Test Report: PMP23338

3.6-kW Single-Phase Totem-Pole Bridgeless PFC Reference Design With E-Meter Functionality

Description

This reference design is a Gallium nitride (GaN) based, 3.6kW, single-phase, continuous conduction mode (CCM) totem-pole bridgeless power factor correction (PFC) converter targeting M-CRPS server power supply. This design includes E-meter functionality with 0.5% accuracy using AMCx306 as current sensing device, eliminating the need for external power metering ICs. An alternative low cost current sensing option using TMCS1133 is also provided in this design. The supply is designed to support a maximum input current of 16-ARMS and peak power of 3.6kW. The power stage is followed by a baby boost converter, which helps to greatly reduce the size of the bulk capacitor. This design can work with either LMG3522EVM-042 or LMG3422EVM-043 GaN EVM. LMG3522R030 and LMG3422R030 are TI 30-mΩ high voltage GaN FET with integrated driver and protections, enable high effciency and high power density. The F28003x C2000™ real-time microcontroller is used for all the advanced controls including re-rush current limit, baby boost operation during AC drop out event, e-metering, and communication between PFC and house-keeping controller. In addition, the F28003x microcontroller has built-in Sigma-Delta filter module to interface with AMC1306 precision current sensing reinforced isolated modulator to achieve industry leading low total harmonic distortion (iTHD) and high measurment accuracy. The PFC operates at a switching frequency of 65kHz and achieves peak efficiency of 98.93%.

Features

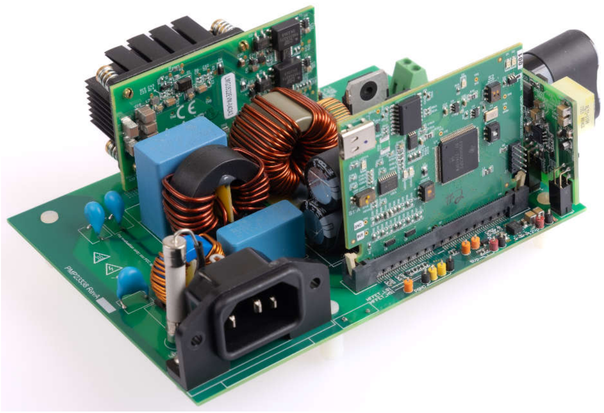
1. Integrated e-metering function with 0.5% accuracy
2. <10% iTHD @ 0-10% load, <5% iTHD @ 10% - 20% load, <3% iTHD @ 20% - 50% load, <2% iTHD @ 50% - 100% load
3. Peak efficiency of 98.93% @ 230Vac
4. Smart re-rush current control when AC comes back from dropout, meet M-CRPS re-rush current specification
5. Include baby boost converter to extend holdup time and allow only 720uF bulk Cap
6. Two current sense options: Isolated Delta-Sigma Modulator (default) or Hall Sensor
7. GaN optimized with driver integration
8. 3.6kW rated power targeting 73.5mm M-CRPS PSU.

1 Applications

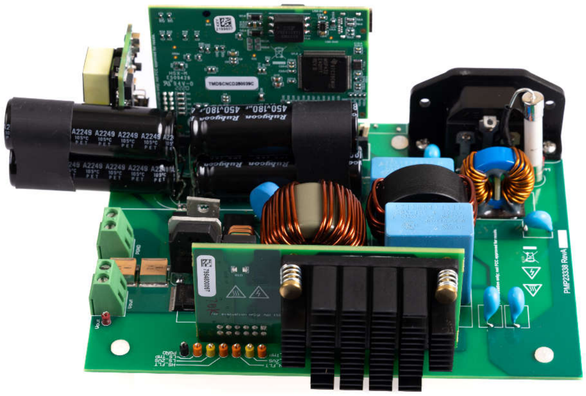
- Rack and server PSU with 48V output
- Server PSU with 12V output
- Merchant telecom rectifiers
- Industrial AC-DC
- Single phase online UPS

Resources

- TMS320F280039C
- LMG3522R030
- AMC1306M05
- TMCS1133
- How to reduce current spikes at AC zero-crossing for totem-pole PFC
- Improve power density with a baby boost converter in a PFC circuit
- Control challenges in a totem-pole PFC
- Increase powr factor by digitally compensating for PFC EMI-capacitor reactive current
- AC cycle skipping inproves PFC light-load efficiency
- Five major trends in power-supply designs for servers



Board Side View



Board Top View

2 System Description

2.1 System Block Diagram

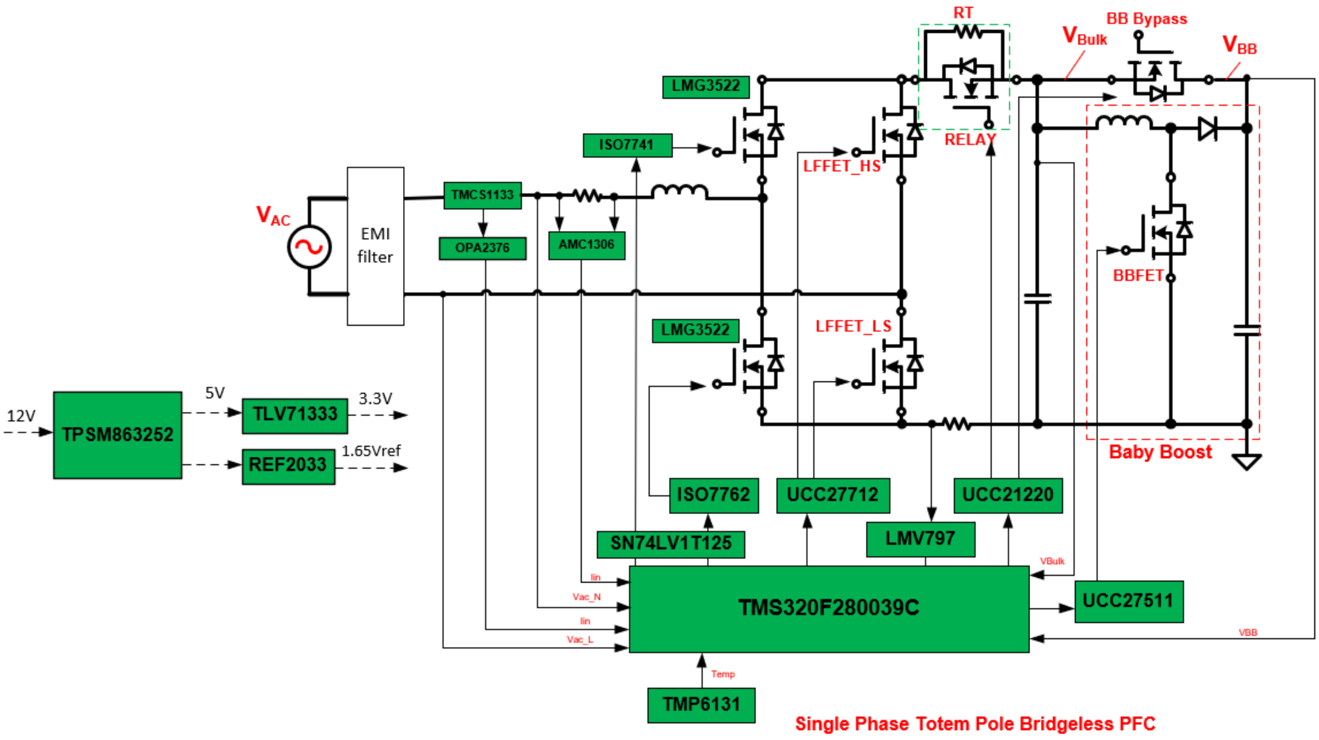


Figure 2-1. PMP23338 Block Diagram

2.2 Key System Specification

Table 2-1. Key System Specifications

Parameter	Specifications	Unit
Input Voltage	90-265	VAC
Line Frequency	50 or 60	Hz
Input Current (Max)	16	A
Output Voltage	385	V
High Line Output Power	3.6	KW

Table 2-1. Key System Specifications (continued)

Parameter	Specifications	Unit
Low Line Output Power	1.8	KW
iTHD (according to M-CRPS iTHD specification Version 1.02 RC2)	<20% @ 0-5% load, <8.5% @ 5%-10% load, <7.5% @ 10% - 20% load, <5% @ 20% - 50% load, <3.5% @ 50% - 100% load	
PF (according to M-CRPS iTHD specification Version 1.02 RC2)	>0.92 @ 10% load, >0.96 @ 20% load, >0.98 @ 50%, >0.99 @ 100% load	
Efficiency (peak)	>98.7	%

2.3 Design Consideration

2.3.1 Boost Inductor Design

Single phase continuous conduction mode (CCM) totem pole bridgeless PFC is selected in this design. As the design is targeting to achieve high power density with inductor height lower than 32mm, the switching frequency is selected at 65kHz so the EMI filter doesn't need to deal with the 1st and 2nd harmonic of the noise generated by PFC switching frequency (the targeted CISPR 32 conduction EMI limitation starts from 150kHz). In order to minimize the inductor dimension, low inductance is selected to allow low inductor winding turns applied. Powder iron core materials have a soft saturation characteristic which is suitable for high power CCM converters with high DC bias current. As the inductor inductance drops when the inductor current increases, core material has to be carefully chosen so the inductor doesn't saturate at heavy or peak loads.

The design target is to have less than 40% inductor current ripple at 3600W full load at 230Vrms input.

Use Equation 1 below:

$$L_{PFC} = \frac{1}{I_{L,ripple}\%} \cdot \frac{V_{IN,RMS}^2}{P_{IN}} \cdot \left(1 - \frac{\sqrt{2} \cdot V_{IN,RMS}}{V_O}\right) \cdot \frac{1}{F_{SW}} \tag{1}$$

The PFC inductor inductance can be calculated to be 92.21μH. That is, inductor inductance needs to be higher than 92.21μH at maximum inductor current. Use Equation 2 below.

$$I_{L,max} = \frac{\sqrt{2} \cdot P_{IN}}{V_{IN,RMS}} \cdot \left(1 + \frac{I_{L,ripple}\%}{2}\right) \tag{2}$$

Maximum inductor current can be calculated to be 26.64A.

Toroid inductors with Kool Mμ Max (Mag-inc P/N: 0079894A7HT19) and high flux cores (Mag-inc P/N: C058894A2HT19) were selected and wounded with the same 44 turns to get around 240μH inductance at 0A current also meet the 33mm height requirement. The two inductors were then applied to the PFC boost stage one by one to test their inductance with current applied. Figure 2-2 shows that the inductor inductance using High Flux core is able to achieve our inductance target with less number of turns over the inductor using Kool Mμ Max core. Therefore, inductor with high flux core is selected in this design.

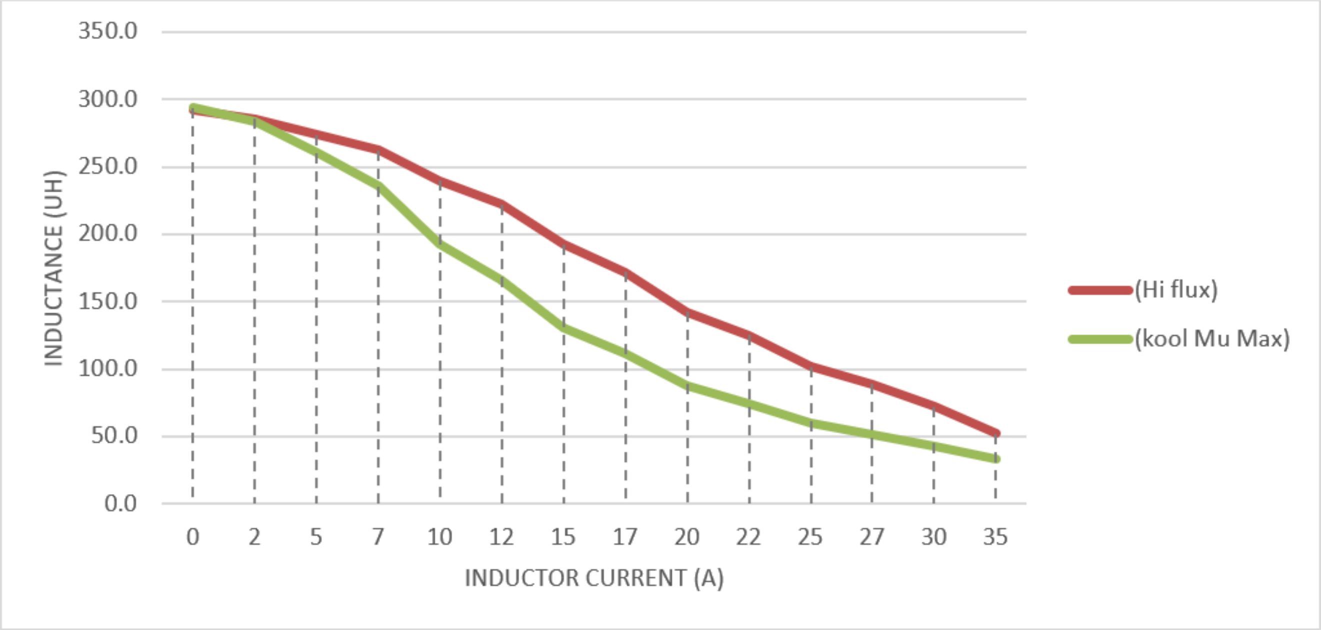
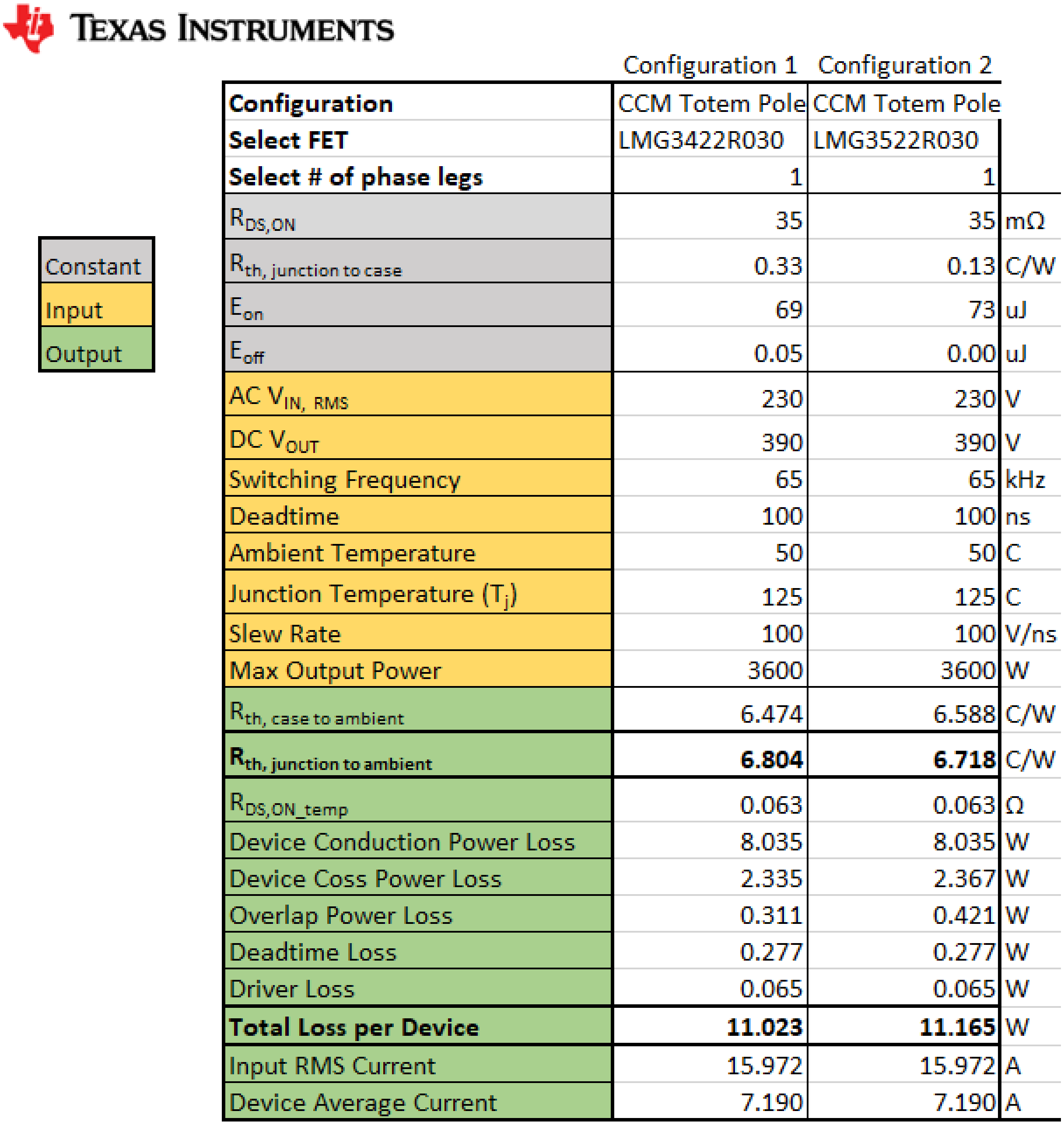


Figure 2-2. Inductance Versus Current

2.3.2 High Frequency Power Switch Selection

As wide-bandgap devices are the necessary high frequency power switches for a CCM totem-pole bridgeless PFC Boost rectifier, TI "GaN CCM Totem Pole PFC Power Loss Calculation Excel Sheet" is used to estimate the loss on the power switches and select which GaN device is applicable. A screen shot of the calculation results is shown in Figure 2-3. 30mΩ GaN devices (LMG3522R030 or LMG3422R030) are eventually selected for this design.



Constant	⬜
Input	🟨
Output	🟩

	Configuration 1	Configuration 2	
Configuration	CCM Totem Pole	CCM Totem Pole	
Select FET	LMG3422R030	LMG3522R030	
Select # of phase legs	1	1	
$R_{DS,ON}$	35	35	mΩ
$R_{th,\ junction\ to\ case}$	0.33	0.13	C/W
E_{on}	69	73	uJ
E_{off}	0.05	0.00	uJ
AC $V_{IN,\ RMS}$	230	230	V
DC V_{OUT}	390	390	V
Switching Frequency	65	65	kHz
Deadtime	100	100	ns
Ambient Temperature	50	50	C
Junction Temperature (T_j)	125	125	C
Slew Rate	100	100	V/ns
Max Output Power	3600	3600	W
$R_{th,\ case\ to\ ambient}$	6.474	6.588	C/W
$R_{th,\ junction\ to\ ambient}$	**6.804**	**6.718**	C/W
R_{DS,ON_temp}	0.063	0.063	Ω
Device Conduction Power Loss	8.035	8.035	W
Device Coss Power Loss	2.335	2.367	W
Overlap Power Loss	0.311	0.421	W
Deadtime Loss	0.277	0.277	W
Driver Loss	0.065	0.065	W
Total Loss per Device	**11.023**	**11.165**	W
Input RMS Current	15.972	15.972	A
Device Average Current	7.190	7.190	A

Figure 2-3. GaN FET Loss Calculation for CCM Totem Pole Bridgeless PFC

2.3.3 Input AC Voltage Sensing

The line and the neutral voltages are sensed by resistor divider to the ground of the board as shown in Figure 2-4. The two readings are subtracted on the controller to get the Vac sensing.

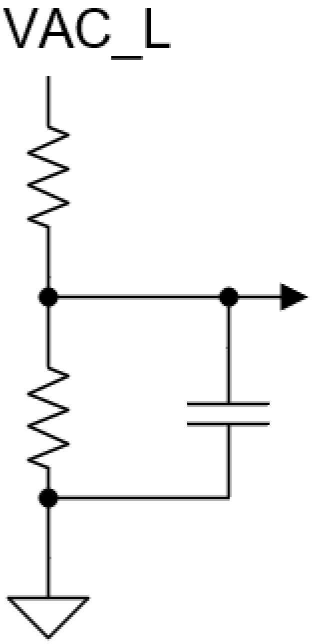


Figure 2-4. Input AC Voltage Sensing

2.3.4 Bulk Voltage Sensing

Similarly the bulk voltage is sensed by a resistor divider network as shown in Figure 2-5.

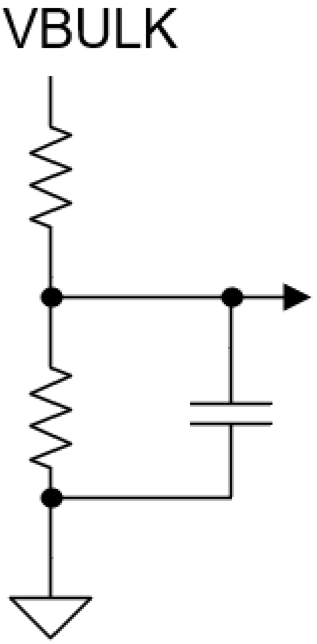


Figure 2-5. Bulk Voltage Sensing

2.3.5 Input Current Sensing

Ther are two current sensors in this design, but only 1 sensor is needed for PFC operation. The code supports both current sensors, seperated by a compiling flag, user can choose which sensor to use by changing the compiling flag and then re-download the code.

Option 1: Use an isolated Delta-Sigma modulator AMC1306 to sense input current (Figure 2-6). This is the deafult configuration in the code. The output of AMC1306 is a 1-bit stream, as shown in Figure 2-7. This 1-bit stream is sent to C2000 and decoded by a built-in delta-sigma digital filter. Two delta-sigma digital filters are used, one is configured with high speed but relatively low resolution for PFC current loop control, the other is configured with high resolution but relatively low speed for e-metering (Figure 2-8). For details of AMC1306 and E-meter, please refer to [2].

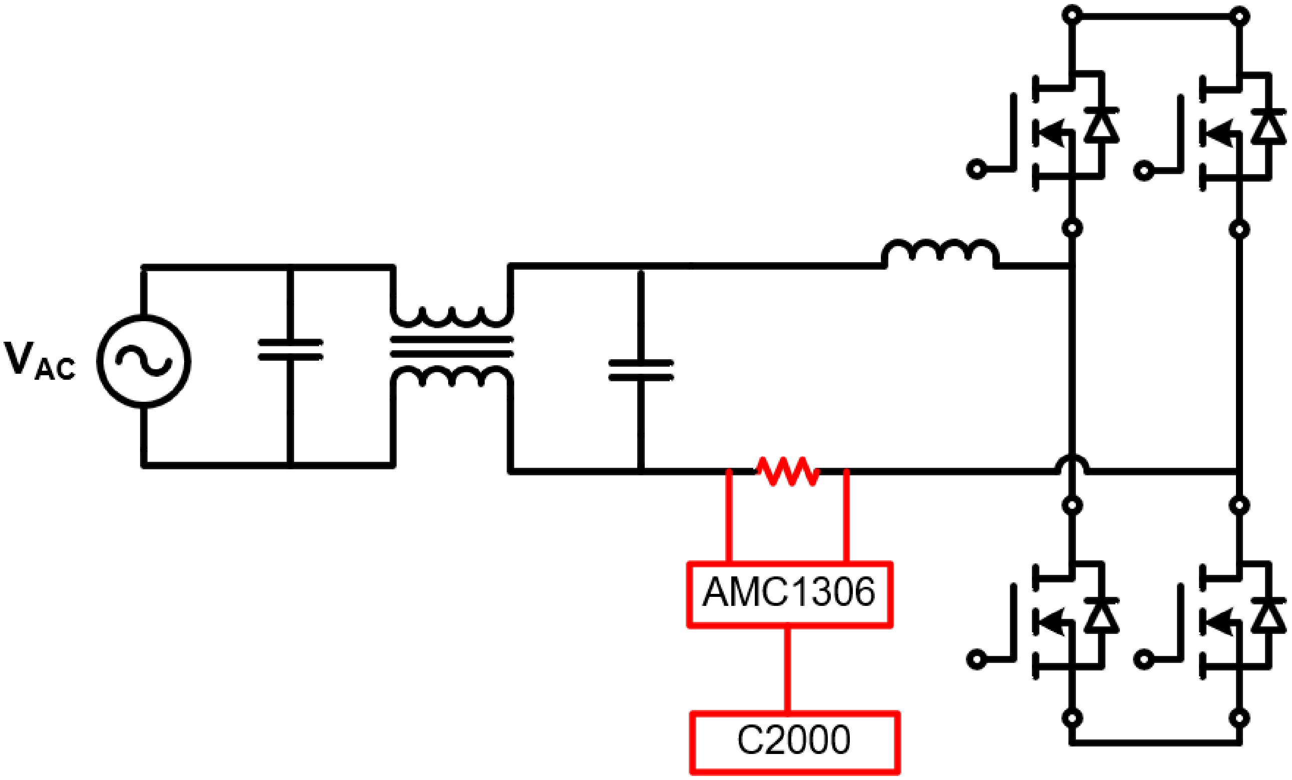


Figure 2-6. Use AMC1306 for Current Sensing

Figure 2-7. AMC1306 Output

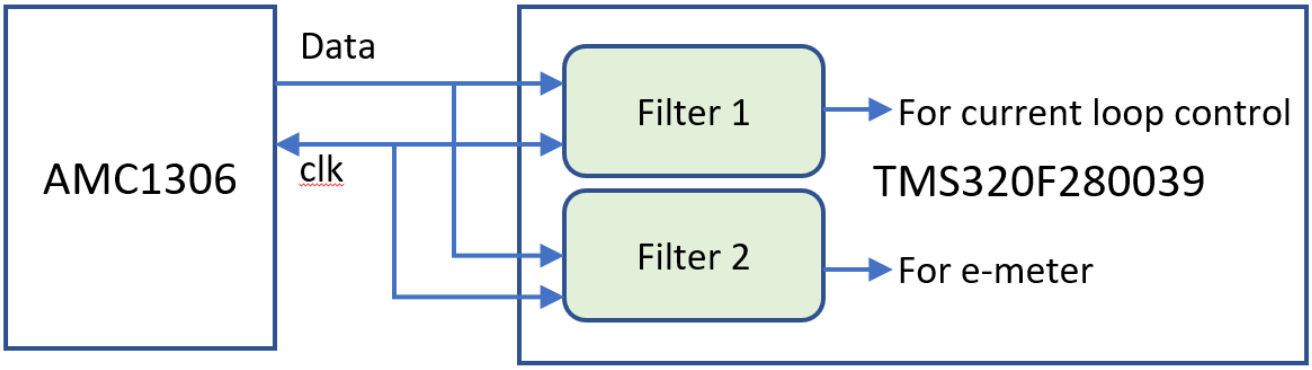


Figure 2-8. Delta-Sigma Filter Configuration

Option 2: Use a hall effect sensor TMCS1133 to sense input current. This is a conventional current sense method. The output of the hall sensor is amplified by a op-amp circuit (Figure 2-9). With sine wave AC input, the output of hall sensor is a sine wave with a DC offset. This signal is measured by C2000, then substract the DC offset to get the real AC input current signal.

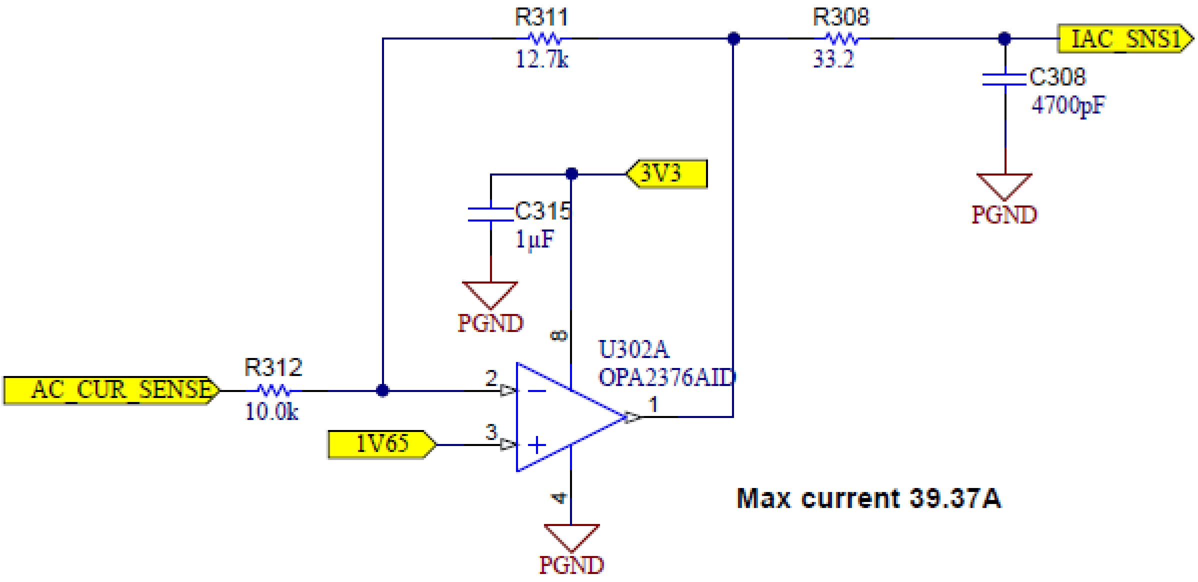


Figure 2-9. Current sense amplifier

2.3.6 Baby Boost Design

To maintain holdup time and reduce bulk capacitance, a baby boost converter is added between the PFC and DC/DC as shown in the Figure 2-1. The baby boost converter is a compact boost converter that only operates during AC dropout events. During normal operation, the baby boost converter is off and bypassed by a MOSFET. When AC line dropout occurs, the Bypass FET turns off, baby boost converter turns on to ensure VBB maintains above the UVLO level for the isolated DC/DC converter. In order to minimize the magnetic dimension, the switching frequency of baby boost is set at 500KHz.

2.3.7 Relay

A MOSFET, as shown in Figure 2-1, is used as a solid-state relay (SSR) in this design. The SSR provides faster response time, wider operational temperature range, higher reliability than the traditional mechanical relay. Moreover, M-CRPS requires input current (re-rush current) must be limited when the input voltage returns after an input brown out / black out event for a few ms. Due to the fast response time, the SSR is controlled to do a rapid on/off operation to limit the re-rush currrent. Details of re-rush control can be found in [1][2].

2.3.8 Protection

2.3.8.1 Over Voltage Protection

Vbus voltage is measured by ADC, firmware turns off PFC if Vbus exceeds 450V.

2.3.8.2 Over Current Protection

Over current protection is achieved through on-chip comparator. It can be configured as shut down and latch (default), or cycle-by-cycle current limit. User can choose which protection to be used by changing the compiling flag and then re-download the code.

3 Power Up

3.1 Required Equipment

- AC Source: 300V, 20A
- Electronic load
- Digital Power Meter
- Isolated voltage probes
- Current probe

3.2 Considerations

1. This PFC needs to be used together with the PMP20306 isolated bias supply reference design and LMG3522EVM-042/LMG3422EVM-043 reference design.
2. Due to the totem-pole topology, the PFC ground (PGND) is floating. This can lead to common-mode current issues with improper test equipment setups. Use differential voltage probes when measuring signals.

3.3 Start-Up Sequence

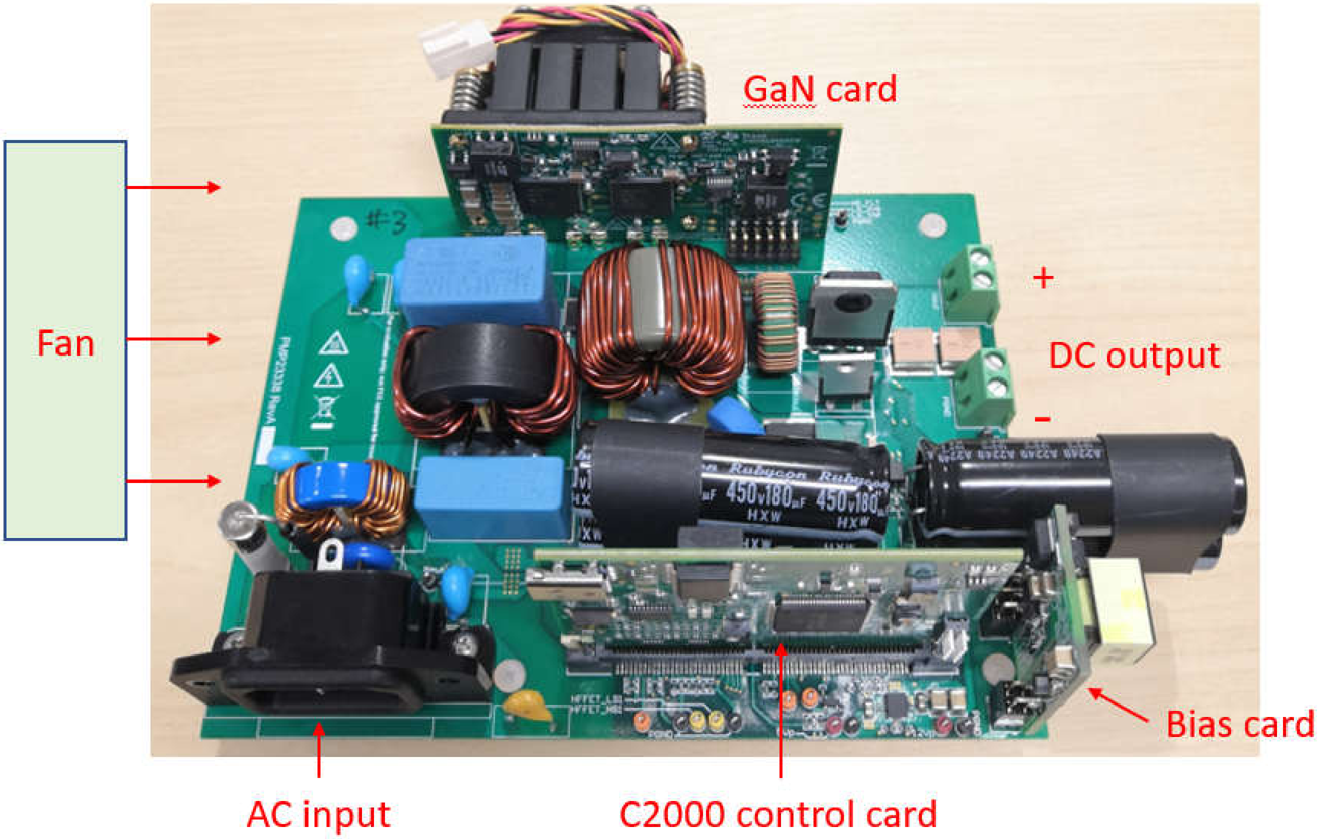


Figure 3-1. Test setup

Start-up sequence:

1. Check GaN card, C2000 control card and Bias card are plugged in correctly and tightly
2. Use a fan for cooling during test
3. Connect a high voltage load to DC output, set load to 0.1A
4. Connect AC source to AC input
5. Use current probe to monitor AC input current, use voltage meter to measure DC output voltage
6. Set AC output at 115V/60Hz, turn on AC, you see DC output voltage is regulated at about 385V
7. Graduate increase load. Full load: 1800W@115VAC, 3600W@230VAC

4 Testing Results

4.1 Start-Up Waveform

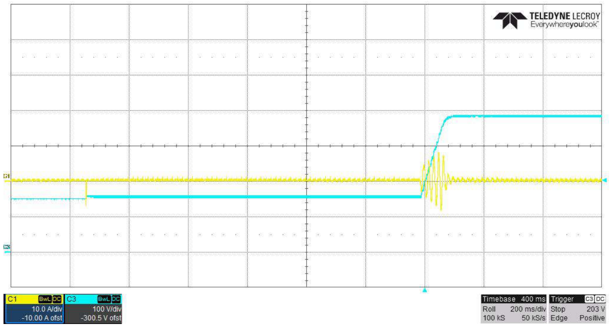


Figure 4-1. PFC starts up at 115 VAC, no load

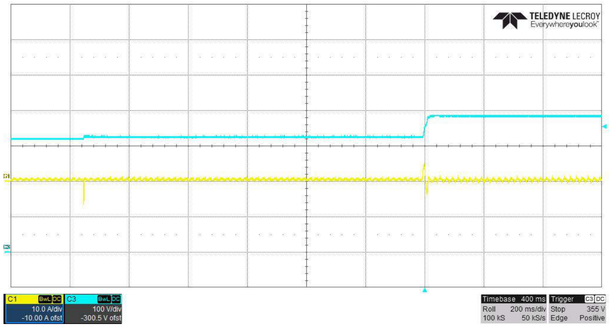


Figure 4-2. PFC starts up at 230 VAC, no load

Note

Blue: Vout, Yellow: Iin

4.2 THD Performance

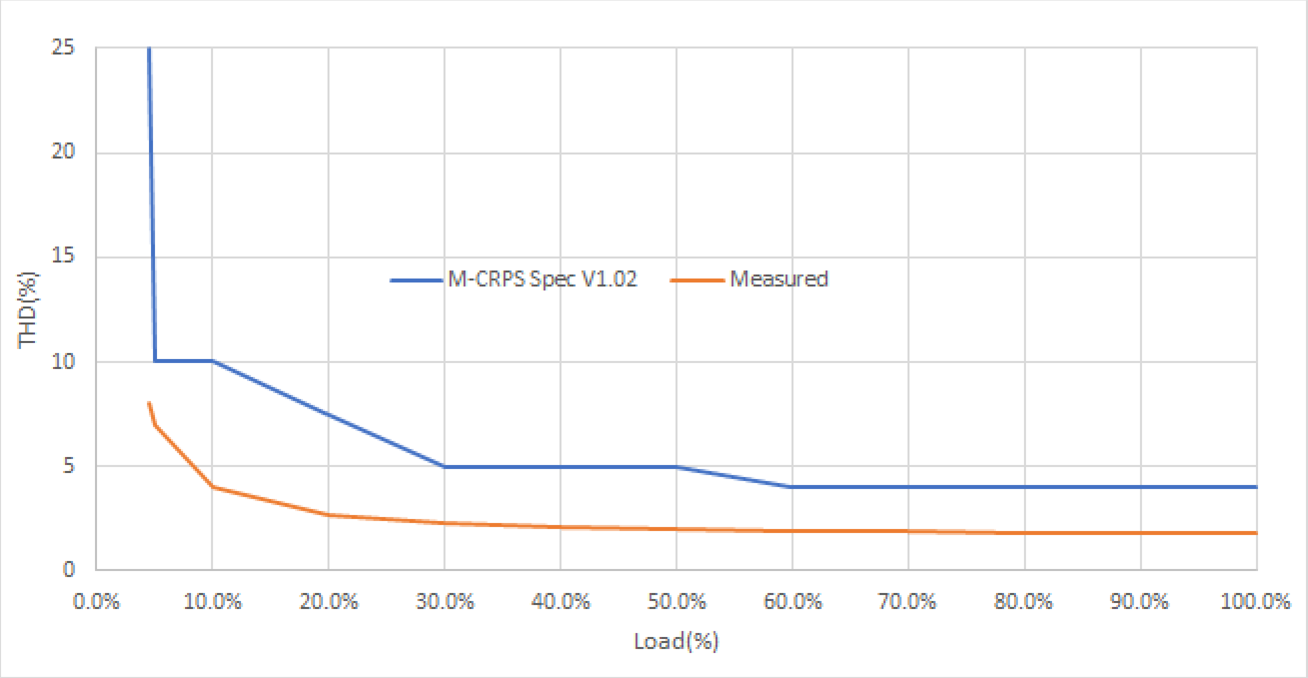


Figure 4-3. THD Graph at 120 VAC Input

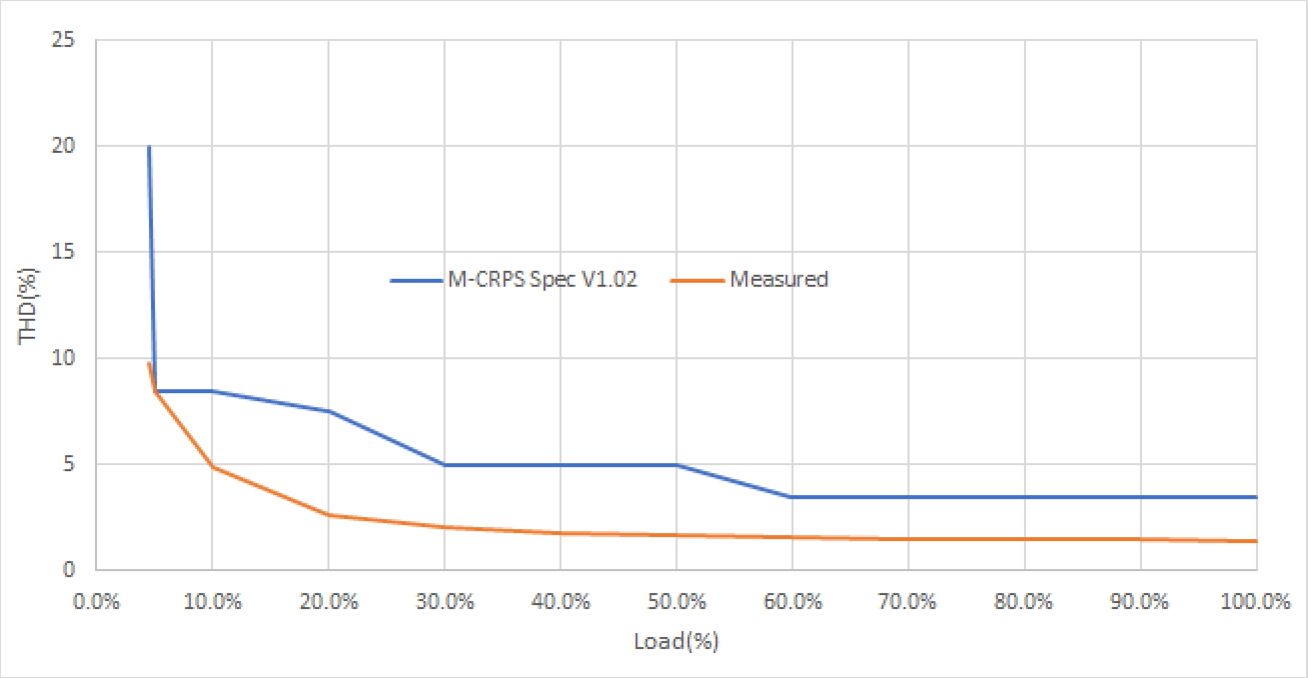


Figure 4-4. THD Graph at 240 VAC Input

4.3 Power Factor

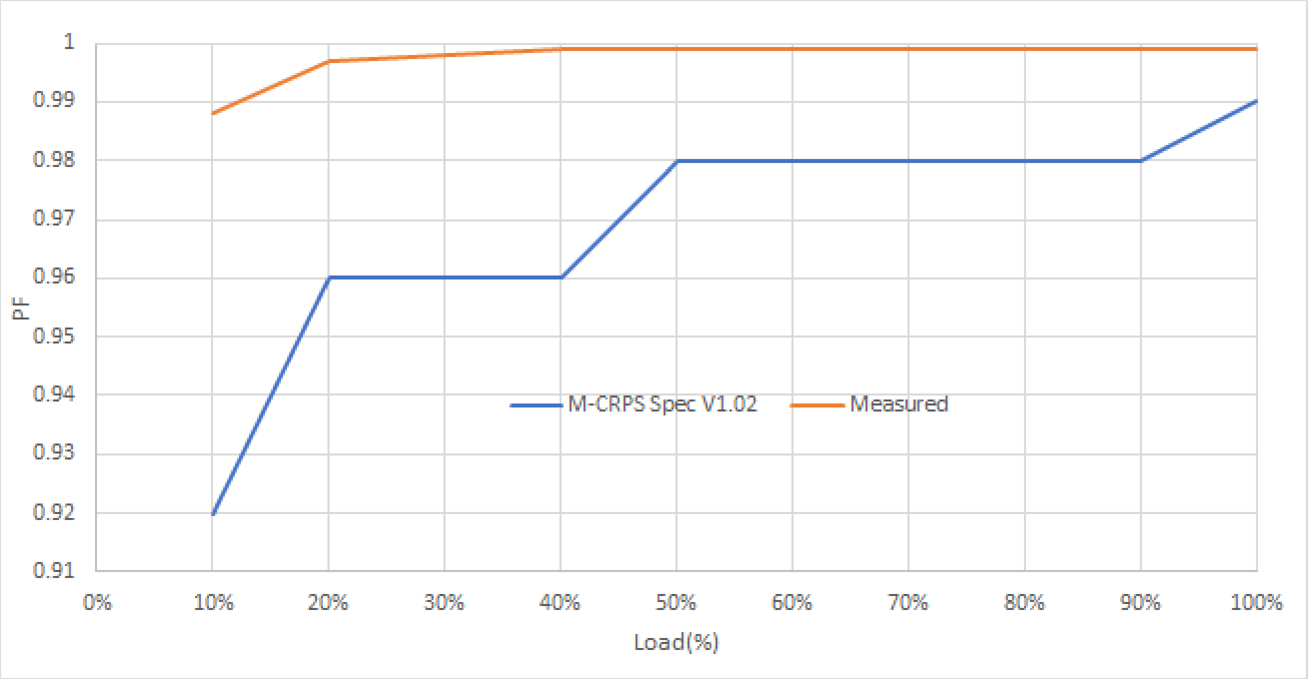


Figure 4-5. Power Factor at 120 VAC input

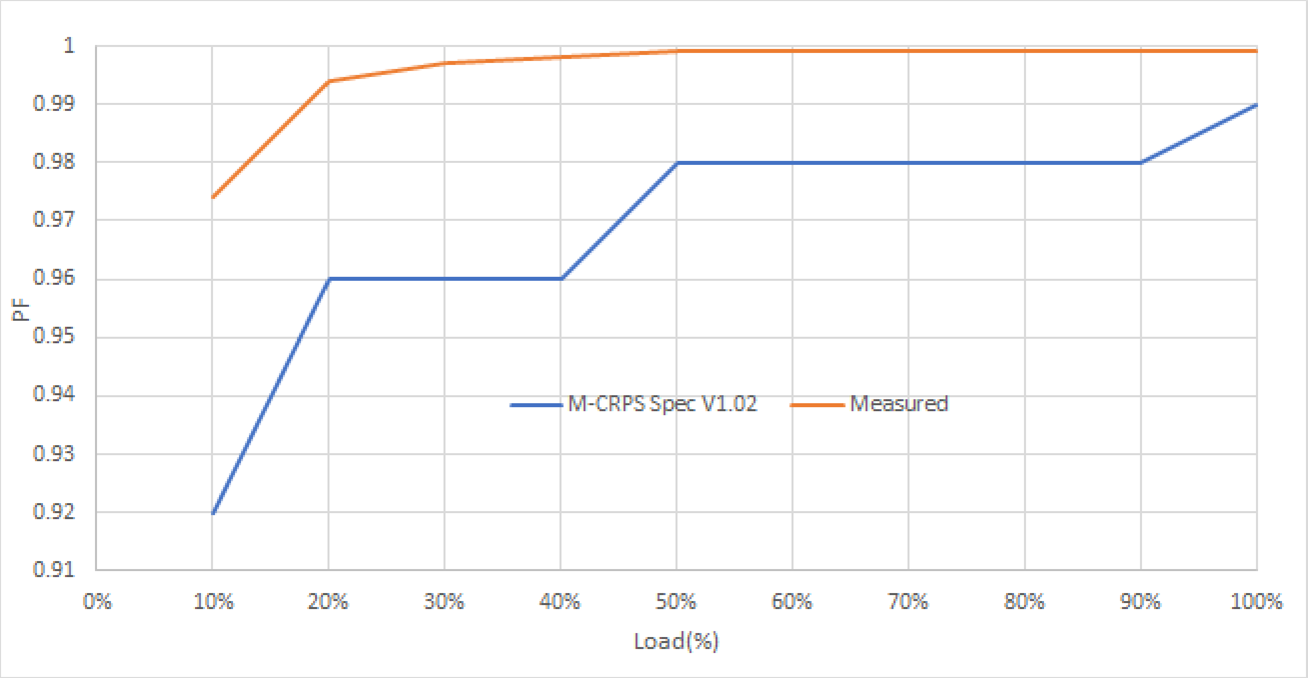


Figure 4-6. Power Factor at 240 VAC Input

4.4 Efficiency

4.4.1 Efficiency Graph

Conditions

- Switching Frequency: 65kHz
- GaN Slew Rate: 100V/ns
- Output: 385V
- Power analyzer: WT5000
- Relay and BB bypass FETs shorted
- Auxiliary supply not included

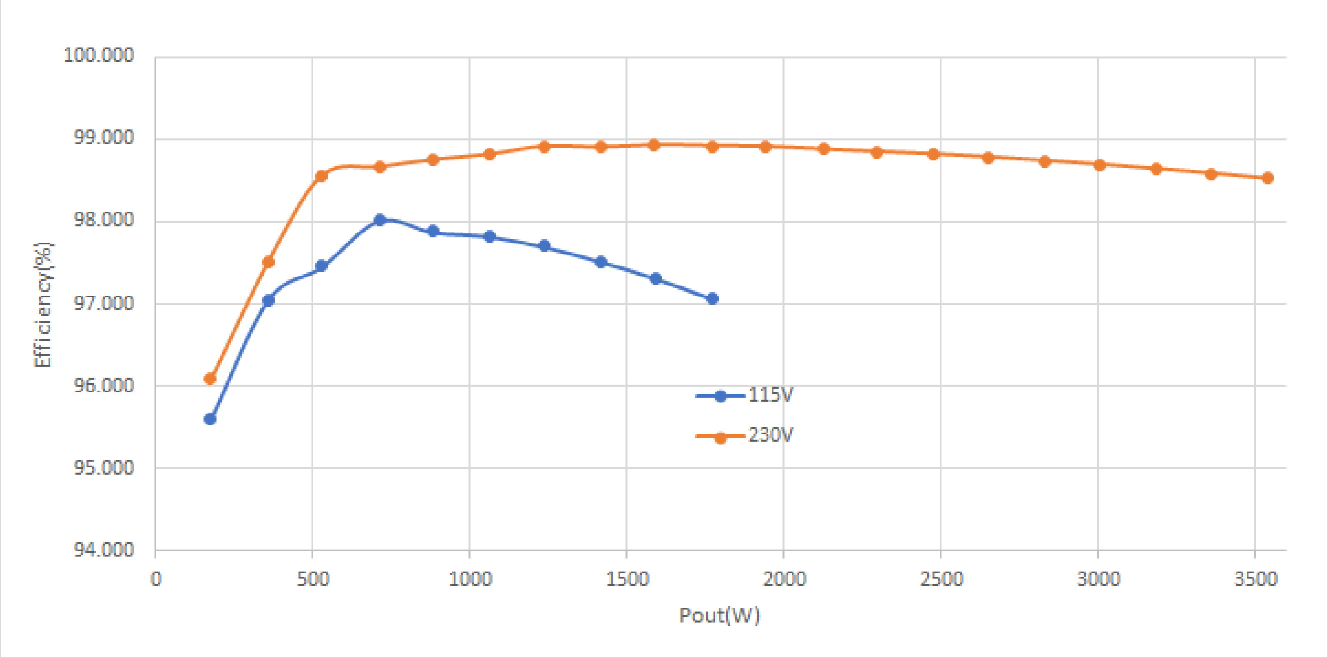


Figure 4-7. Efficiency Graph

4.4.2 Efficiency Data

Table 4-1. Efficiency data at 115VAC/60 HZ

Pin(W)	Pout(W)	efficiency(%)
183.83	175.75	95.605
368.66	357.8	97.054
542.96	529.16	97.458
725.68	711.29	98.017
901.78	882.65	97.879
1088.3	1064.62	97.824
1265.07	1236	97.702
1453.69	1417.66	97.521
1632.77	1589.05	97.322
1825.01	1771.55	97.07

Table 4-2. Efficiency data at 230 VAC/50 HZ

Pin(W)	Pout(W)	efficiency(%)
183.31	176.13	96.083
367.18	358.03	97.508
537.1	529.33	98.553
720.86	711.2	98.660
894.04	882.83	98.746
1077.69	1064.9	98.813
1249.48	1235.84	98.908
1433.54	1417.76	98.899
1606.04	1588.8	98.927
1790.5	1771.11	98.917
1963.73	1942.25	98.906
2148.61	2124.44	98.875
2322.31	2295.51	98.846

Table 4-2. Efficiency data at 230 VAC/50 HZ (continued)

2507.34	2477.63	98.815
2681.28	2648.59	98.781
2867.35	2831.14	98.737
3042.22	3002.47	98.693
3228.67	3184.74	98.639
3404.51	3356.36	98.586
3590.67	3537.67	98.524

4.5 E-meter Performance

Power analyzer used in the test: WT5000

4.5.1 E-meter Graphs

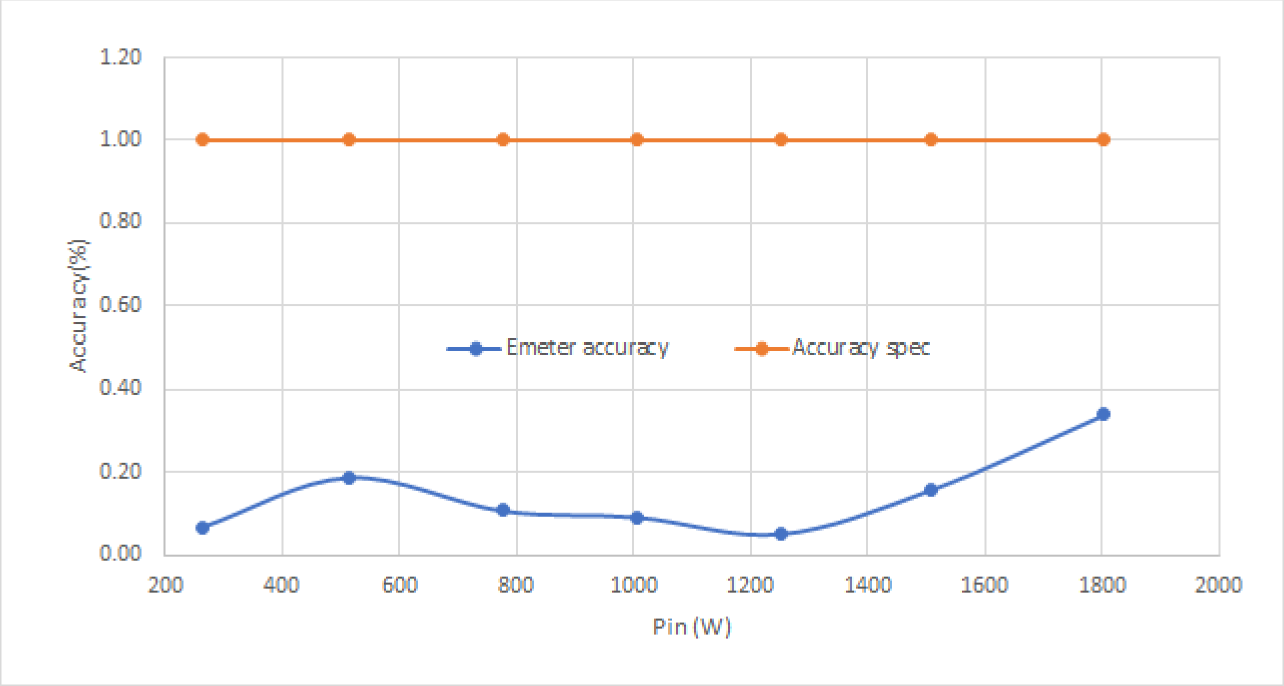


Figure 4-8. E-meter Graph at 115VAC Input

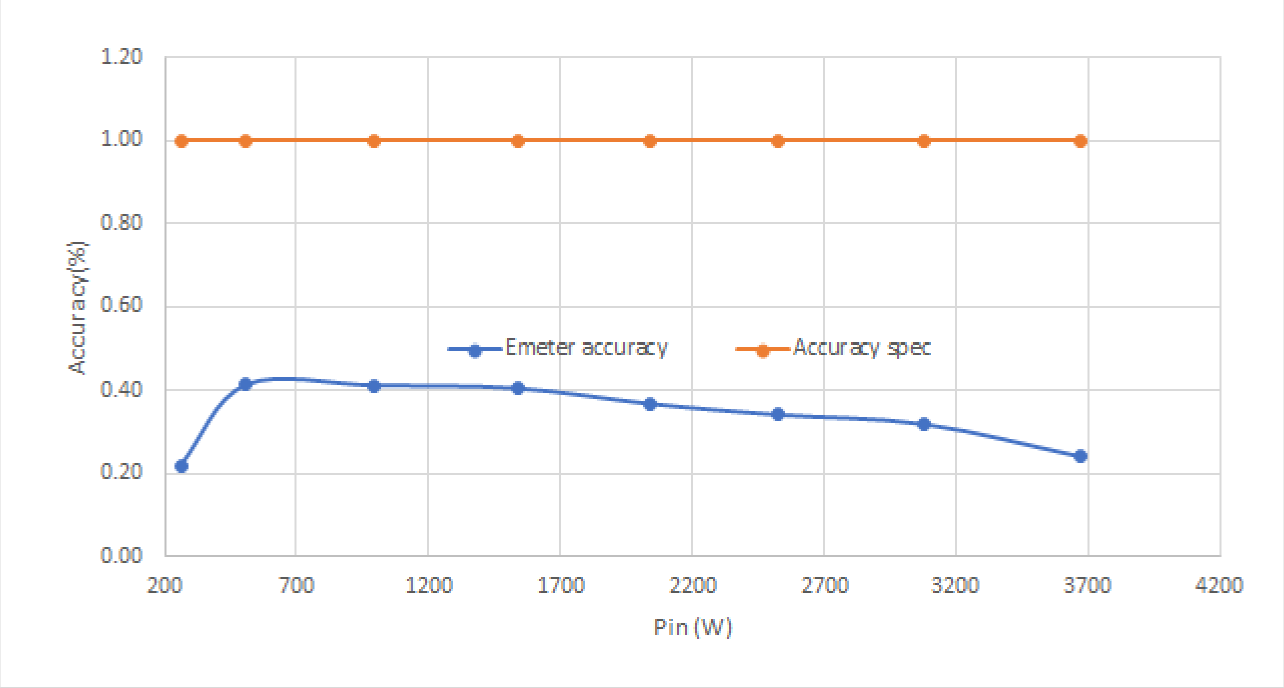


Figure 4-9. E-meter Graph at 230VAC Input

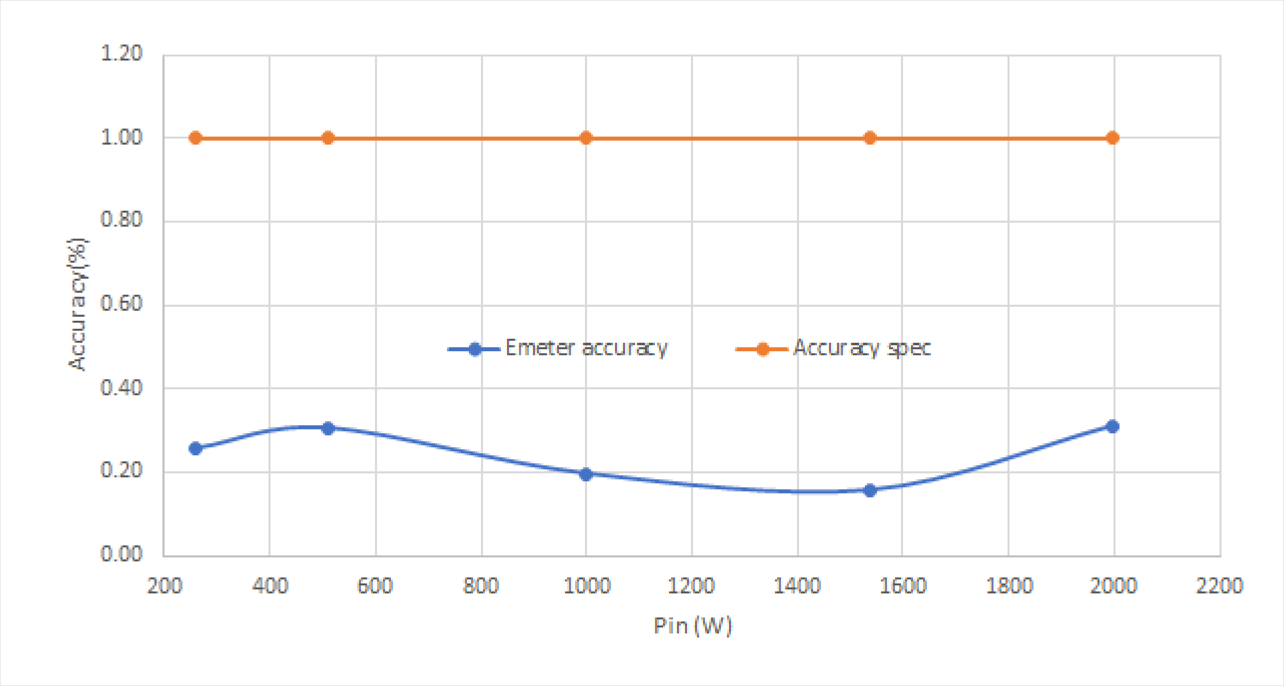


Figure 4-10. E-meter Graph at 240VDC Input

4.5.2 E-meter Data

Table 4-3. E-meter data at AC input

	Pin						
Vin(V)	WT5000	PMP23338	error(W)	abs(error)(W	error spec (W)	error(%)	error spec(%)
115 VAC/60 HZ	34.25	34.35	-0.1	0.1	5		
	55.48	55.57	-0.09	0.09	1.25		
	121.01	121.16	-0.15	0.15	1.25		
	263.63	263.81	-0.18	0.18	2.64	0.07	1
	513.45	514.42	-0.97	0.97	5.13	0.19	1
	776.29	777.13	-0.84	0.84	7.76	0.11	1
	1007.37	1008.3	-0.93	0.93	10.07	0.09	1
	1251.95	1251.3	0.65	0.65	12.52	0.05	1
	1509.4	1507	2.4	2.4	15.09	0.16	1
	1804.1	1797.95	6.15	6.15	18.04	0.34	1
230 VAC/50 HZ	32.520	33.11	-0.59	0.59	5		
	54.11	54.58	-0.47	0.47	1.25		
	118.79	119.55	-0.76	0.76	1.25		
	260.58	261.15	-0.57	0.57	2.61	0.22	1
	509.22	511.33	-2.11	2.11	5.09	0.41	1
	995.93	1000.04	-4.11	4.11	9.96	0.41	1
	1537.87	1544.1	-6.23	6.23	15.38	0.41	1
	2039.11	2046.61	-7.5	7.5	20.39	0.37	1
	2520.5	2529.1	-8.6	8.6	25.21	0.34	1
	3080.43	3090.23	-9.8	9.8	30.8043	0.32	1
	3666.7	3675.5	-8.8	8.8	36.667	0.24	1

Table 4-4. E-meter data at DC input

	Pin						
Vin(V)	WT5000	PMP23338	error(W)	abs(error)(W)	error spec (W)	error(%)	error spec(%)
240 VDC	32.94	31.16	1.78	1.78	5		
	53.89	52.77	1.12	1.12	1.25		
	119.42	119.75	-0.33	0.33	1.25		
	260.06	259.39	0.67	0.67	2.60	0.26	1
	510.01	511.57	-1.56	1.56	5.10	0.31	1
	997.05	999.01	-1.96	1.96	9.97	0.20	1
	1537.6	1540	-2.4	2.4	15.38	0.16	1
	1996.3	2002.5	-6.2	6.2	19.96	0.31	1

4.6 Load Transients

Note

In the follwing figures: Blue: Vout, Pink: Iin, Yellow: Iout

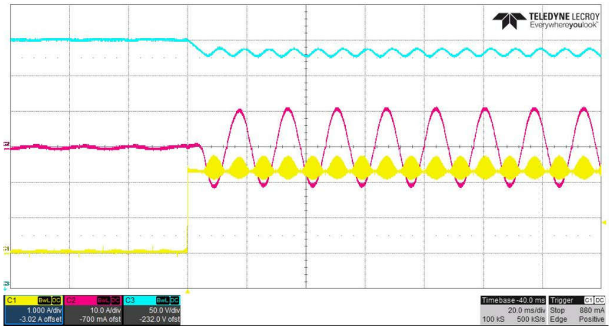


Figure 4-11. 115VAC, 0% -> 50% load

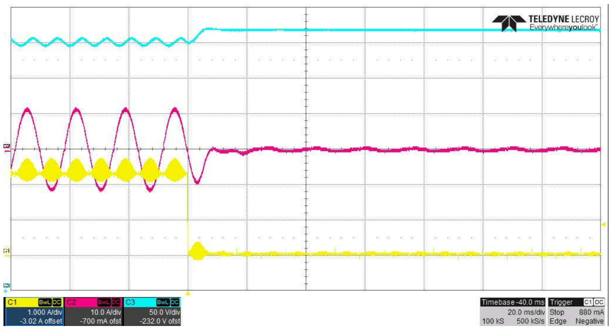


Figure 4-12. 115VAC, 50% -> 0% load

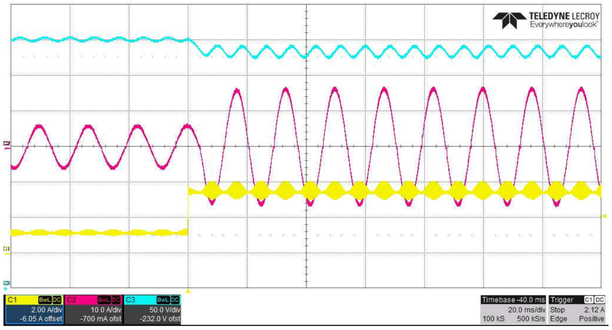


Figure 4-13. 115VAC, 25% -> 75% load

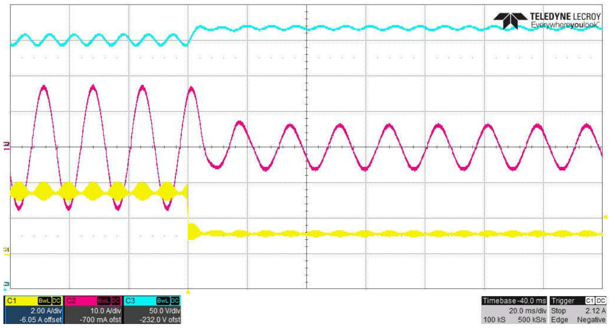


Figure 4-14. 115VAC, 75% -> 25% load

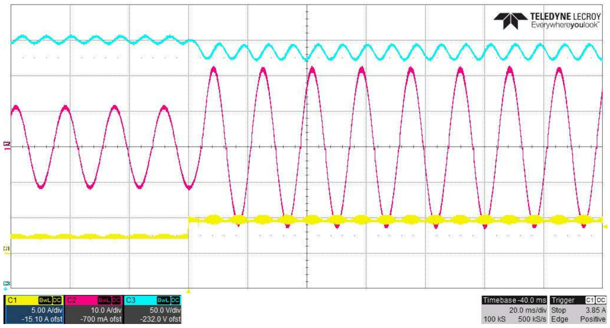


Figure 4-15. 115VAC, 50% -> 100% load

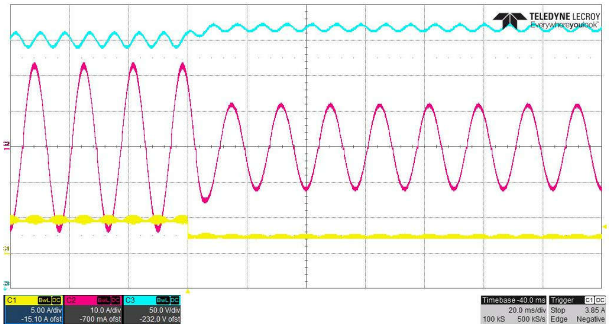


Figure 4-16. 115VAC, 100% -> 50% load

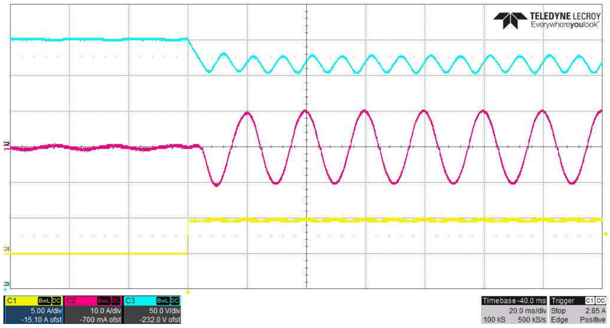


Figure 4-17. 230VAC, 0% -> 50% load

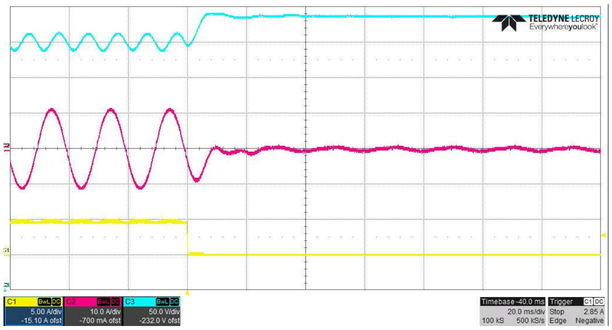


Figure 4-18. 230VAC, 50% -> 0% load

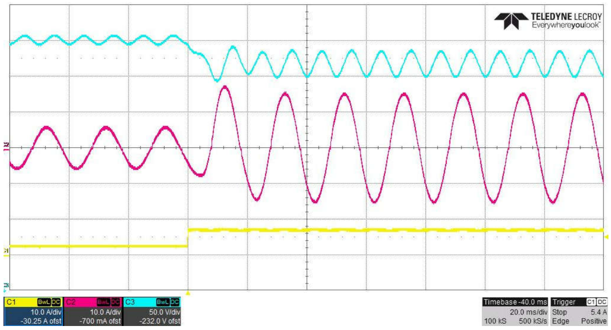


Figure 4-19. 230VAC, 25% -> 75% load

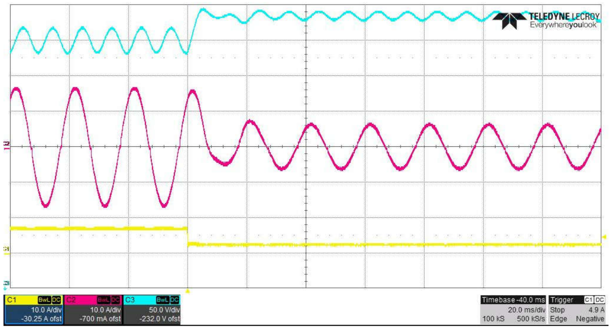


Figure 4-20. 230VAC, 75% -> 25% load

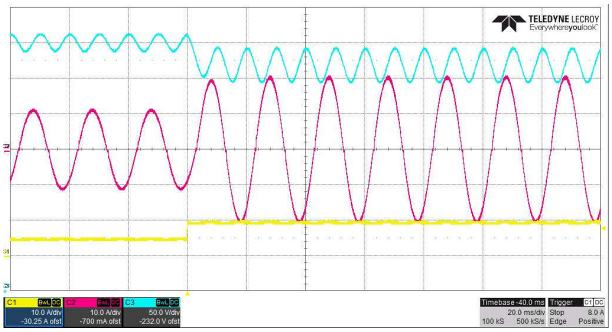


Figure 4-21. 230VAC, 50% -> 100% load

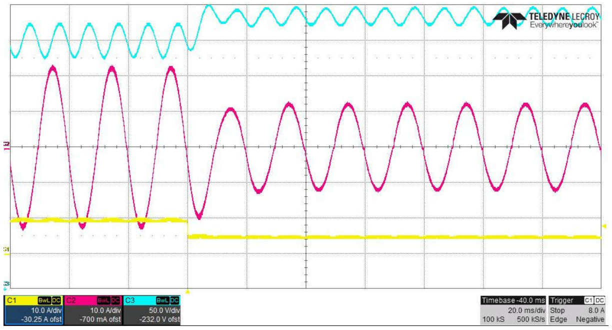


Figure 4-22. 230VAC, 100% -> 50% load

4.7 Input Current Waveforms

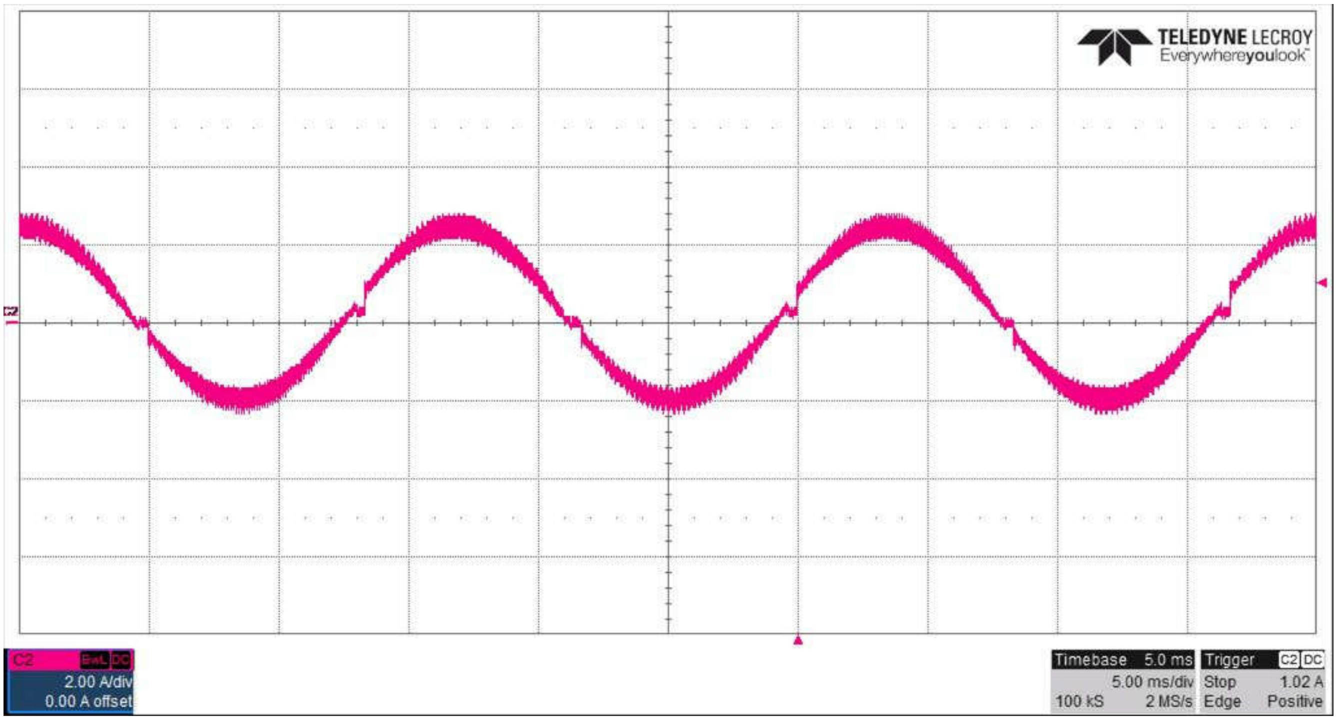


Figure 4-23. 120VAC 10% Load

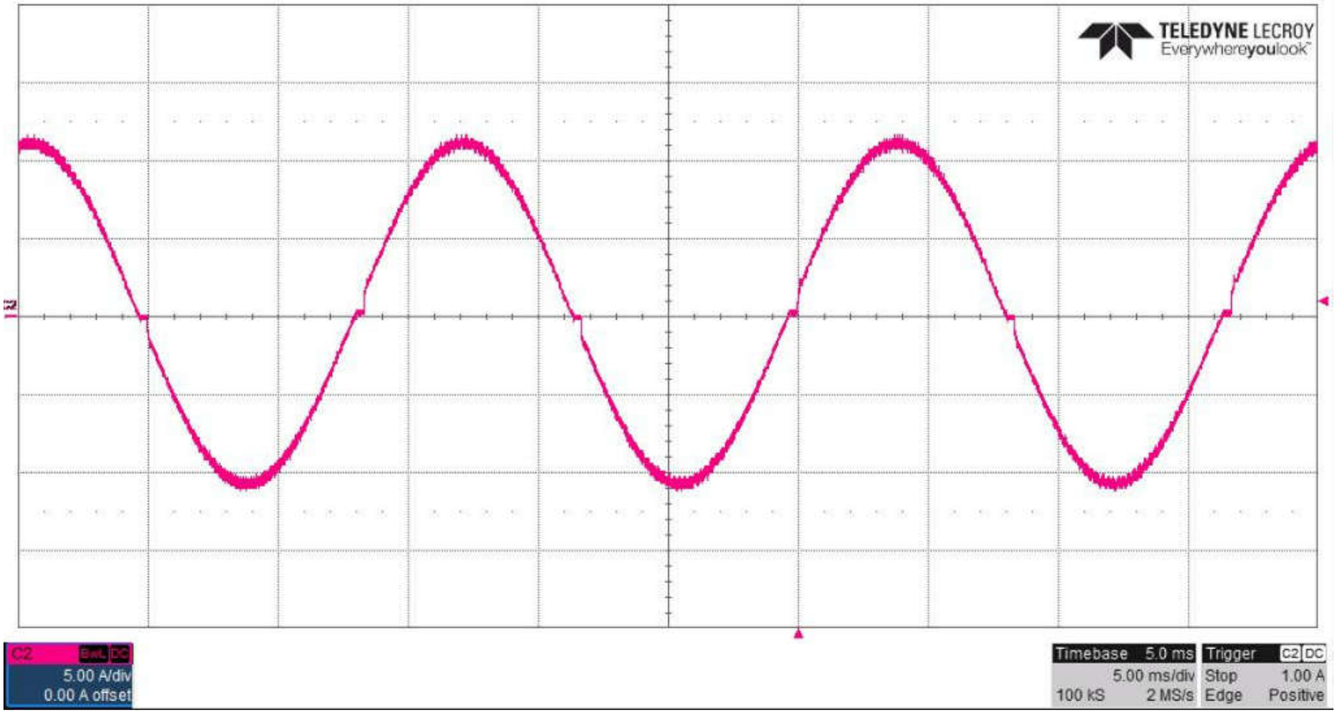


Figure 4-24. 120VAC 50% Load

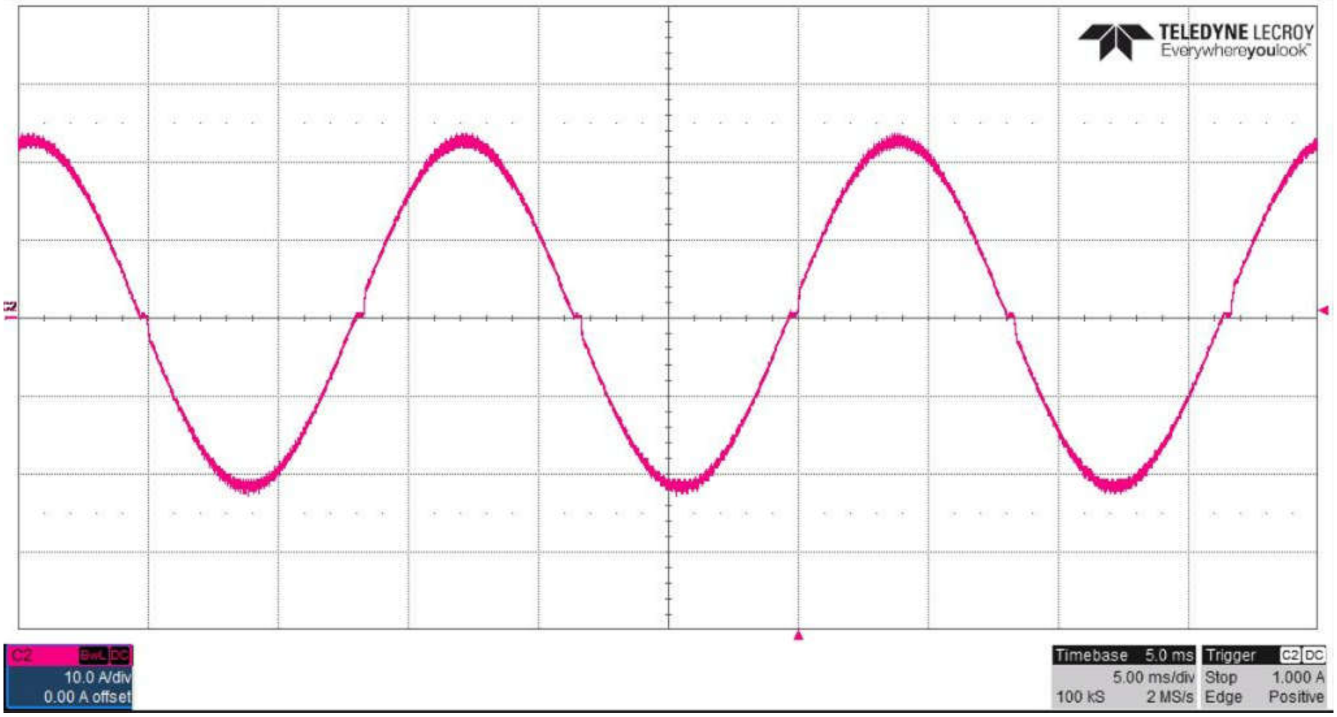


Figure 4-25. 120VAC 100% Load

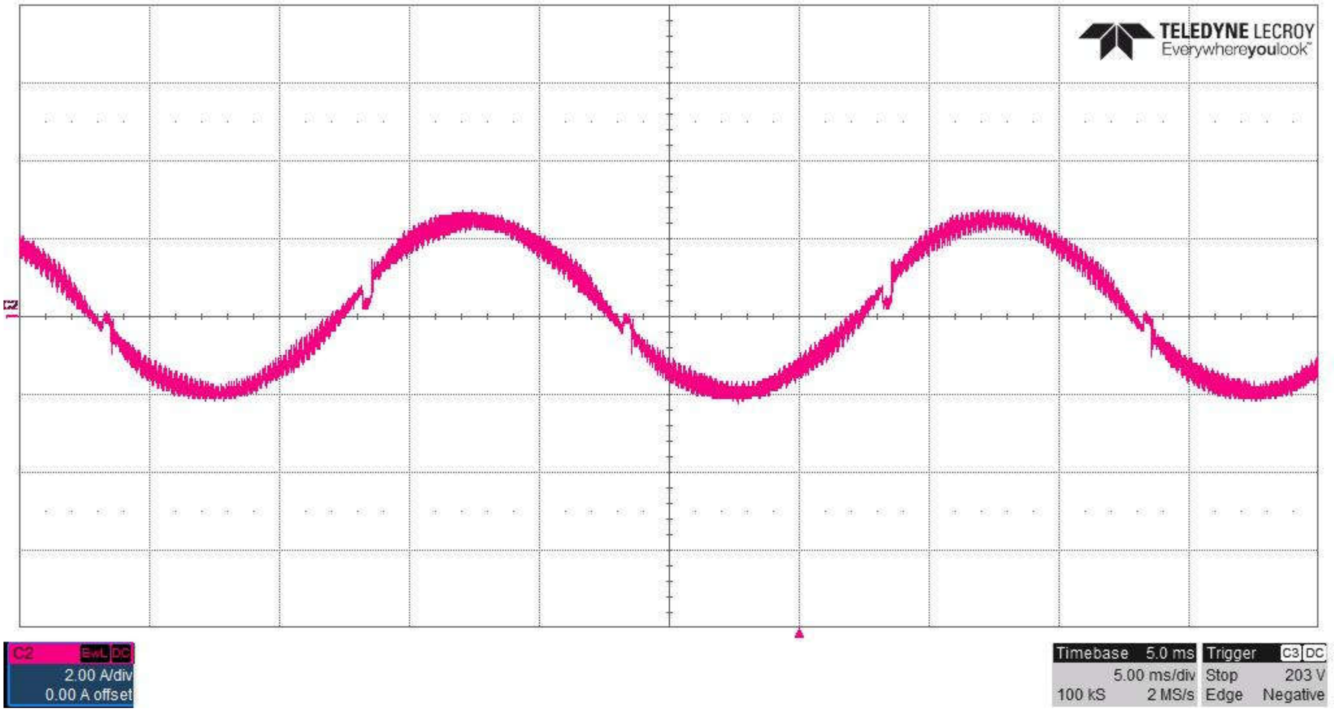


Figure 4-26. 240VAC 10% Load

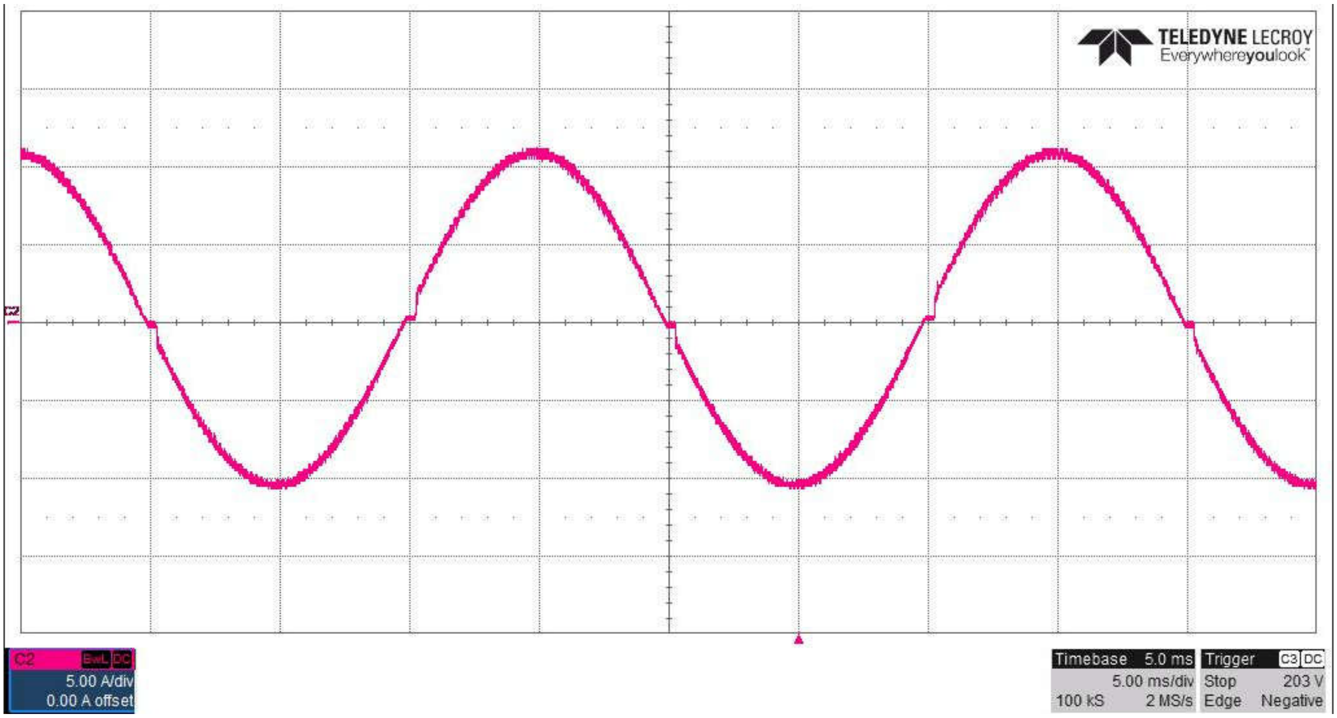


Figure 4-27. 240VAC 50% Load

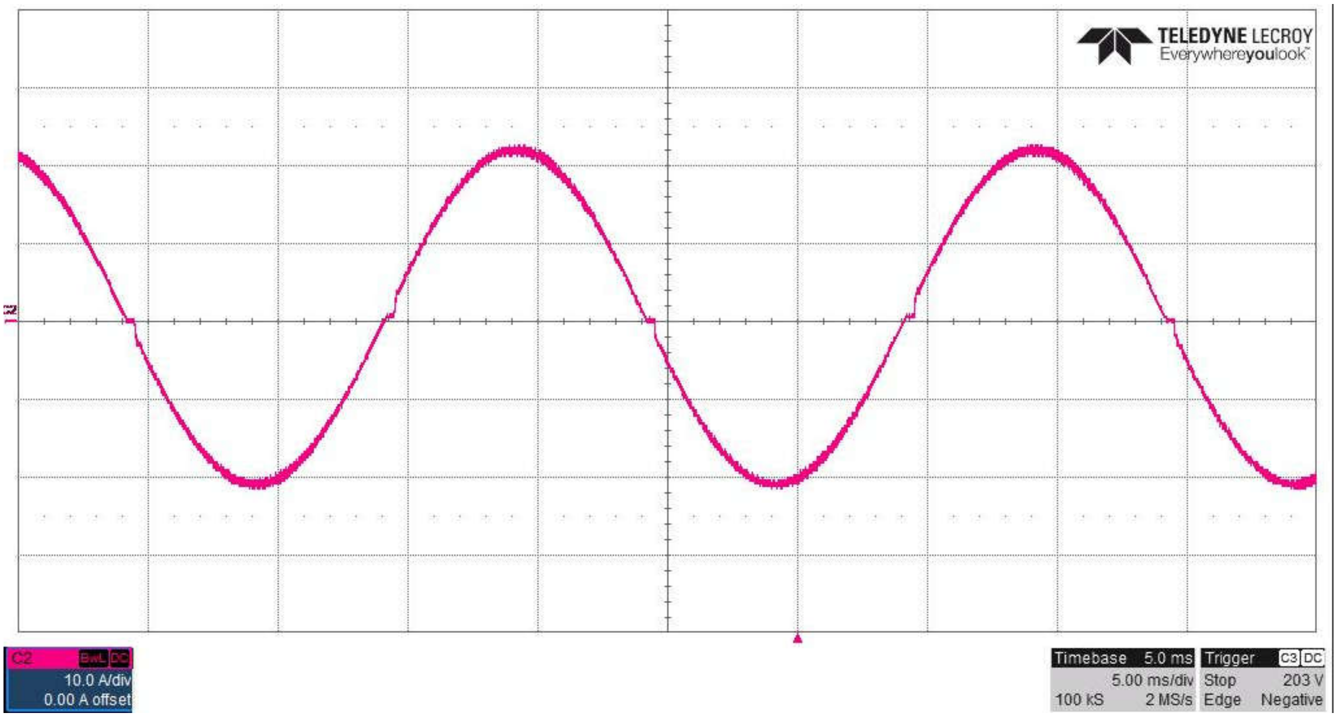


Figure 4-28. 240VAC 100% Load

4.8 AC Drop Test

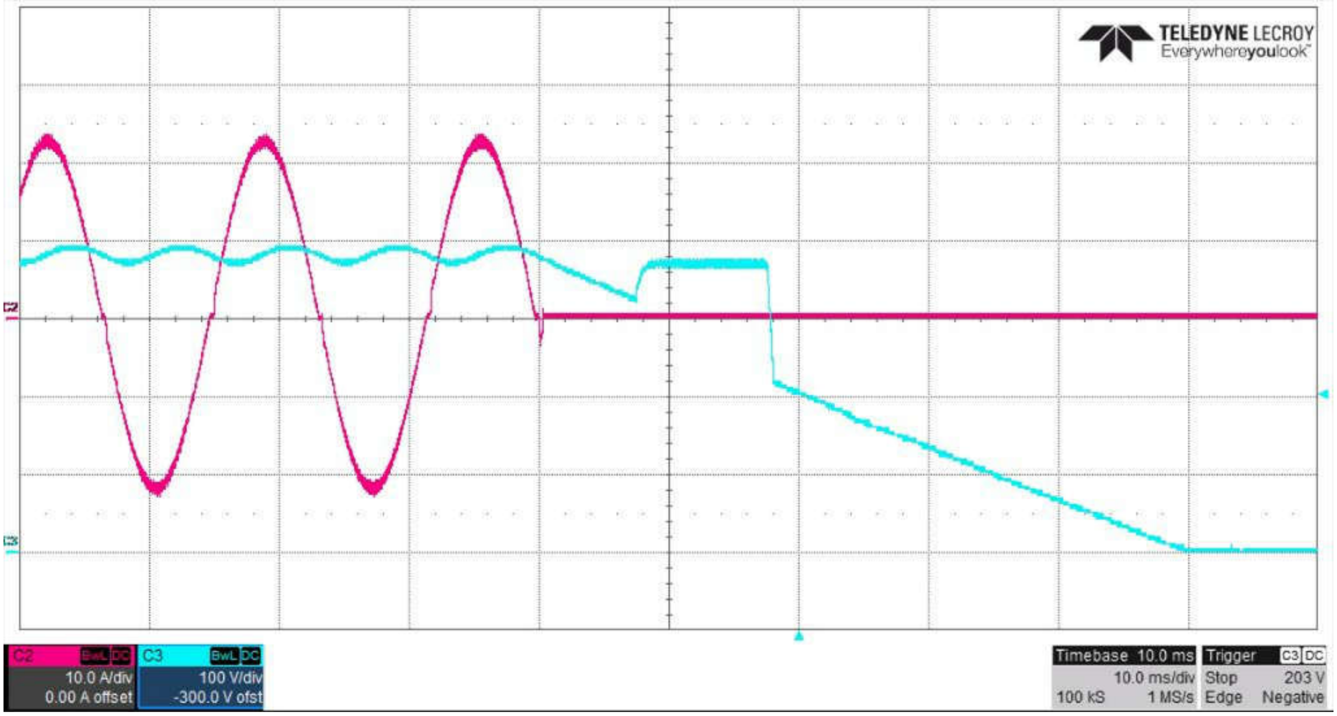


Figure 4-29. AC Drop at 120 VAC, 1800 W Load (Blue: Vout, Pink: Iin)

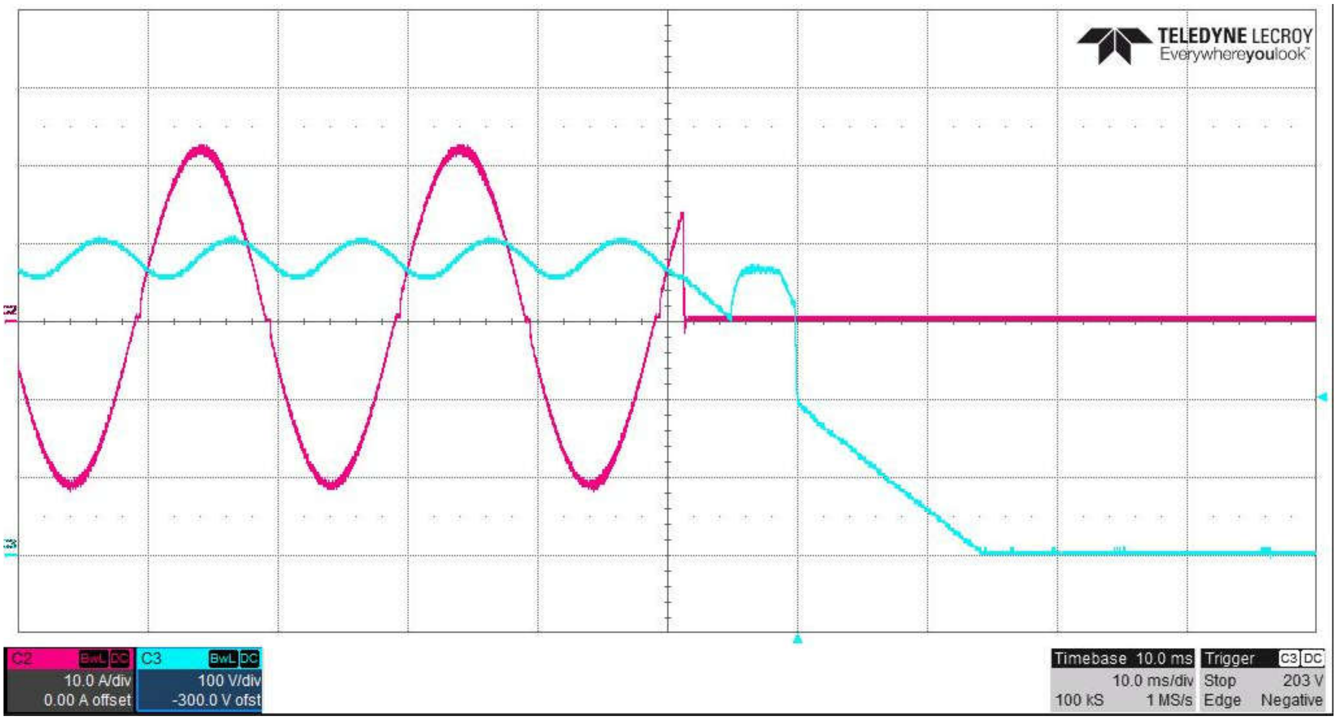
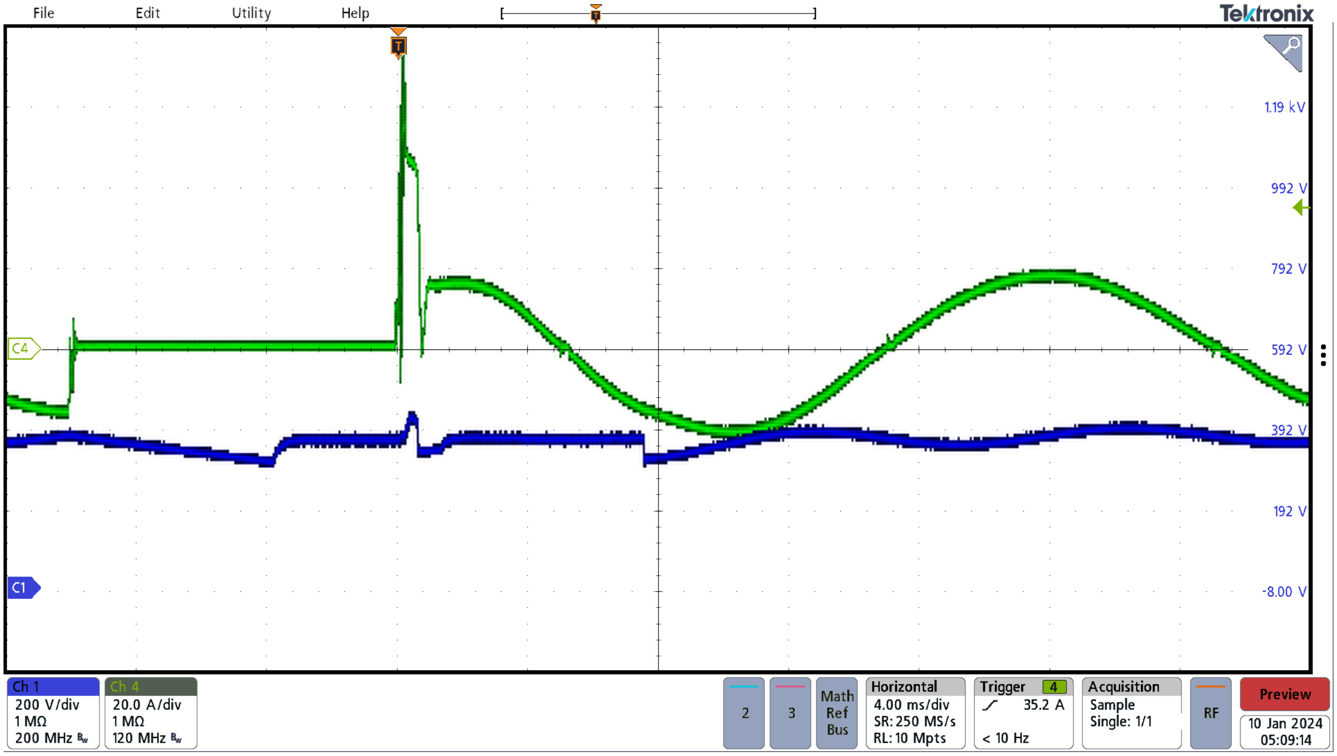


Figure 4-30. AC Drop at 240 VAC, 3600 W Load (Blue: Vout, Pink: Iin)



Ch 1
200 V/div
1 MΩ
200 MHz

Ch 4
20.0 A/div
1 MΩ
120 MHz

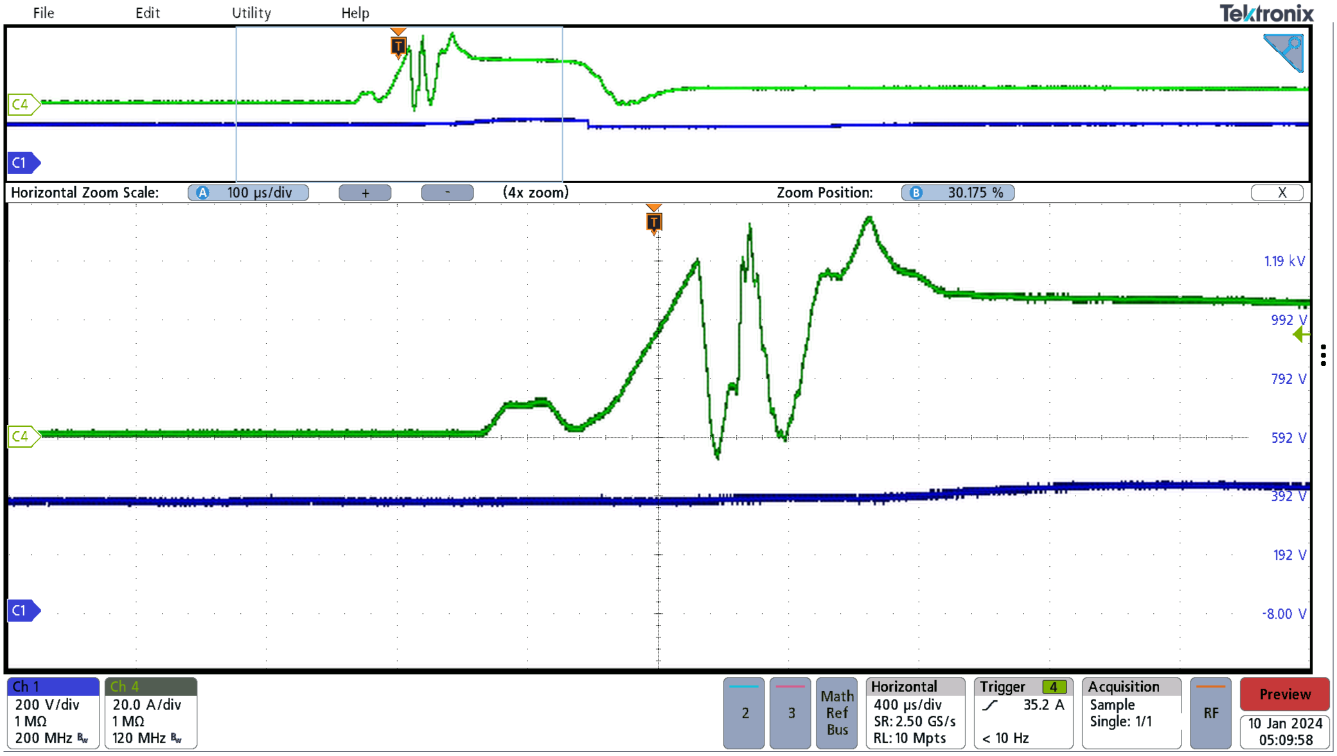
Horizontal
4.00 ms/div
SR: 250 MS/s
RL: 10 Mpts

Trigger 4
35.2 A
< 10 Hz

Acquisition
Sample
Single: 1/1

10 Jan 2024
05:09:14

Figure 4-31. Re-rush Current When AC Comes Back From 10ms Drop Out (Green: Iin, Blue: Vout)



Horizontal Zoom Scale: A 100 µs/div (4x zoom)
Zoom Position: B 30.175 %

Ch 1
200 V/div
1 MΩ
200 MHz

Ch 4
20.0 A/div
1 MΩ
120 MHz

Horizontal
400 µs/div
SR: 2.50 GS/s
RL: 10 Mpts

Trigger 4
35.2 A
< 10 Hz

Acquisition
Sample
Single: 1/1

10 Jan 2024
05:09:58

Figure 4-32. Zoom In of Re-rush Current

4.9 Thermal Images

Test Conditions:

Vin:230 VAC

Vout: 385V

Load: 3.6KW

Air flow: same as "Start-Up Sequence"

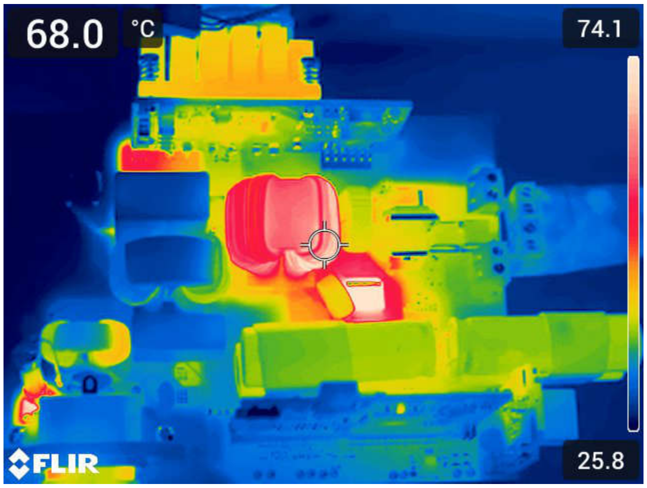


Figure 4-33. Thermal Image

Figure 4-34. Relay Bypass Switch Thermal Image

5 External Reference

[1] B. Sun, S. Yu, B. Genereaux, L. Yin, "Design and Control Strategy of PFC During AC Dropout in a High Reliability and High-Power Density Server Power Supply", ECCE 2023

[2] B. Sun, S. Yu, T. Hud, "A Totem-pole PFC with Re-rush Current Control, Accurate E-metering, Low iTHD and High Power Density", APEC 2024

[3] Modular Hardware System – Common Redundant Power Supply (MCRPS) Base Specification. Open Compute Project, Version 1.02 RC2, Aug. 23, 2023. [Online].

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[7] R. Yin, “Five major trends in power supply design for servers”, August 2022, EDN

[8] B. Sun, “How to improve the power factor of a PFC”, January 2024, EDN

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