Design of Boost PFC

EN665 Course Project

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Abstract

This project presents the design, analysis, and performance evaluation of a Boost Power Factor Correction (PFC) converter operating in Continuous Conduction Mode (CCM). The main objective is to achieve a high power factor and low input current distortion in single-phase AC–DC conversion systems. Conventional diode bridge rectifiers suffer from poor power quality due to non-sinusoidal input current and low power factor. The proposed Boost PFC topology overcomes these limitations by regulating the DC output voltage while forcing the input current to follow the shape of the input voltage. Operating the converter in CCM minimizes current ripple, reduces switching losses, and enhances the dynamic response of the system. A control strategy based on average current mode control is implemented to ensure precise current shaping and stable output voltage regulation under varying load and supply conditions. The converter is modeled and simulated using MATLAB/Simulink to analyze steady-state and dynamic performance. Simulation results confirm that the proposed Boost PFC in CCM achieves a near-unity power factor (>0.98), low Total Harmonic Distortion (THD), and high efficiency, making it highly suitable for front-end power supplies in industrial equipment, computer systems, and electric vehicle chargers.

Contents

List of Figures

Chapter 1

Introduction

1.1 Boost PFC Converter: Working Principle and Modes of Operation

1.1.1 Working principle

A Boost Power Factor Correction (PFC) converter converts a single-phase AC input into a regulated DC output while shaping the input current to be sinusoidal and in phase with the instantaneous input voltage. The main power-stage components are:

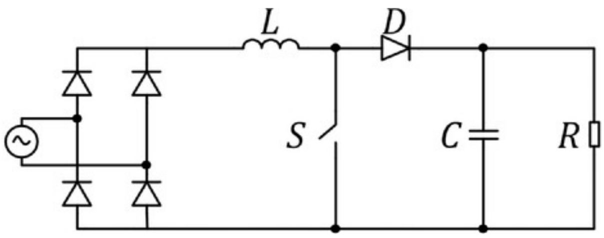


Figure 1.1: Boost PFC Circuit

- a full-bridge rectifier that produces a pulsating DC,
- a boost inductor L,
- an active switch (MOSFET) S,
- a freewheeling/output diode D, and
- an energy-storage capacitor C at the DC bus.

Control objective: regulate the average input current $i_s(t)$ per switching period such that

$$i_s(t) \approx I_m \sin(\omega t),$$

where I_m is chosen so that the instantaneous power drawn matches the DC-side demand. When the inductor current is controlled to be proportional to the rectified line voltage, the converter achieves near-unity power factor and low THD.

Basic on/off intervals (idealized):

- **Switch ON:** Inductor stores energy while diode D is reverse-biased.
- **Switch OFF:** Inductor releases energy to the DC bus through D, raising the output voltage above the instantaneous rectified source.

1.1.2 Modes of operation

The mode depends primarily on the inductor value, load current and control strategy. The three canonical modes are:

Continuous Conduction Mode (CCM)

- **Definition:** Inductor current $i_L(t)$ never falls to zero during the switching cycle.
- **Waveform:** Continuous with small ripple around a nonzero average.
- **Pros:** Lowest peak currents and RMS stress, highest achievable power factor (close to unity), smaller RMS losses for a given fundamental current amplitude. Good for medium/high-power applications.
- **Cons:** Requires larger inductor; diode reverse-recovery can increase switching losses at MOSFET turn-on.
- **Typical use:** SMPS front-ends, EV chargers, industrial supplies (power few 100 W).

Critical / Boundary Conduction Mode (CRM / BCM)

- **Definition:** Inductor current just reaches zero at the end of each switching cycle (boundary between CCM and DCM).
- **Waveform:** $i_L(t)$ returns to zero each switching period; switching frequency varies with input and load.
- **Pros:** Zero-current turn-on (reduced turn-on switching loss), smaller inductor compared to CCM.
- **Cons:** Variable switching frequency complicates EMI filter design and control; at light loads the switching frequency can become large (efficiency and control delays affected).
- **Typical use:** Medium-power LED drivers, adapters where a compromise between size and efficiency is needed.

Discontinuous Conduction Mode (DCM)

- **Definition:** Inductor current falls to zero and remains zero for a portion of the switching period (a dead interval exists).
- **Waveform:** Distinct on / discharge / idle intervals each switching cycle.
- **Pros:** Zero-current MOSFET turn-on (no diode reverse-recovery losses), small inductor; simple control.
- **Cons:** High peak and RMS currents for a given average fundamental current $\rightarrow$ higher conduction losses and higher THD; typically lower efficiency at higher powers.
- **Typical use:** Low-power supplies (LED drivers, small adapters, 100 W).

Table 1.1: Comparison of CCM, CRM (BCM) and DCM operation for boost PFC converters.

Parameter	**CCM**	**CRM / BCM**	**DCM**
Inductor current (per cycle)	never zero	reaches zero at boundary	reaches zero with dead time
Inductor size	large	medium	small
Switching frequency	(nearly) constant	variable	variable
Current ripple	low	moderate	high
Peak current	lowest	moderate	highest
Conduction losses	low	moderate	high
Diode reverse-recovery	present	not present	not present
Control complexity	moderate	higher (variable freq.)	simple
Suitable power range	medium – high	medium	low
Power factor potential	highest	medium	lowest

1.1.3 Practical remarks and control

Common control strategies for Boost PFC include:

- **Average current mode control:** Explicitly regulates the average inductor current per switching period to track a sinusoidal reference (high quality PF, good dynamic response).
- **Hysteresis (peak) control:** Simple implementation — comparator/hysteresis forces current to follow the envelope; typically used in CRM/DCM topologies.
- **Current-mode control (peak):** Uses a clocked peak comparator with slope compensation when required (mitigates subharmonic oscillations for duty > 0.5).

Chapter 2

Design Parameter

2.1 Schematic and Component used

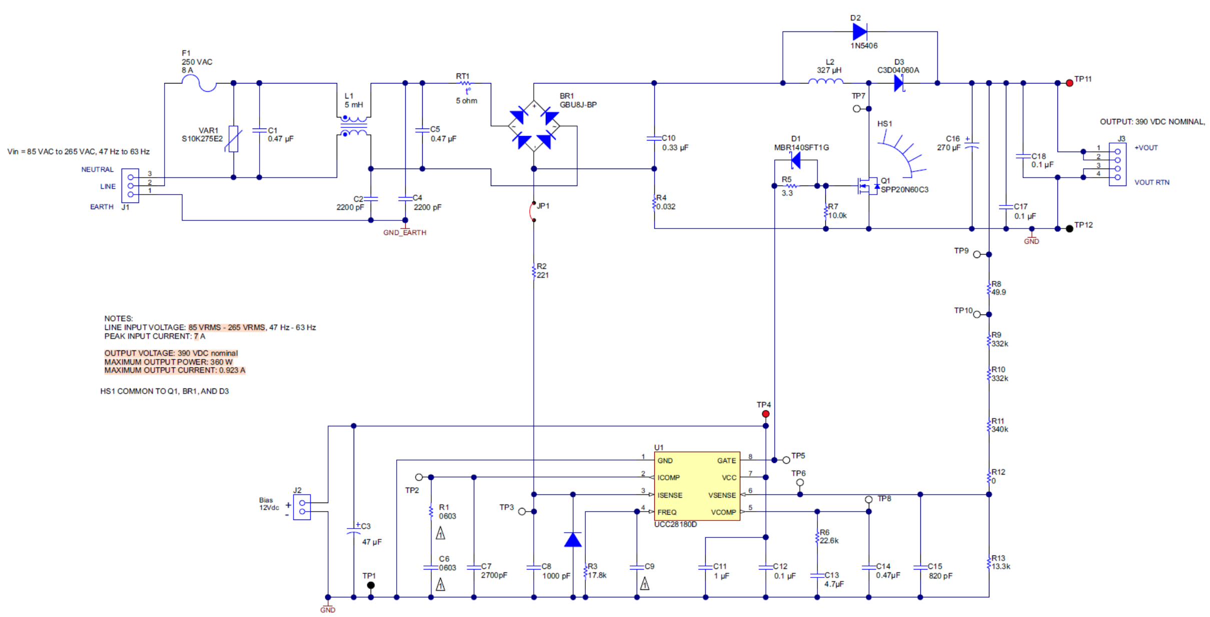


Figure 2.1: Schematic [2]

Table 2.1: Component Specifications of Boost PFC Converter Hardware

Sr. No.	Component	Specification
1	Bridge Rectifier	KBPC806 / 420 V, 8 A
2	Diode	1N5406 / 600 V, 3 A C3D04060A / 600 V, 4 A (SiC) MBR140SFT1G / 40 V, 1 A Replacement: 1N5819
3	MOSFET	SPP20N60C3
4	IC	UCC28180 (TI PFC Controller)
5	Resistors	R1: 100 Ω, 0.1 W, ±1% R2: 221 Ω, 0.1 W, ±1% R3: 17.8 kΩ, 0.1 W, ±1% R4: 0.032 Ω, 2 W, ±1% R5: 3.3 Ω, 0.5 W, 5% R6: 22.6 kΩ, 0.1 W, ±1% R7: 10 kΩ, 0.25 W, ±1% R8: 49.9 Ω, 0.125 W, ±1% R10: 332 kΩ, 0.125 W, ±1% R11: 340 kΩ, 0.125 W, ±1% R13: 13.3 kΩ, 0.1 W, ±1%
6	Capacitors	C3: 47 μF, 35 V, aluminum C6: 0.1 μF, 50 V, ceramic C7: 2700 pF, 50 V, ceramic C8: 1000 pF, 100 V, ceramic C9: 0.68 μF, 10 V, ceramic C10: 0.33 μF, 275 V, film C11: 1 μF, 50 V, ceramic C12: 0.1 μF, 50 V, ceramic C13: 4.7 μF, 10 V, ceramic C14: 0.47 μF, 16 V, ceramic C15: 820 pF, 50 V, ceramic

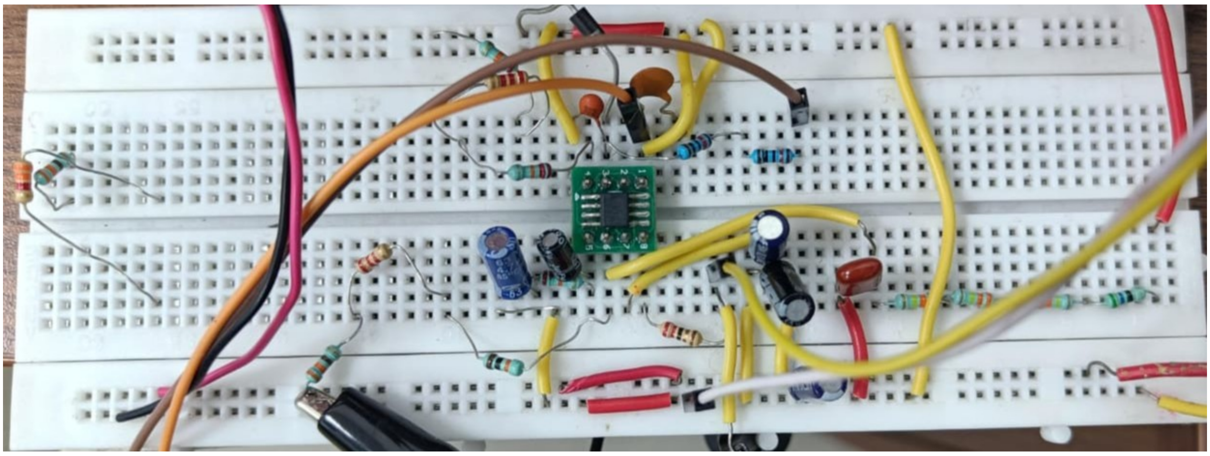


Figure 2.2: Controller IC and Other Component

2.2 Boost PFC operating parameters

Table 2.2: Boost PFC Operating Parameters

Parameter	**Specification**
Input Voltage (AC)	230 V
Output Voltage (DC)	400 V
Inductor (L)	2 mH
Controller IC	TI: UCC28180
Switches	D1: 1N5406 — 600 V, 3 A D2: U1560 — 15 A Sw: K40H1203 — 1200 V, 40 A
Output Capacitor	820 μF, 450 V
Frequency of Operation	45 kHz
Shunt Resistance (for current measurement)	10 mΩ

2.3 Design Parameters Calculation [1]

2.3.1 R_{Freq} Calculation

$$R_{\text{FREQ}} = \frac{f_{\text{TYP}} \times R_{\text{TYP}} \times R_{\text{INT}}}{(f_{\text{SW}} \times R_{\text{INT}}) + (R_{\text{TYP}} \times f_{\text{SW}}) - (R_{\text{TYP}} \times f_{\text{TYP}})} \tag{2.1}$$

$$\text{Given: } f_{\text{TYP}} = 65 \text{ kHz}, \quad R_{\text{TYP}} = 32.7 \text{ k}\Omega, \quad R_{\text{INT}} = 1 \text{ M}\Omega, \quad f_{\text{SW}} = 45 \text{ kHz} \tag{2.2}$$

$$R_{\text{FREQ}} = \frac{(65 \times 10^3) \times (32.7 \times 10^3) \times (1 \times 10^6)}{(45 \times 10^3) \times (1 \times 10^6) + (32.7 \times 10^3) \times (45 \times 10^3) - (32.7 \times 10^3) \times (65 \times 10^3)} \tag{2.3}$$

$$R_{\text{FREQ}} = \frac{2.1255 \times 10^{15}}{4.5 \times 10^{10} + 1.4715 \times 10^9 - 2.1255 \times 10^9} = \frac{2.1255 \times 10^{15}}{4.4346 \times 10^{10}} \tag{2.4}$$

$$\boxed{R_{\text{FREQ}} = 4.792 \times 10^4\ \Omega = 47.92\ \text{k}\Omega} \tag{2.5}$$

2.3.2 Minimum Inductor value

$$D \;=\; 1 - \frac{\sqrt{2}\,V_{\text{in}}}{V_o} \tag{2.6}$$

$$\text{Given: } V_{\text{in}} = 190\ \text{V},\ V_o = 390\ \text{V} \tag{2.7}$$

$$D \;=\; 1 - \frac{\sqrt{2} \times 190}{390} \;=\; 1 - \frac{268.7005768}{390} \;=\; 1 - 0.68897584 \;=\; 0.31102416 \tag{2.8}$$

$$I_{\text{pk}} \;=\; \frac{\sqrt{2}\,P_o}{\eta\,V_{\text{in}}} \tag{2.9}$$

$$\text{Given: } P_o = 3500\ \text{W},\ \eta = 0.98,\ V_{\text{in}} = 190\ \text{V} \tag{2.10}$$

$$I_{\text{pk}} \;=\; \frac{\sqrt{2} \times 3500}{0.98 \times 190} \;=\; \frac{4949.747467}{186.2} \;\approx\; 26.58296\ \text{A} \tag{2.11}$$

$$L_{\text{min}} \;=\; \frac{\sqrt{2}\,V_{\text{in}}\,D \times 10^6}{I_{\text{pk}} \times (\text{ripple fraction}) \times f_{\text{sw}}} \tag{2.12}$$

$$\text{Given: ripple} = 0.40,\ f_{\text{sw}} = 45 \times 10^3\ \text{Hz} \tag{2.13}$$

$$\text{Numerator} = \sqrt{2} \times 190 \times 0.31102416 \times 10^6 \;=\; 83\,572\,371 \tag{2.14}$$

$$\text{Denominator} = 26.58296 \times 0.40 \times 45 \times 10^3 \;=\; 478\,493.28 \tag{2.15}$$

$$L_{\text{min}} \;=\; \frac{83\,572\,371}{478\,493.28} \;\approx\; 174.65\ \mu\text{H} \;=\; 0.17465\ \text{mH} \tag{2.16}$$

$$\boxed{L_{\text{min}} \approx 174.7\ \mu\text{H}} \tag{2.17}$$

2.3.3 Resistance for V_{REF}

$$R_{\text{FB2}} = \frac{V_{\text{REF}} \times R_{\text{FB1}}}{V_{\text{OUT}} - V_{\text{REF}}} \tag{2.18}$$

$$R_{\text{FB2}} = \frac{5\ \text{V} \times 1\ \text{M}\Omega}{390\ \text{V} - 5\ \text{V}} = \frac{5 \times 10^6}{385} = 12.987 \times 10^3\ \Omega \approx 13.04\ \text{k}\Omega \tag{2.19}$$

2.3.4 R_{SENSE} Calculation

$$R_{\text{SENSE}} = \frac{V_{\text{SOC(min)}}}{I_{L,\text{PEAK(max)}} \times 1.1} \tag{2.20}$$

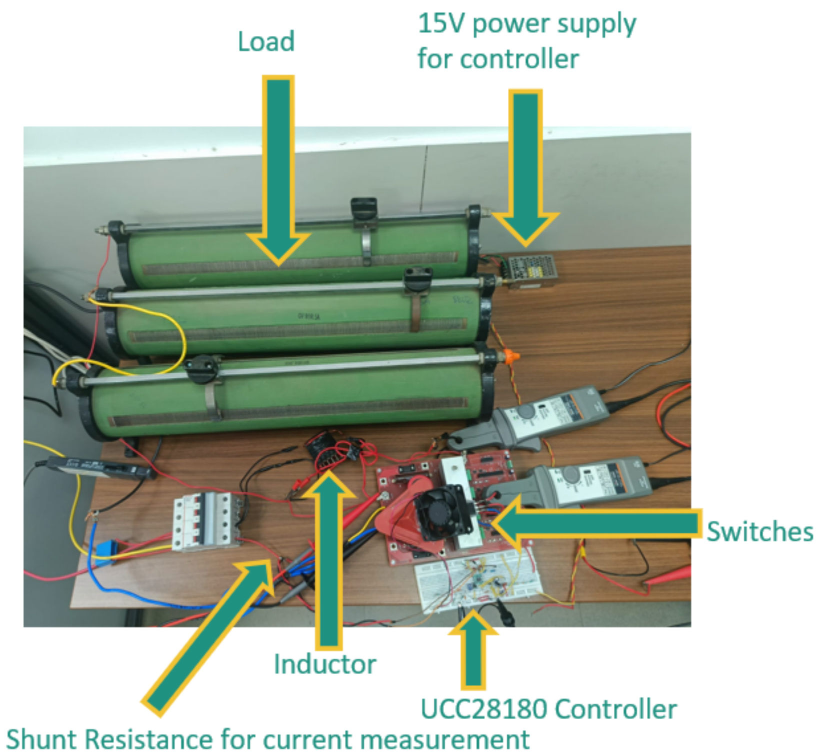
$$R_{\text{SENSE}} = \frac{0.259\ \text{V}}{7.7\ \text{A} \times 1.1} = \frac{0.259}{8.47} = 0.0306\ \Omega \approx 0.032\ \Omega \tag{2.21}$$

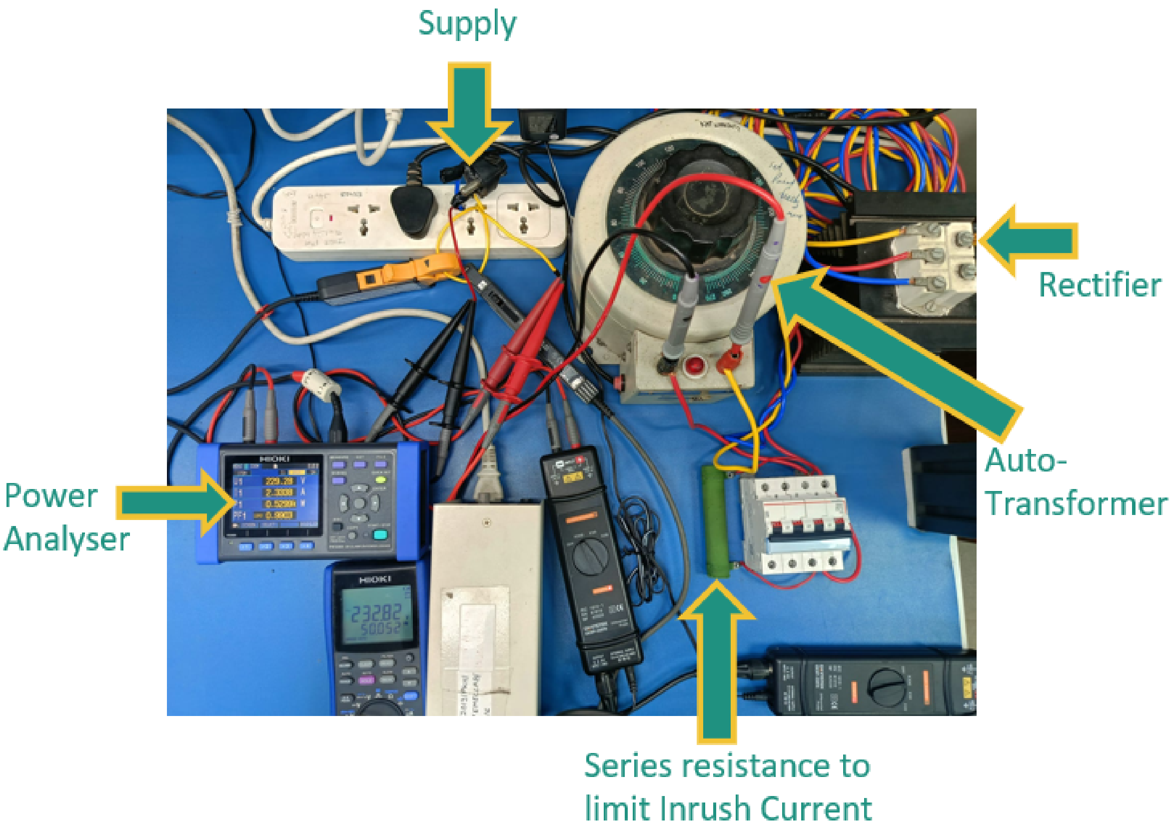
Chapter 3

Hardware Setup and Experimental Results

3.1 Experimental Setup

The converter has been developed to operate from a single-phase AC input of 230.000 V and deliver a regulated DC output of approximately 400.000 V under various load conditions. The hardware consists of a single-phase full-bridge rectifier, boost inductor, power MOSFET with isolated gate-driver circuit, ultra-fast recovery diode, and an output capacitor for energy storage. Current-mode control—is employed to shape the input current in phase with the input voltage, thereby achieving high power factor and low harmonic distortion. All measurements were performed using an isolated laboratory setup for safety and accuracy.





The setup includes:

- AC input source,
- Full-bridge rectifier,
- Boost converter stage (inductor, switch, diode, and output capacitor),
- Gate driver and control circuitry,
- Power analyzer, digital oscilloscope, and probes for waveform capture.

Each subcircuit was individually verified before full integration. During testing, the following quantities were recorded:

1. Input voltage and current waveforms (for phase verification),
2. Inductor current and switch voltage (to observe CCM behavior),
3. Output voltage regulation and ripple,
4. Input/output power for efficiency and power factor calculations.

3.2 Failures

Table 3.1: Failures Observed in Hardware

Sr. No.	Component Failure	Possible Reason (Assumed)
1	Fuse	Ignored.
2	Fuse + D2 + Sw (MOSFET)	It was initially assumed that the gate terminal was not properly pulled down, which might have caused a false triggering of the MOSFET gate (though this was later found to be untrue).
3	Fuse + D2 + Sw (IGBT)	The diode D2 (3A rated) failed due to short-circuiting at its terminal, resulting in the DC link getting short-circuited through the switch.
4	Fuse + D1 + Sw (IGBT)	D1 experienced short-circuit failure caused by multiple inrush current spikes from the source, leading to a DC link short-circuit path through the inductor and switch.
5	Fuse + Rsh + Sw (SiC)	Failure occurred due to possible inductor saturation or overvoltage stress on the switch. The issue was mitigated by tuning the gate resistor (R_{gon}).
6	Fuse + Sw (MOSFET)	Thermal breakdown of the switch occurred after approximately 45 minutes of operation at 650.000 W and 65.000 kHz. The heat spreader was not sufficiently efficient, leading to overheating (thermal issue not observed in earlier tests).

3.3 Observed Waveforms

The captured waveforms confirm that the input current follows the sinusoidal envelope of the input voltage, validating proper PFC operation. Figure **??** illustrates the typical input voltage and current waveforms at rated load. The measured power factor exceeded 0.98, with a Total Harmonic Distortion (THD) below 5%, indicating high-quality input current shaping.

The output voltage remained regulated around 400.000 V, with less than 5% ripple under steady-state conditions. The converter efficiency improved significantly under CCM due to reduced conduction losses and smooth current flow.

During prototype testing, a few failures such as MOSFET overheating and inductor core saturation were initially observed. These issues were mitigated by optimizing component ratings, improving gate drive timing, and ensuring sufficient thermal dissipation.Three operating conditions are given here.

Mode 1

V_{in} = 100 V_{AC} V_{out} = 200 V_{DC} P_{in} = 252 W P_{out} = 211.49 W η = 83.926% PF = 0.9955

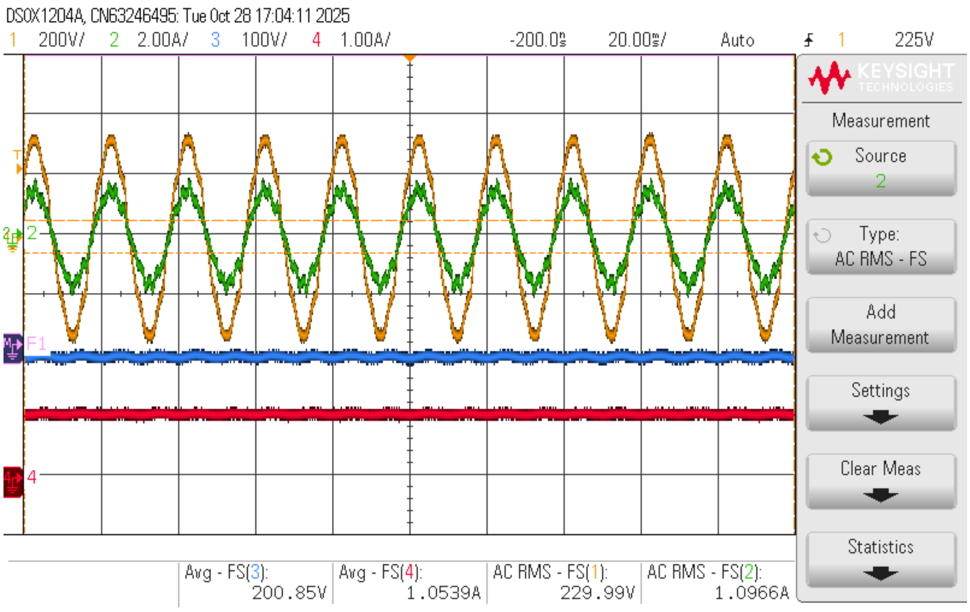


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Figure 3.1: Input/Output waveforms

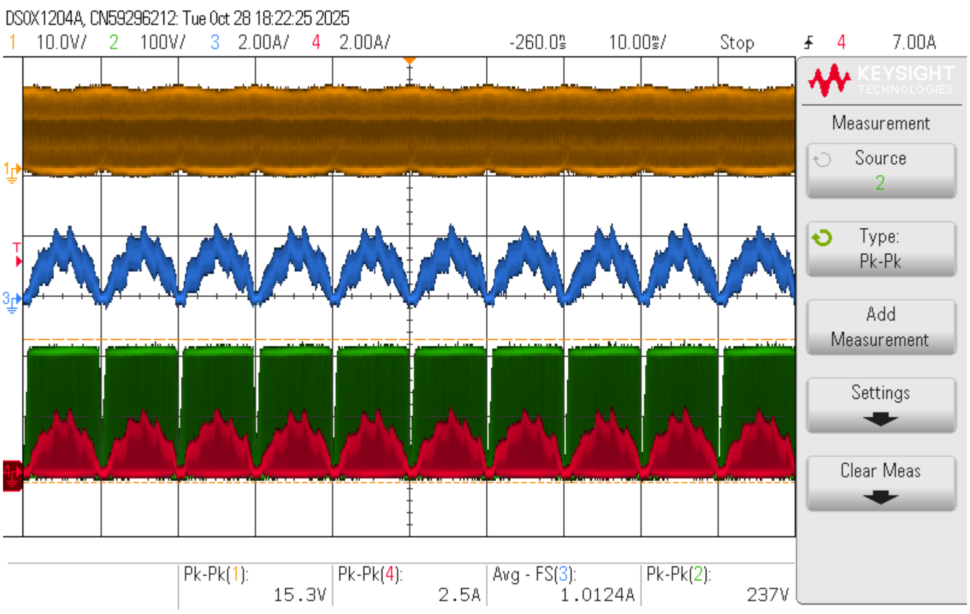

Figure 3.2: Switching Pulses and Current waveforms

Mode 2

$V_{\text{in}} = 230\ \text{V}_{\text{AC}}$ $\quad V_{\text{out}} = 400\ \text{V}_{\text{DC}}$ $\quad P_{\text{in}} = 539.63\ \text{W}$ $\quad P_{\text{out}} = 482.5\ \text{W}$ $\quad \eta = 89.4\%$ $\quad \text{PF} = 0.9903$

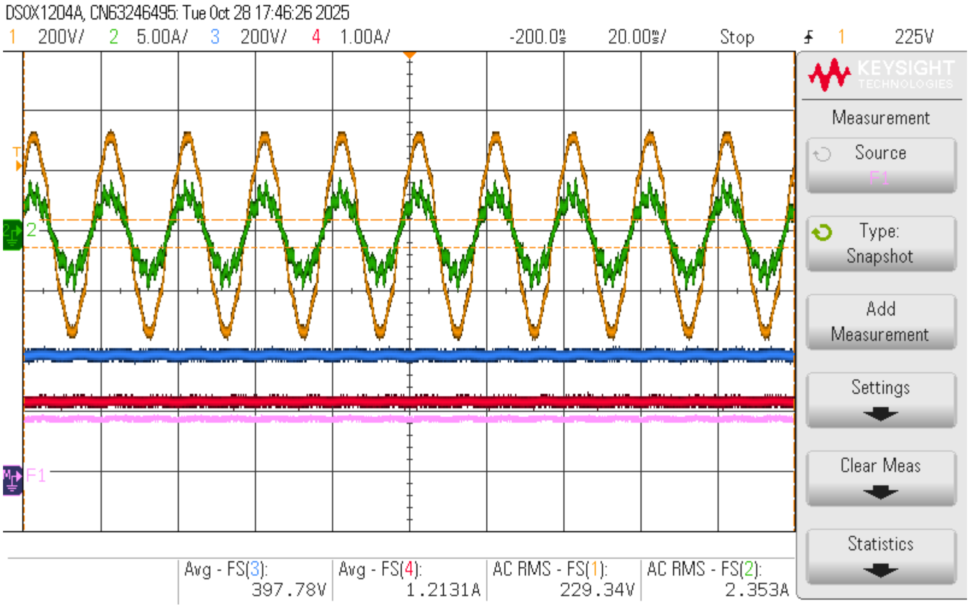

Figure 3.3: Input/Output waveforms

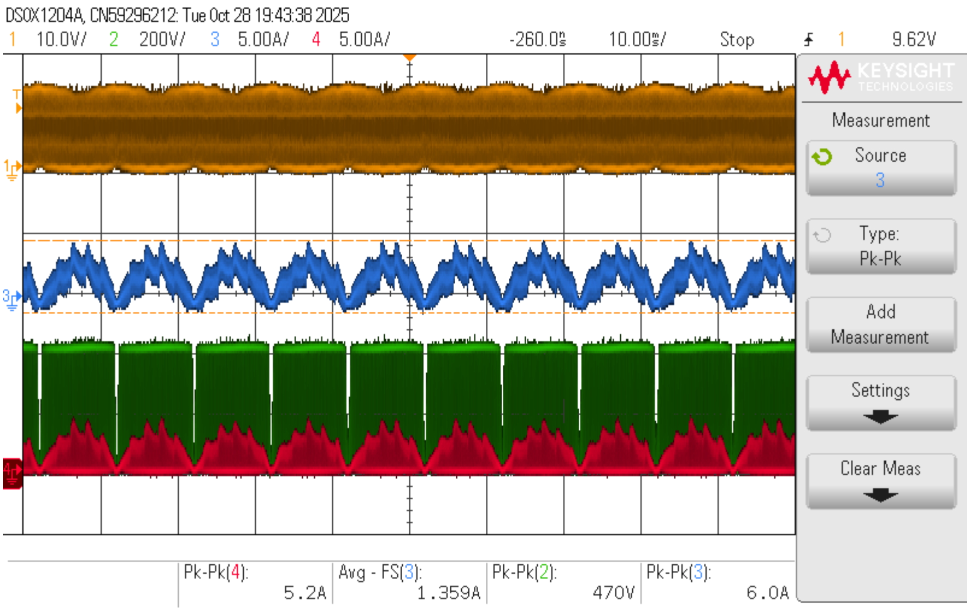

Figure 3.4: Switching Pulses and Current waveforms

Mode 3

$V_{\text{in}} = 230\ \text{V}_{\text{AC}}$ $V_{\text{out}} = 400\ \text{V}_{\text{DC}}$ $P_{\text{in}} = 1020$ W $P_{\text{out}} = 927.89$ W $\eta = 90.9\%$ PF = 0.985

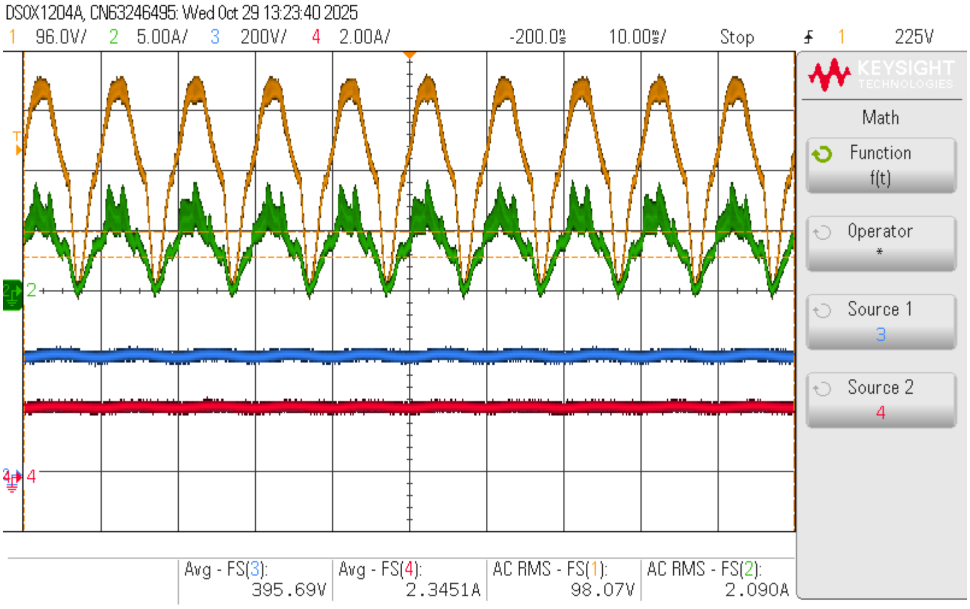

Figure 3.5: Input/Output waveforms

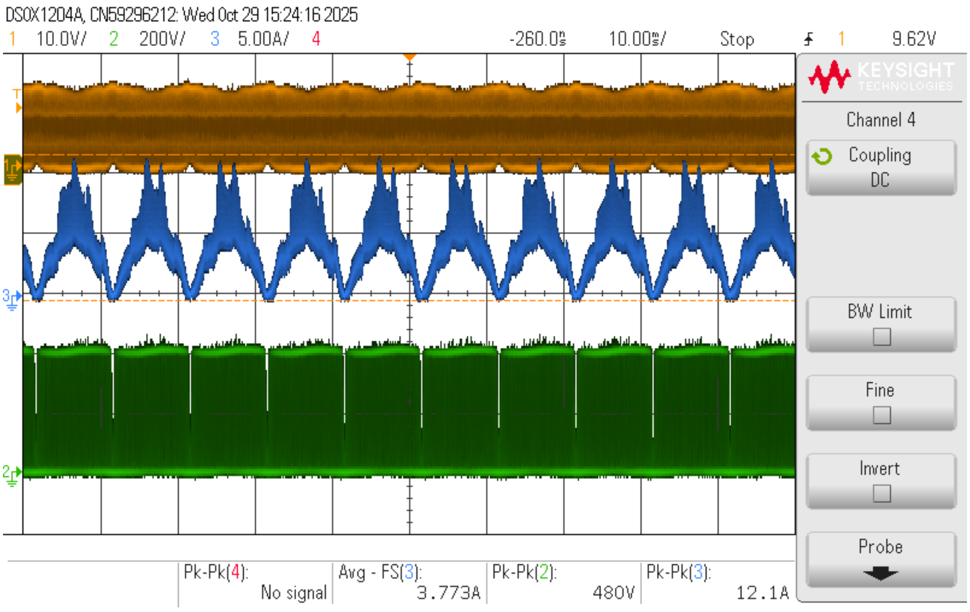

Figure 3.6: Switching Pulses and Current waveforms

3.4 Table of Results

Table 3.2 summarizes the experimental measurements obtained at different load conditions. The comparison between theoretical and practical results confirms that the converter meets the expected performance parameters.

Table 3.2: Measured Results of Boost PFC Converter in CCM Operation

Specs	$V_{\text{in,rms}}$ **(V)**	$V_{\text{o,dc}}$ **(V)**	$I_{\text{in,rms}}$ **(A)**	$I_{\text{in,p-p}}$ **(A)**	I_L **avg (A)**	I_L **rms (A)**	I_L **p-p (A)**	R_{load} **(Ω)**	P_{o} **(W)**	P_{in} **(W)**	**P.F.**	**Efficiency (%)**
100V, 66.67W	50.0	104.7	1.57	4.8	1.3	3.2	3.2	150	73.08	78.23	0.9965	93.42
150V, 100W	74.3	152.4	1.46	5.25	1.46	3.2	3.2	225	103.23	108.21	0.9975	95.40
150V, 175W	74.9	151.0	2.50	8.20	2.50	5.0	5.0	128	178.13	186.89	0.9968	95.31
200V, 200W	101.0	201.0	2.09	6.80	2.09	4.4	4.4	201	201.00	211.83	0.9968	94.90
250V, 250W	125.3	256.0	2.18	7.20	2.18	5.0	5.0	250	262.14	274.13	0.9993	95.63
300V, 300W	150.2	305.0	2.03	7.40	2.03	5.4	5.4	302	308.03	337.68	0.9992	91.22
Inductor changed from 1.5 mH to 1.9 mH												
300V, 300W	151.5	305.5	2.27	7.40	2.27	4.4	4.4	301	310.07	343.63	0.9992	90.23
350V, 350W	175.7	354.0	2.09	7.40	2.09	4.2	4.2	350	358.05	403.67	0.9898	88.70
400V, 400W	201.2	403.5	2.19	7.20	2.19	4.2	4.2	400	407.03	440.10	0.9988	92.49
400V, 450W	232.5	402.0	1.87	6.20	1.87	3.6	3.6	400	404.01	436.40	0.9984	92.58
400V, 500W	231.8	402.0	2.02	7.20	2.02	3.6	3.6	320	505.01	516.09	0.9984	97.85

3.5 Conclusion

The experimental investigation confirms that the Boost PFC converter operating in Continuous Conduction Mode (CCM) achieves near-unity power factor, low current distortion, and high conversion efficiency.

Overall, the converter exhibits excellent steady-state performance and robustness, making it suitable for front-end power supplies in applications such as electric vehicle chargers, industrial SMPS units, and computer power systems.

References

[1]. Texas Instruments. 230-v, 3.5-kw pfc with> 98% efficiency, optimized for bom and size reference design. 2016.

[2]. Texas Instruments. Ucc28180 programmable frequency, continuous conduction mode (ccm), boost power factor correction (pfc) controller, 2016.