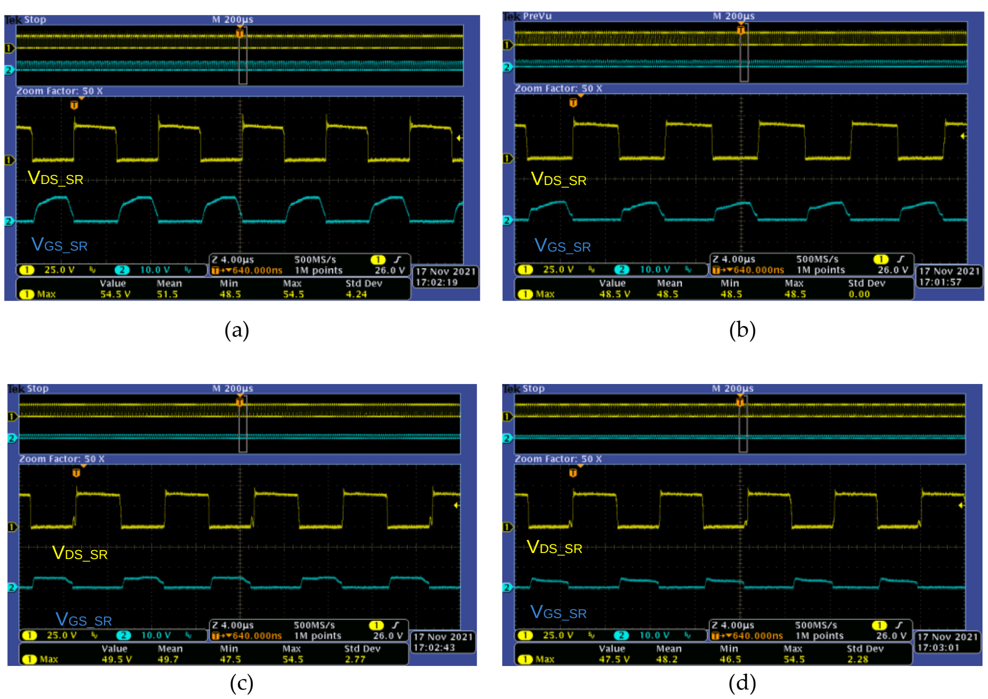


Figure 14. Synchronous rectifier waveforms at (a) full load, (b) 75% load, (c) 50% load, and (d) 25% load.

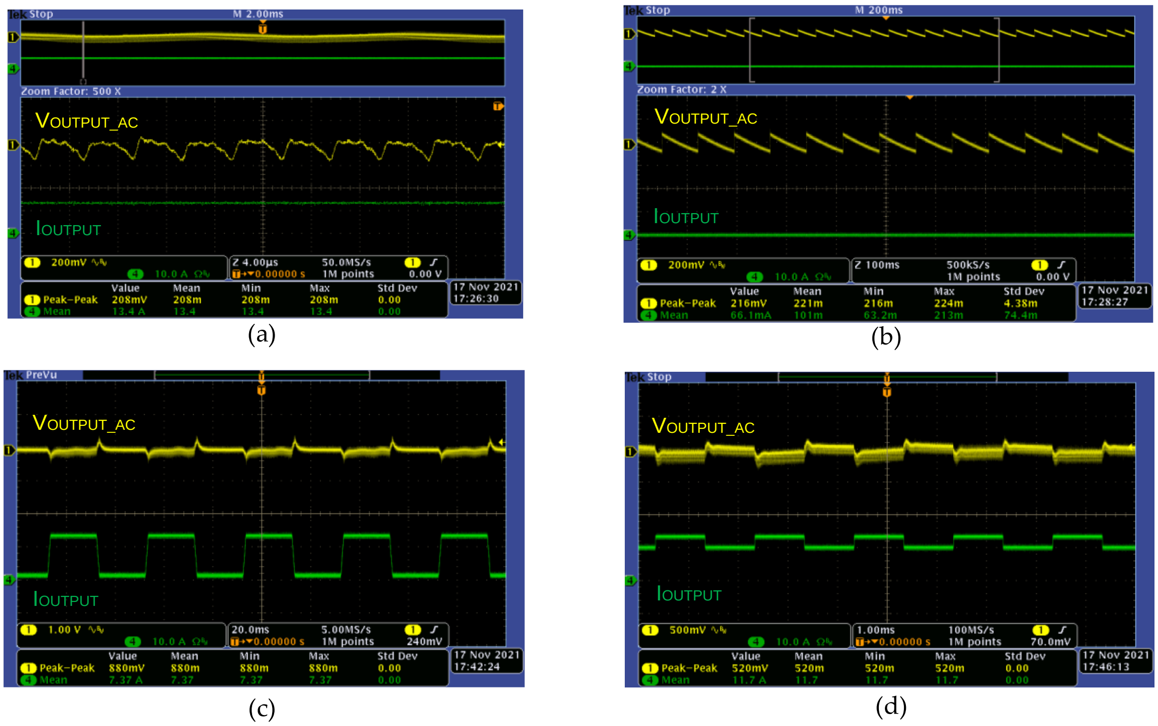


Figure 15. Output voltage/current performance at (a) full load, (b) no load, (c) 10-100% load, and (d) 75-100% load.

5. Conclusion

The GaN-based 250W adapter reference design is introduced in this technical manual. The reference design achieves the following best-in-class features and performance:

- Topology: Boost PFC & H-B LLC
- Cased Power density: 16W/in^3 (256cc)
- Efficiency: >96%
- Standby power: Exceeds standards with <150mW
- Waveforms: Clean with full protections (SCP, OCP, OVP, etc.)
- Thermal: <78°C (meet IEC 62368-1 touch temperature)
- EMI: Pass EN55032 CE Class B with >10dB margin

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