Test Report: PMP8740

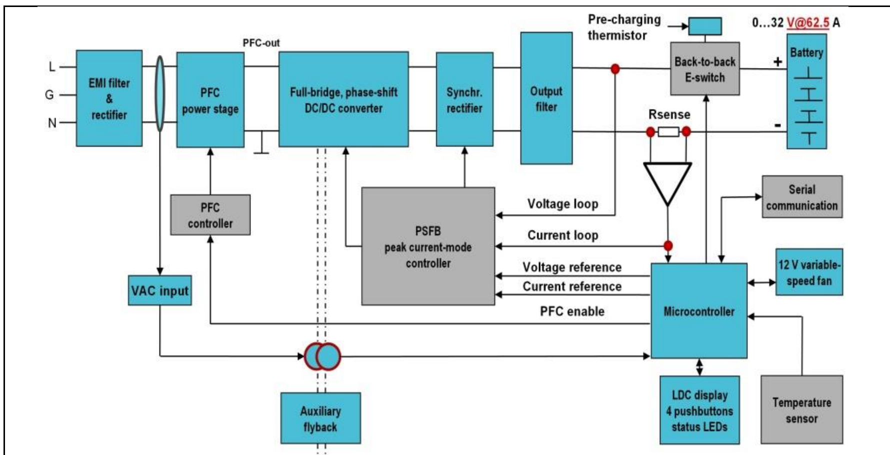
2-kW Industrial AC/DC Battery Charger Reference Design With 92% Full-Load Efficiency

TEXAS INSTRUMENTS

Description

This reference design is a module that can be set as standard power supply or a battery charger. The output voltage ranges from 0 V to 32 V at a maximum current of 62.5 A. It consists of four boards, a boost PFC, a phase shift full bridge, a small daughter board (hosting the microcontroller), and a display board with three LEDs and four push-buttons. The input voltage range is universal: 90 VAC to 264 VAC and the input current is limited to 10 Arms, which limits the input power below 200 VAC. The microcontroller interfaces the power supply to an operator and controls all functions, including enabling and shutting down the PFC and DC/DC stage, setting different output voltage levels and charging current limits.

The reference design PMP8740 Rev_E has been built on PMP8740 Rev_C Boards.



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1 Test Prerequisites

1.1 Voltage and Current Requirements

Table 1. Voltage and Current Requirements

PARAMETER	SPECIFICATIONS
Input Voltage	90 VAC – 264 VAC
Output Voltage:	0…32 VDC
Output Current:	0…62.5 A

1.2 Required Equipment

- 0…270 VAC, (minimum current limit 15 Arms), AC constant voltage source (VS1)
- Electronic load, (constant current and constant voltage, range 0…70 A)
- Oscilloscope (min. 100 MHz bandwidth)
- Current probe (min. 100 KHz bandwidth)
- Optional: infrared camera

1.3 Testing Conditions

The power supply has two outputs and the feedback loop is closed to 19Vout (Output #1). It has been designed to work also from zero to 100 W with only 19Vout loaded and the 56Vout (Output #2) unloaded. A minimum load (≥ 150 mW) on 19Vout, for correct Vout regulation, should be always present. From 10 W up to full load, the PFC should be enabled by supplying a voltage > 3.3 V on J1; this can be done by adding a switch connecting pin 1 of J1 to 19Vout, or connecting pin 1of J1 to a digital output of a microcontroller. In order to improve the efficiency at light load, the PFC stage can be kept off from 150 mW to 10 W load.

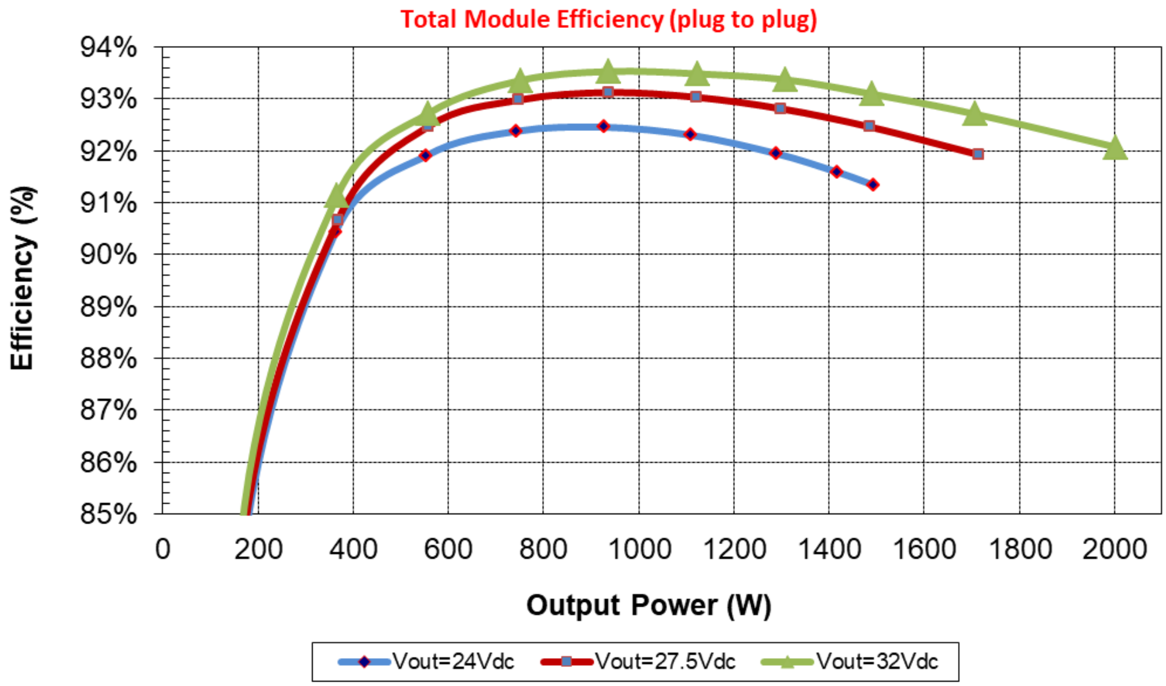
a) Connect the source VS1 to J4-3 and J4-1; earth connection to J4-2.
b) Connect the loads to J2 (1-2) and J3 (2-1)
c) Attach current probe to the jumper that connects TP3 and TP4, to measure the resonant current.
d) Connect a 150 mW minimum load to 19Vout
e) Turn on Vs1 (accepted range: 90 VAC…264 VAC).
f) Increase the load on the outputs.
g) Turn on the PFC stage if total output power is higher than 10 W.
h) After turn off, wait ~ 5 minutes until C44 and C45 PFC capacitors are completely discharged (warning: HIGH VOLTAGE)

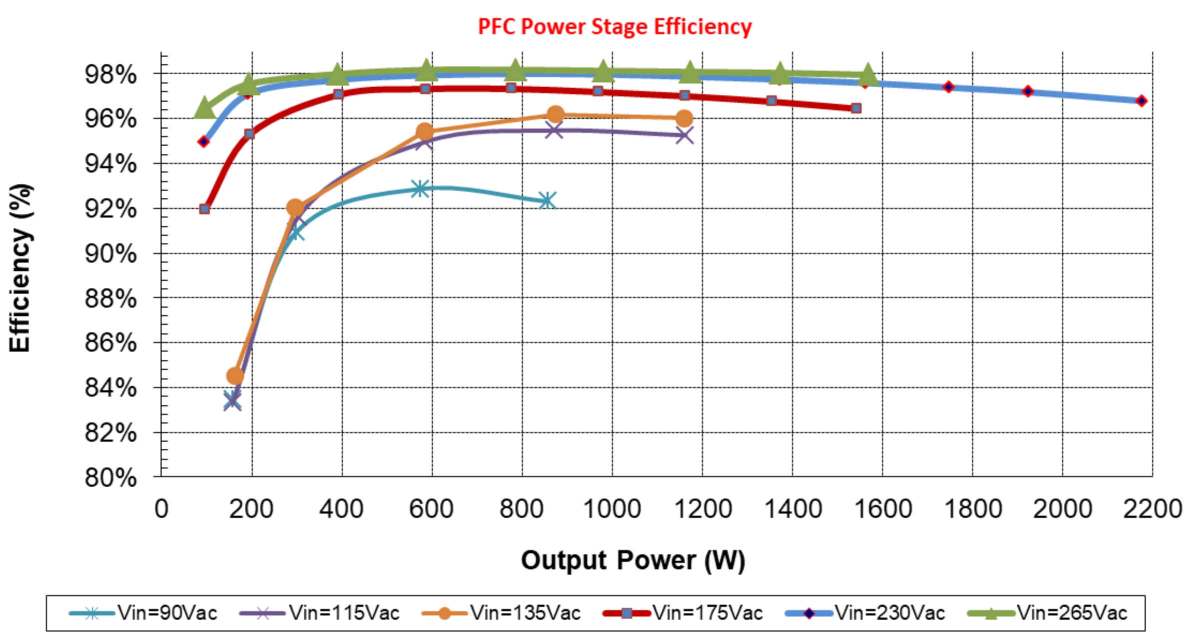
2 Testing and Results

2.1 Efficiency Graph & Data, power factor

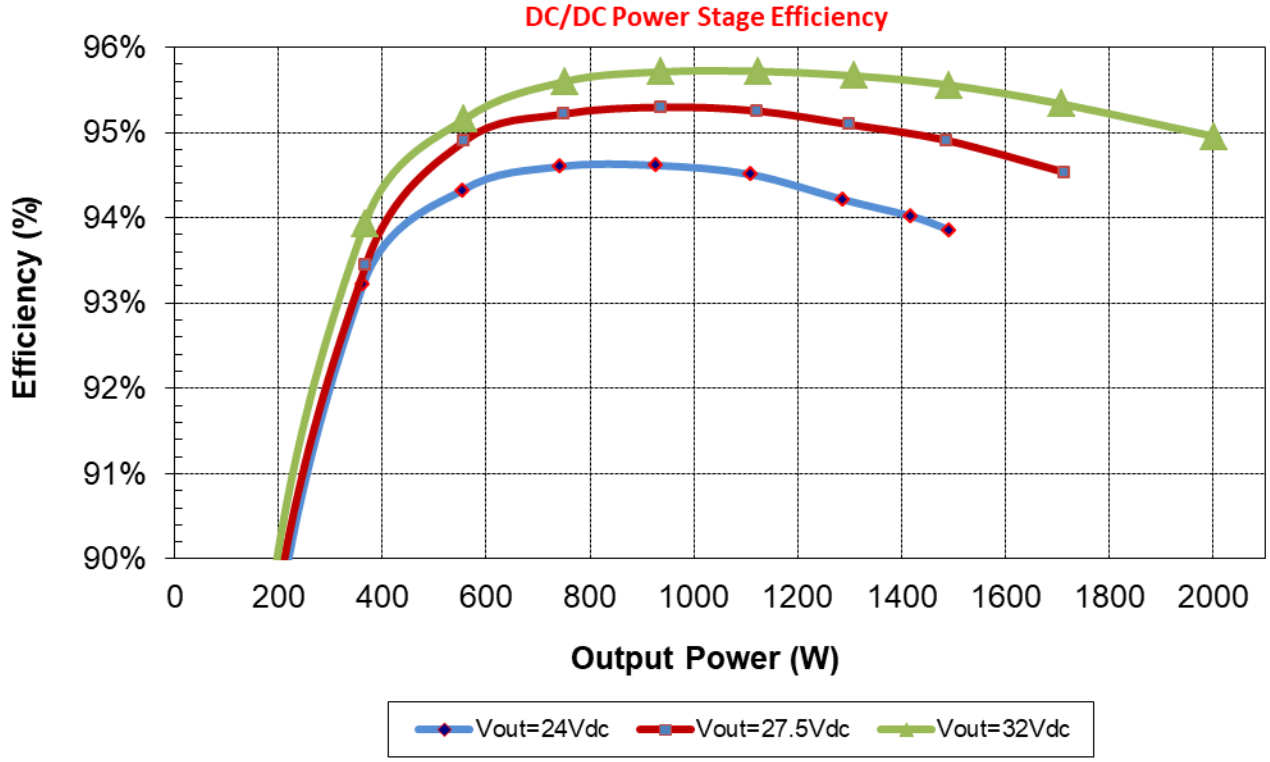
2.1.1 Efficiency Graphs:

The efficiency graphs (plug to plug, PFC stage and DC/DC stage), versus output power, are shown below.
The output voltage has been set to 24V, 27.5V and 32V, with Vin = 230 VAC, 50 Hz.
The highest power of each curve is referred to the maximum output current, which is 62.5A.





For the PFC stage, we measured both efficiency and power factor, versus output power.
The AC source was able to supply up to 1.6KW with clean sinusoidal waveform (at 50Hz and 60Hz), therefore useful to measure accurately the power factor. We connected the module directly to AC mains outlet, to extend the test up to 2KW. In this case the power factor hasn't been measured due to the slightly distorted mains voltage waveform.
This power supply has been specified to work mainly in high-line mains. For this reason, the load current applied at mains voltage below 230V, has been reduced progressively in order to limit the input current to 10A.



2.1.2 Efficiency Data:

The efficiency graphs report the data from the tables shown below, in the whole power and input VAC range.

PFC Stage only, Vin = 90Vac, 60Hz								
Iout (mA)	Vout (V)	Pout (W)	Iaux (mA)	Vin (V)	Pin (W)	Paux (W)	PF	Eff (%)
3.6	400.9	1.44	19.397	90	5.12	2.469	48.00	54.4%
397.7	401.0	159.48	19.612	90	193.5	2.496	99.54	83.5%
744.6	401.0	298.6	19.741	90	330.9	2.513	99.88	90.9%
1435	400.9	575.3	19.828	90	622.0	2.524	99.97	92.9%
2140	400.9	857.9	19.914	90	932.0	2.535	99.40	92.3%

PFC Stage only, Vin = 115Vac, 60Hz								
Iout (mA)	Vout (V)	Pout (W)	Iaux (mA)	Vin (V)	Pin (W)	Paux (W)	PF	Eff (%)
3.6	400.9	1.44	15.086	115	4.90	2.454	37.00	59.0%
394.0	401.0	157.99	15.172	115	192.1	2.468	99.06	83.3%
756.8	401.0	303.5	15.302	115	333.7	2.489	99.68	91.6%
1457	400.9	584.1	15.345	115	617.6	2.496	99.91	95.0%
2175	400.9	872.0	15.431	115	915.8	2.510	99.95	95.5%
2900	400.9	1162.6	15.517	115	1223.0	2.524	99.95	95.3%

PFC Stage only, Vin = 135Vac, 60Hz								
Iout (mA)	Vout (V)	Pout (W)	Iaux (mA)	Vin (V)	Pin (W)	Paux (W)	PF	Eff (%)
3.6	400.9	1.44	12.931	135	4.90	2.469	29.00	59.4%
405.2	401.0	162.49	13.017	135	194.7	2.485	98.80	84.5%
740.4	401.0	296.9	13.147	135	325.2	2.510	99.50	92.0%
1456	400.9	583.6	13.276	135	614.0	2.535	99.86	95.4%
2179	400.9	873.4	13.448	135	910.5	2.568	99.93	96.2%
2893	400.9	1159.7	13.578	135	1210.2	2.592	99.95	96.0%

PFC Stage only, Vin = 175Vac, 50Hz								
Iout (mA)	Vout (V)	Pout (W)	Iaux (mA)	Vin (V)	Pin (W)	Paux (W)	PF	Eff (%)
3.6	400.9	1.44	8.664	175	4.62	2.144	29	58.3%
240.1	401.0	96.28	9.142	175	107.0	2.263	95.1	91.9%
489.1	401.0	196.1	8.966	175	208.0	2.219	96.90	95.3%
984.9	400.9	394.8	9.151	175	409.0	2.265	99.50	97.1%
1462	400.9	586.1	9.181	175	604.5	2.272	99.74	97.3%
1937	400.9	776.5	9.194	175	800.1	2.275	99.83	97.3%
2421	400.9	970.6	9.220	175	1000.9	2.282	99.87	97.2%
2900	401.0	1162.9	9.237	175	1201.1	2.286	99.89	97.0%
3379	400.9	1354.6	9.254	175	1402.3	2.290	99.89	96.8%
3849	400.8	1542.7	9.267	175	1601.8	2.294	99.89	96.4%

PFC Stage only, Vin = 230Vac, 50Hz								
Iout (mA)	Vout (V)	Pout (W)	Iaux (mA)	Vin (V)	Pin (W)	Paux (W)	PF	Eff (%)
1.6	400.3	0.64	7.228	230	3.62	2.351	17	50.5%
233.8	400.3	93.59	7.552	230	101.0	2.456	90.5	95.0%
480.4	400.3	192.3	7.539	230	200.5	2.452	95.34	97.1%
969.1	400.3	387.9	7.539	230	399.4	2.452	98.80	97.7%
1475	400.3	590.4	7.539	230	605.3	2.452	99.40	97.9%
1968	400.3	787.8	7.543	230	806.3	2.454	99.59	98.0%
2445	401.0	980.4	7.526	230	1003.1	2.448	99.70	98.0%
2925	401.0	1172.9	7.534	230	1200.8	2.451	99.77	97.9%
3421	400.9	1371.5	7.534	230	1405.5	2.451	99.80	97.7%
3896	400.8	1561.5	7.532	230	1602.4	2.450	99.83	97.6%
4363	400.8	1748.7	7.533	230	1798.0	2.450	N/A	97.4%
4800	400.6	1922.9	7.531	230	1981.0	2.450	N/A	97.2%
5432	400.5	2175.5	7.530	230	2250.0	2.449	N/A	96.8%

PFC Stage only, Vin = 265Vac, 50Hz								
Iout (mA)	Vout (V)	Pout (W)	Iaux (mA)	Vin (V)	Pin (W)	Paux (W)	PF	Eff (%)
3.7	400.9	1.48	6.642	265	4.40	2.489	15	77.6%
240.4	401.0	96.40	6.935	265	102.5	2.599	86.7	96.5%
481.3	400.9	193.0	6.922	265	200.4	2.594	92.75	97.5%
976.8	400.9	391.6	6.922	265	402.2	2.594	98.01	98.0%
1467	400.9	588.1	6.909	265	601.6	2.589	99.02	98.2%
1959	400.9	785.4	6.909	265	802.5	2.589	99.35	98.2%
2446	400.9	980.6	6.909	265	1001.8	2.589	99.53	98.1%
2930	400.9	1174.6	6.922	265	1200.1	2.594	99.63	98.1%
3427	400.9	1373.9	6.914	265	1403.9	2.591	99.70	98.0%
3912	400.9	1568.3	6.927	265	1603.6	2.596	99.74	98.0%

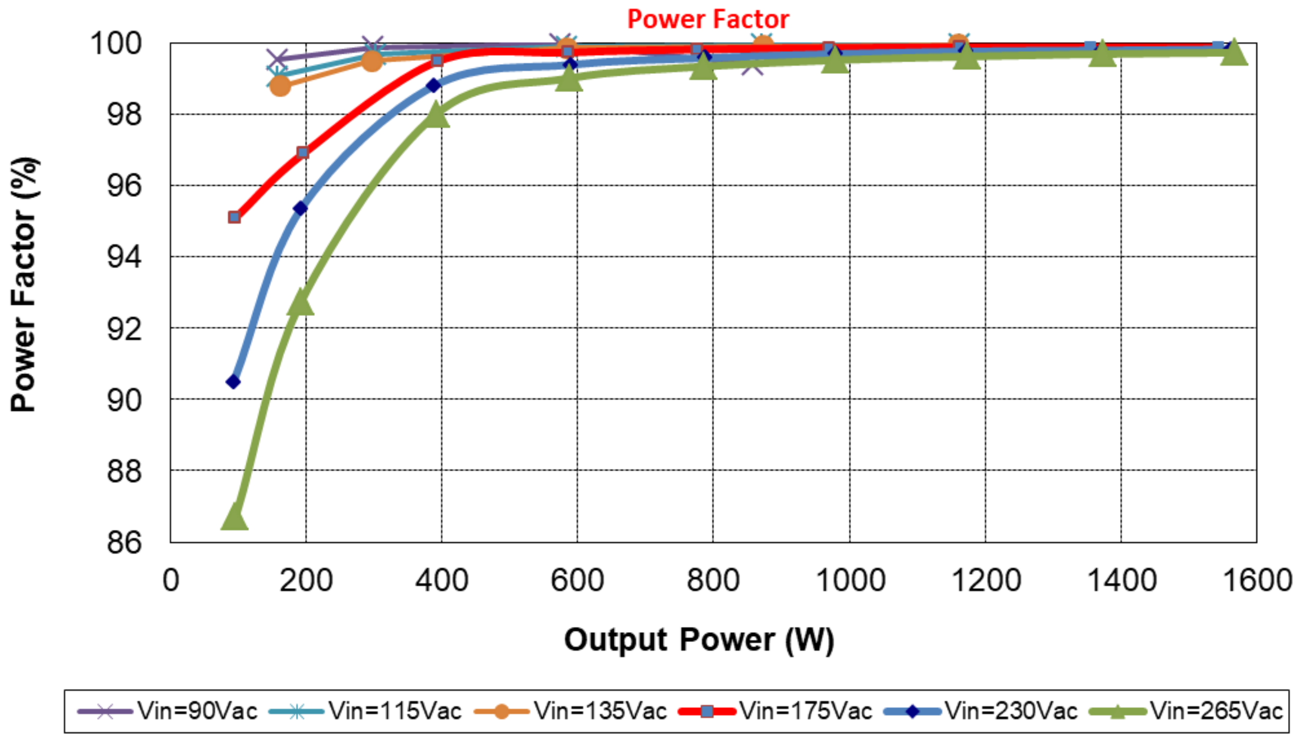
DC/DC Stage only, Vout = 24Vdc					
Iout (A)	Vout (V)	Pout (W)	PFC eff.	Pin (W)	Eff (%)
0.0	23.98	0.00	0.0	2.35	0.0%
2.698	23.98	64.70	96.5	100.3	68.6%
6.621	23.98	158.77	97.1	190.0	87.2%
15.14	23.96	362.63	97.7	401.0	93.2%
23.13	23.95	553.92	97.9	602.7	94.3%
31.00	23.93	741.85	98.0	803.1	94.6%
38.77	23.92	927.31	98.0	1003	94.6%
46.42	23.90	1109.4	97.9	1202	94.5%
53.91	23.89	1287.9	97.8	1401	94.2%
59.37	23.88	1417.8	97.6	1548	94.0%
62.50	23.88	1492.5	97.5	1634	93.9%

DC/DC Stage only, Vout = 27.5Vdc					
Iout (A)	Vout (V)	Pout (W)	PFC eff.	Pin (W)	Eff (%)
0.0	27.55	0.00	0.0	2.38	0.0%
2.365	27.55	65.16	96.5	101.0	68.6%
5.855	27.54	161.25	97.1	192.0	87.7%
13.36	27.53	367.72	97.7	405.6	93.4%
20.26	27.52	557.67	97.9	603.1	94.9%
27.21	27.50	748.28	98.0	804.8	95.2%
34.09	27.49	937.08	98.0	1006	95.3%
40.83	27.48	1122.0	97.9	1206	95.3%
47.33	27.46	1299.7	97.8	1400	95.1%
54.13	27.45	1485.9	97.6	1607	94.9%
62.50	27.43	1714.4	97.4	1865	94.5%

DC/DC Stage only, Vout = 32Vdc					
Iout (A)	Vout (V)	Pout (W)	PFC eff.	Pin (W)	Eff (%)
0.0	32.13	0.00	0.0	2.48	0.0%
2.057	32.13	66.09	96.5	102.0	68.9%
5.078	32.13	163.16	97.1	193.0	88.2%
11.40	32.12	366.17	97.7	401.8	93.9%
17.38	32.11	558.07	97.9	601.9	95.2%
23.43	32.09	751.87	98.0	805.4	95.6%
29.18	32.08	936.19	98.0	1001	95.7%
35.02	32.07	1123.2	97.9	1202	95.7%
40.83	32.06	1309.0	97.8	1402	95.7%
46.53	32.05	1491.3	97.6	1602	95.6%
53.28	32.05	1707.6	97.4	1842	95.3%
62.50	32.04	2002.5	97.1	2175	95.0%

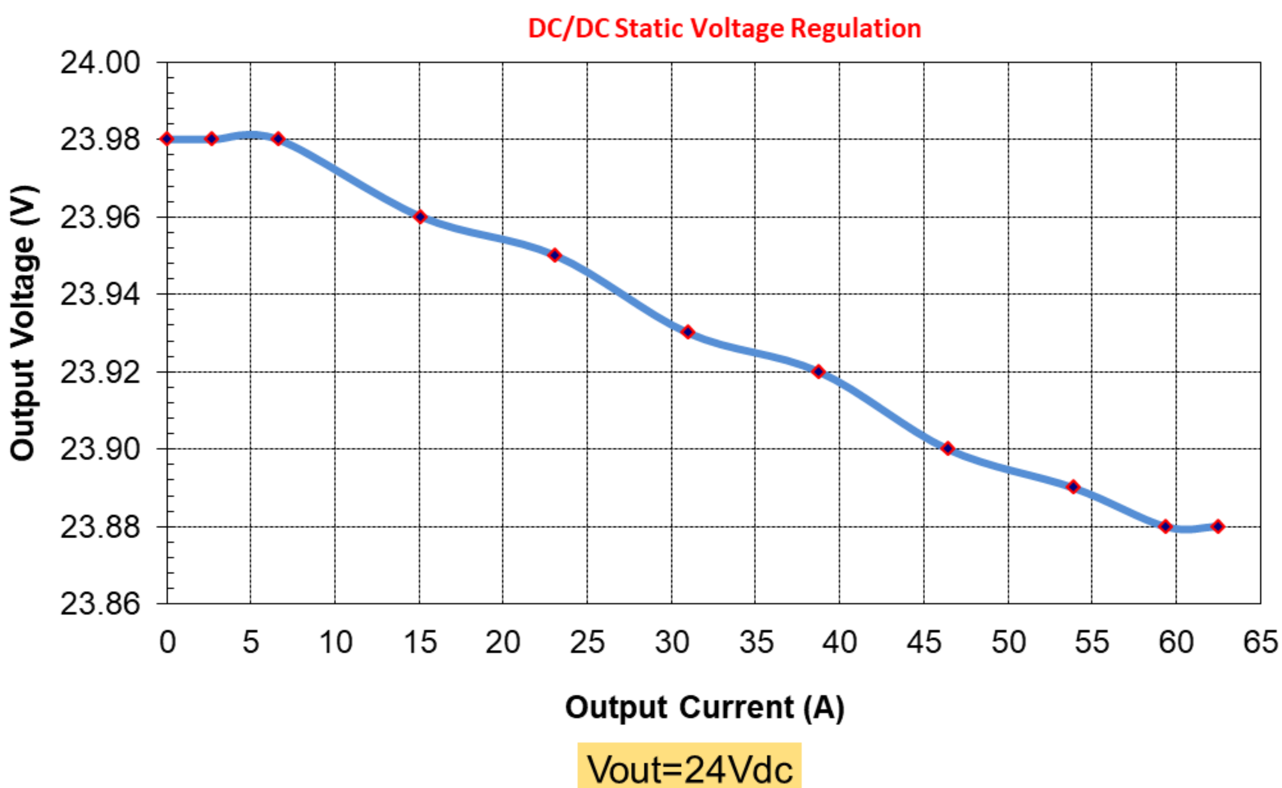
2.2 Power Factor versus Load and VAC

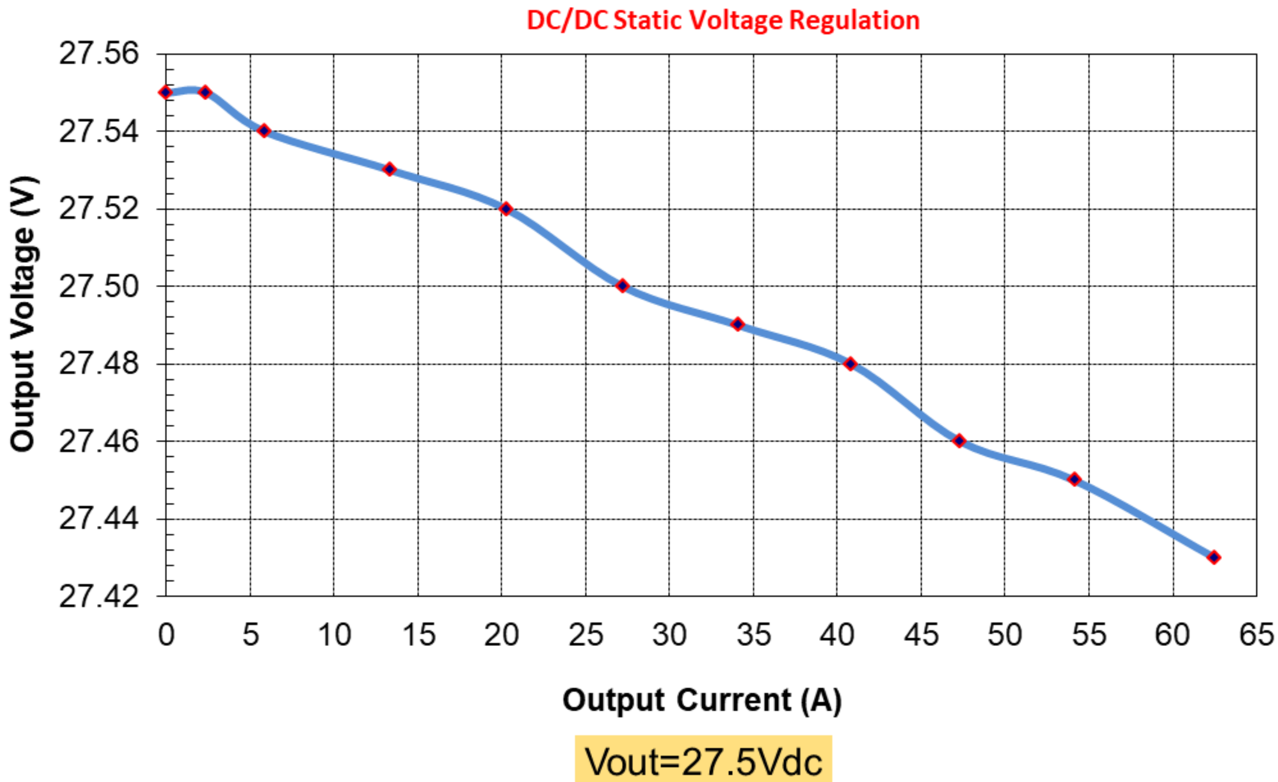
The power factor value has been measured by varying the total load power from 100W to 1.6KW (input power of the module). As described above, 1.6KW is the limit of AC electronic source.

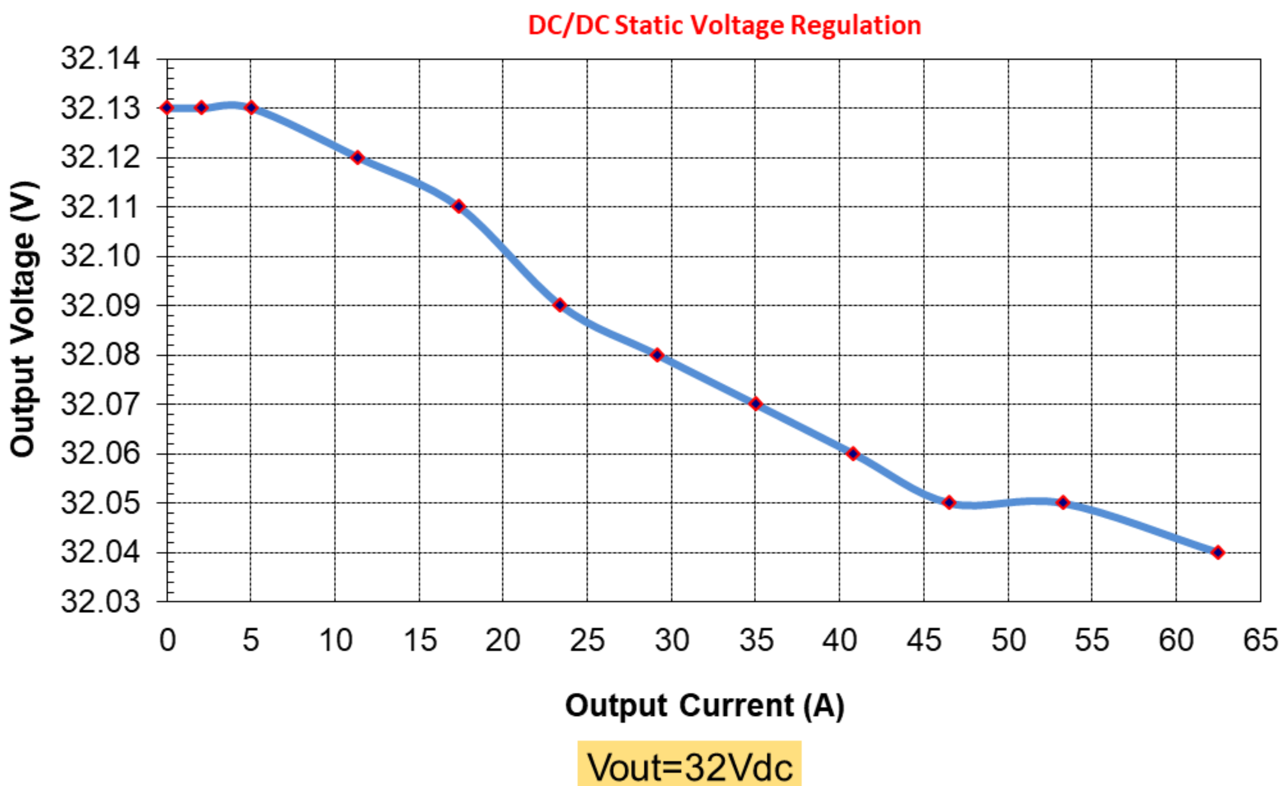


3 Static Output Voltage Variation versus Load

The output voltage regulation versus load current is shown in the graphs below.




DC/DC Static Voltage Regulation
Output Voltage (V)
27.56
27.54
27.52
27.50
27.48
27.46
27.44
27.42
0 5 10 15 20 25 30 35 40 45 50 55 60 65
Output Current (A)
Vout=27.5Vdc


DC/DC Static Voltage Regulation
Output Voltage (V)
32.14
32.13
32.12
32.11
32.10
32.09
32.08
32.07
32.06
32.05
32.04
32.03
0 5 10 15 20 25 30 35 40 45 50 55 60 65
Output Current (A)
Vout=32Vdc

4 Board Dimensions

The dimensions of the three boards are:

1) PFC Boost + auxiliary power supply: 263 mm x 149 mm, height 45 mm.
2) DC/DC Phase shift full bridge: 263 mm x 149 mm, height 50 mm.
3) Daughterboard with the microcontroller: 45 mm x 29 mm, height 4 mm.

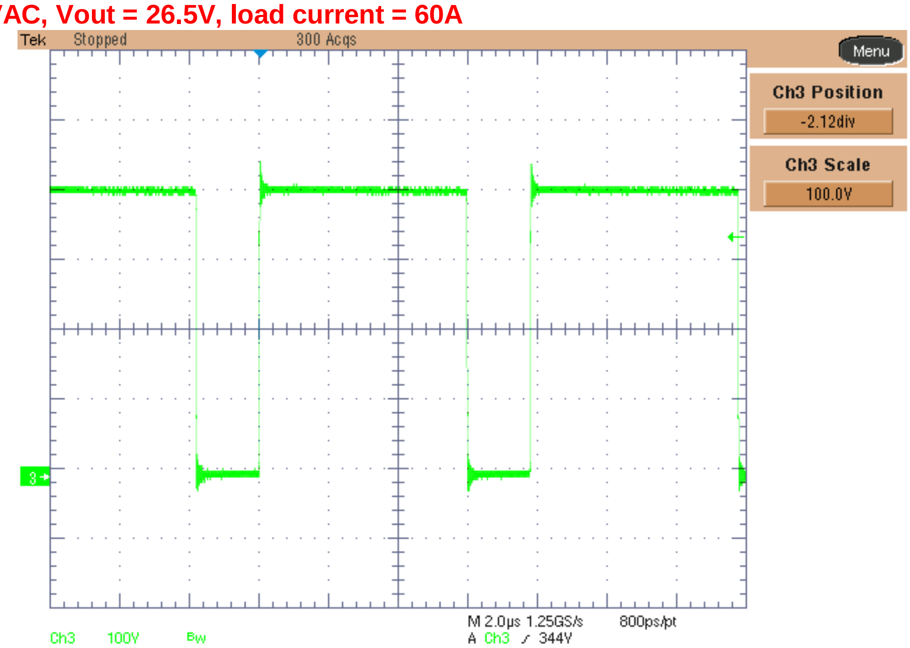
5 Waveforms

5.1 Switching Waveforms from Boost Stage

The switching waveforms have been measured by supplying the converter at 230 VAC (50 Hz), at 50A and 60A load current, while Vout was set to 26.5V.

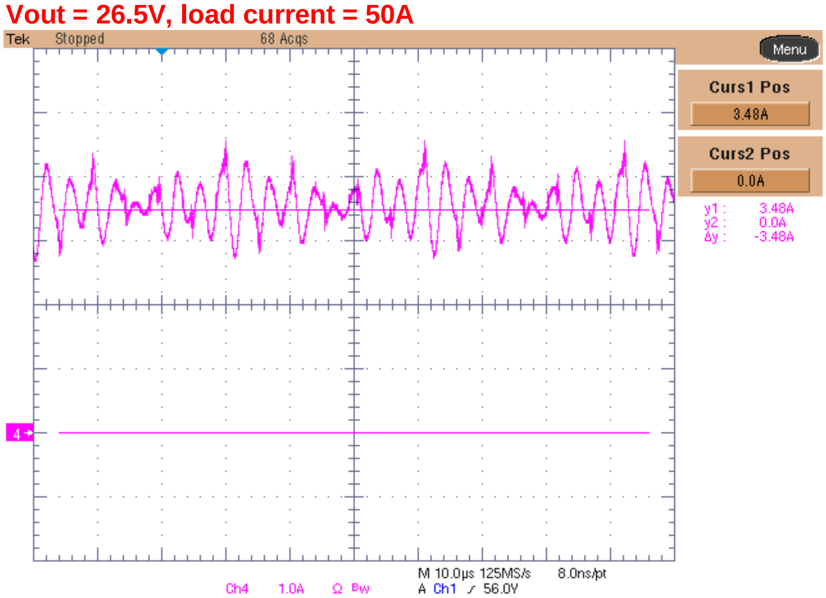
Ch3: Boost switch node (Q1-Vds) (100 V/div, 2 usec/div, 200 MHz BWL)

Vin = 230VAC, Vout = 26.5V, load current = 60A



Ch4: Output current of J1 (Boost stage) (1 A/div, 10 usec/div, 200 MHz BWL)

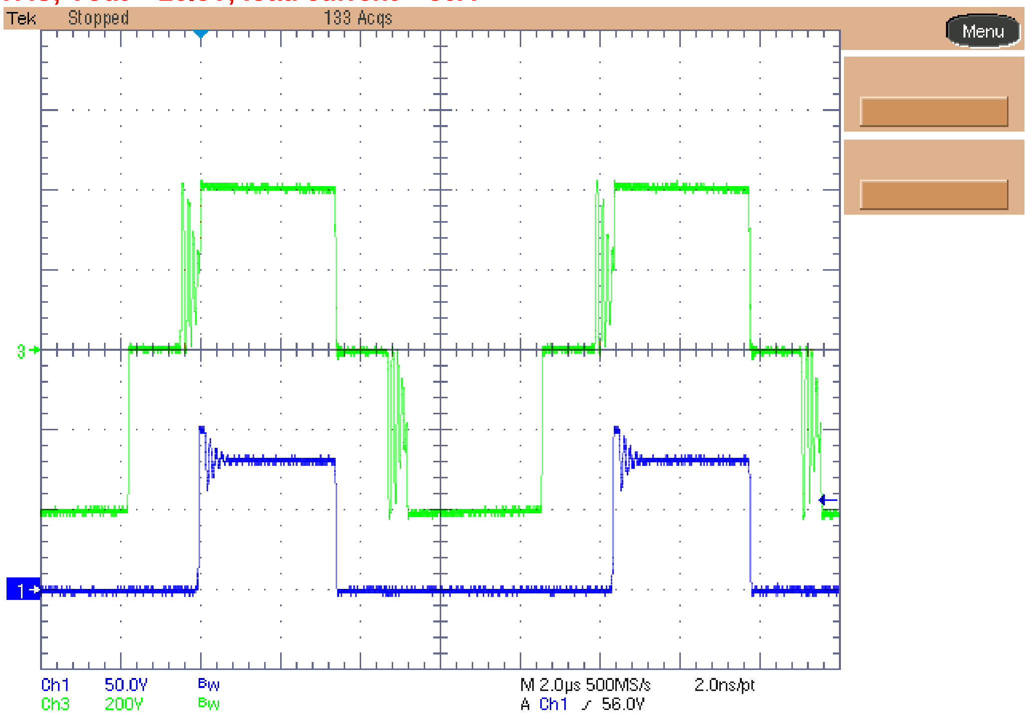
Vin = 230VAC, Vout = 26.5V, load current = 50A



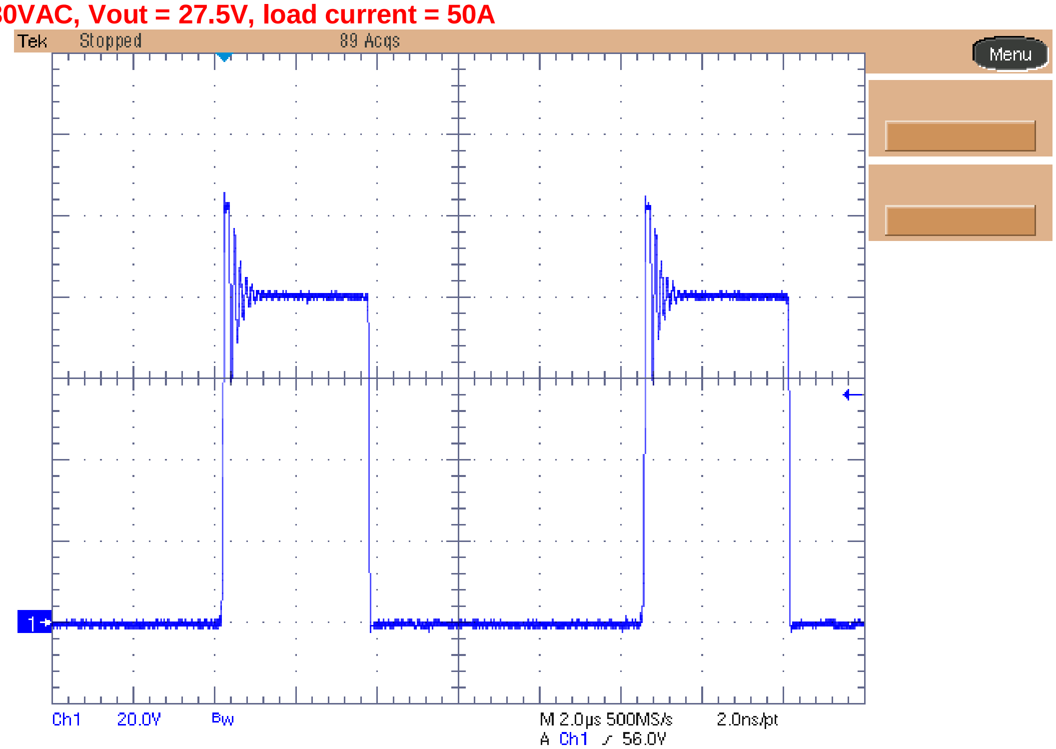
5.2 *Switching Waveforms from DC/DC Stage*

The DC/DC switching waveforms have been measured by supplying the converter at 230 VAC (50 Hz), at 50A load current, while Vout was set to 26.5V and 27.5V.

Ch3: Transformer voltage (pin 1-6) (200 V/div, 2 usec/div, 200 MHz BWL)
Ch1: Sync. rectifier (Q21-Vds) (50 V/div, 200 MHz BWL)
Vin = 230VAC, Vout = 26.5V, load current = 50A



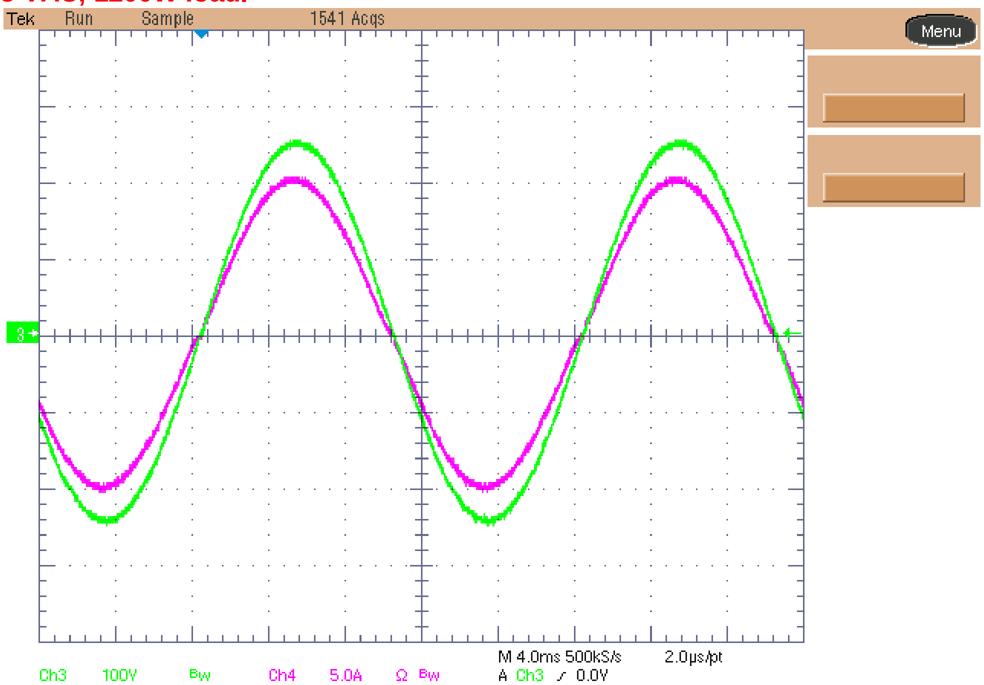
Ch1: Sync. rectifier (Q21-Vds) (20 V/div, 2 usec/div, 200 MHz BWL)
Vin = 230VAC, Vout = 27.5V, load current = 50A



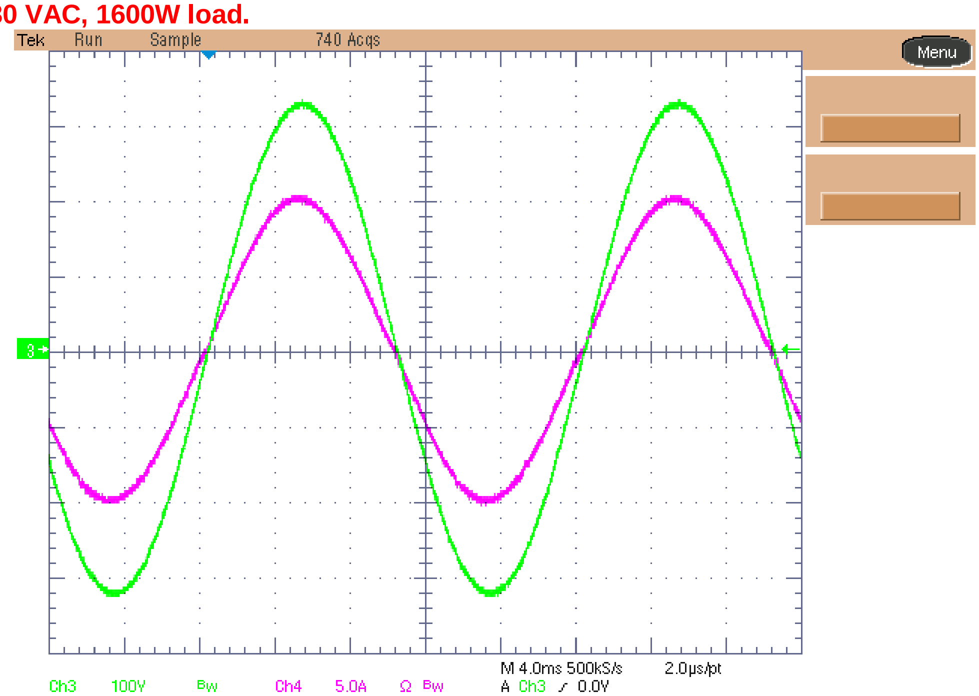
5.3 AC waveforms (Input Voltage and Input PFC Stage Current)

The screenshots shown below show the input voltage and current of the PFC stage, at 175 VAC, 230 VAC and 265VAC, in two different load conditions (all waveforms with 20 MHz BWL).

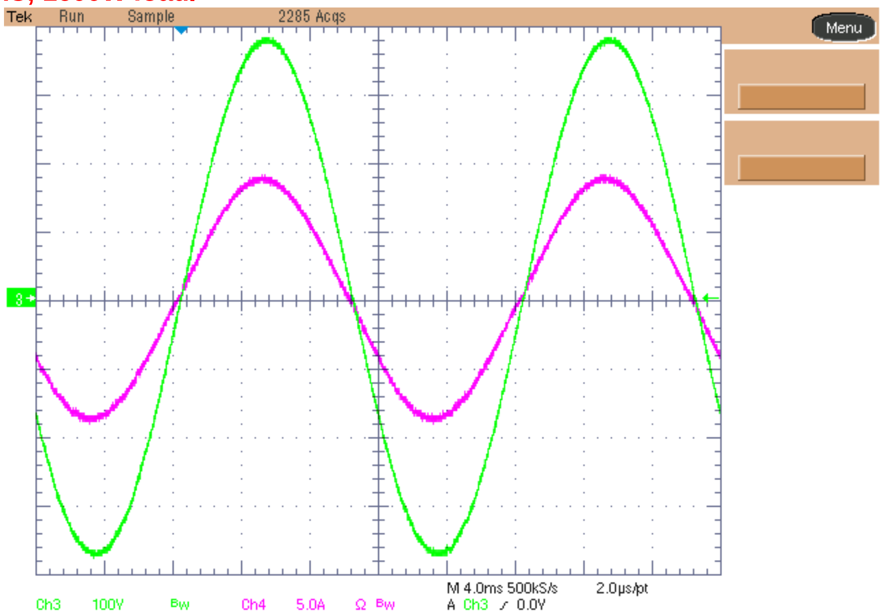
Ch3: Input AC voltage (100 V/div, 4 msec/div, DC coupling)
Ch4: Input AC current (5 A/div, DC coupling)
Vin = 175 VAC, 1200W load.



Ch3: Input AC voltage (100 V/div, 4 msec/div, DC coupling)
Ch4: Input AC current (5 A/div, DC coupling)
Vin = 230 VAC, 1600W load.



Ch3: Input AC voltage (100 V/div, 4 msec/div, DC coupling)
Ch4: Input AC current (5 A/div, DC coupling)
Vin = 265 VAC, 1600W load.

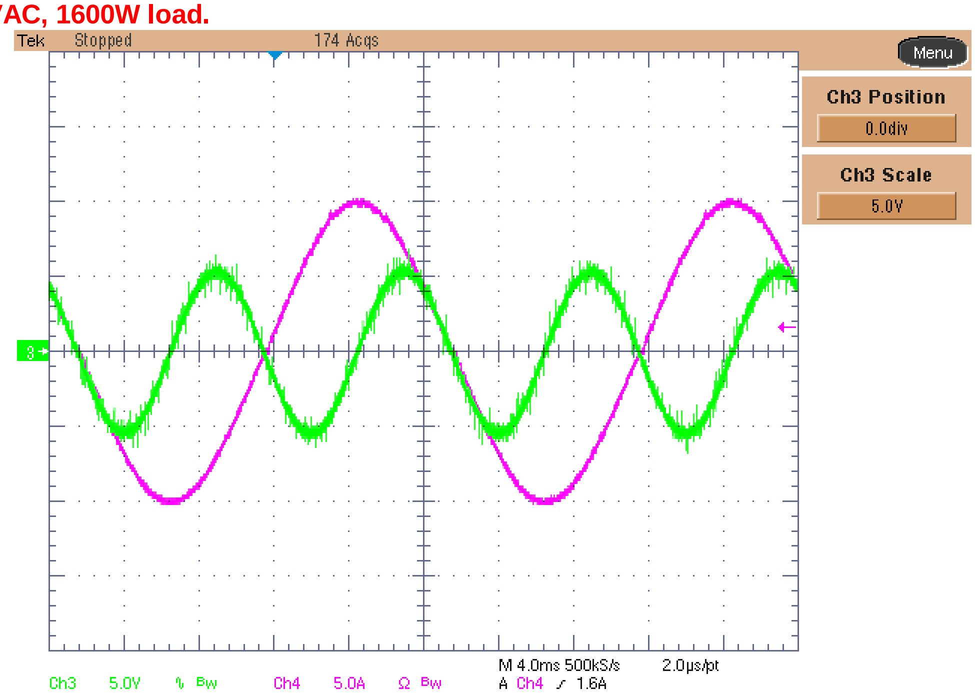


5.4 *Output Voltage Ripple*

5.4.1 PFC Stage

The PFC output voltage ripple has been measured by supplying the converter at 230 VAC, with 1.6KW load.

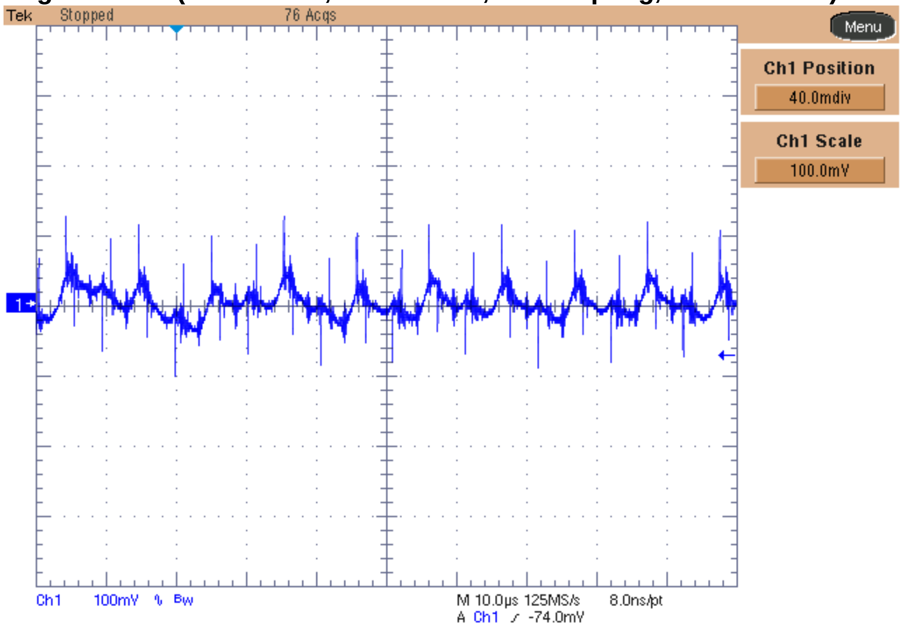
Ch3: Ripple voltage on J1-1 (5 V/div, 4 msec/div, AC coupling, 20 MHz BWL)
Ch4: Input AC current (5 A/div, DC coupling, 20 MHz BWL)
Vin = 230 VAC, 1600W load.



5.4.2 DC/DC Stage

The DC/DC output voltage ripple has been measured by supplying the converter at 230 VAC, setting Vout to 26.5V and with a load current of 50A.

Ch1: Ripple voltage on J8-1 (100 mV/div, 10 usec/div, AC coupling, 20 MHz BWL)

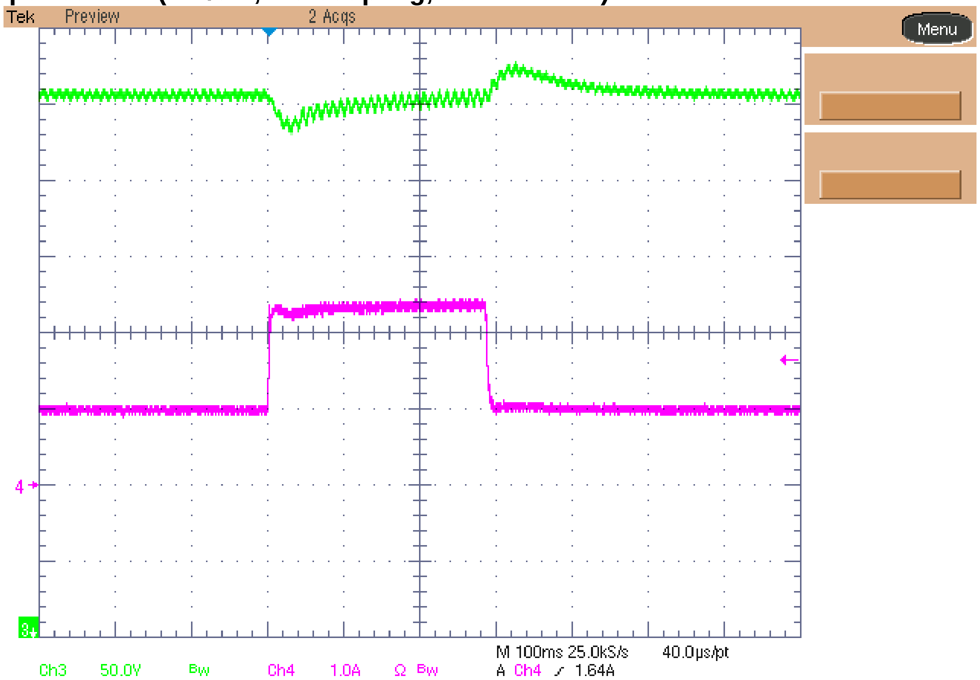


5.5 *Transients on PFC Stage*

5.5.1 Load Transients

The following screenshot shows the PFC output voltage during load transients. The module has been supplied at 230VAC, while the load current switched between 1A and 2.4A (equivalent to 400W to 960W).

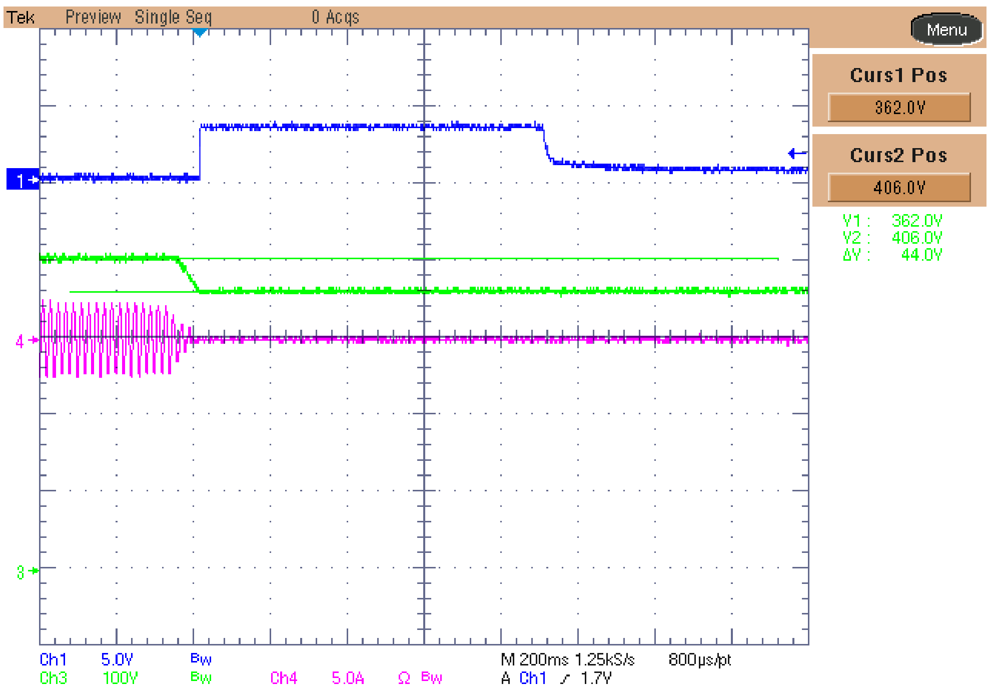
Ch3: Output voltage (J1-1) (50 V/div, 100 msec/div, DC coupling, 20 MHz BWL)
Ch4: Output current (1 A/div, DC coupling, 20 MHz BWL)



5.5.2 Voltage Transients (Mains Fail)

The next screenshot shows the situation where the mains source is switched off. The PFC output voltage has been captured, as well as the "power good" signal (pin 4 of U8, named "PG_PFC").

Ch1: PG_PFC Voltage (pin 4 of U8) (5 V/div, 200 msec/div, DC coupling, 20 MHz BWL)
Ch3: Output voltage (J1-1) (100 V/div, DC coupling, 20 MHz BWL)
Ch4: Input AC current (5 A/div, DC coupling, 20 MHz BWL)
Vin = 230VAC, Vout = 27.5V, load current = 14A



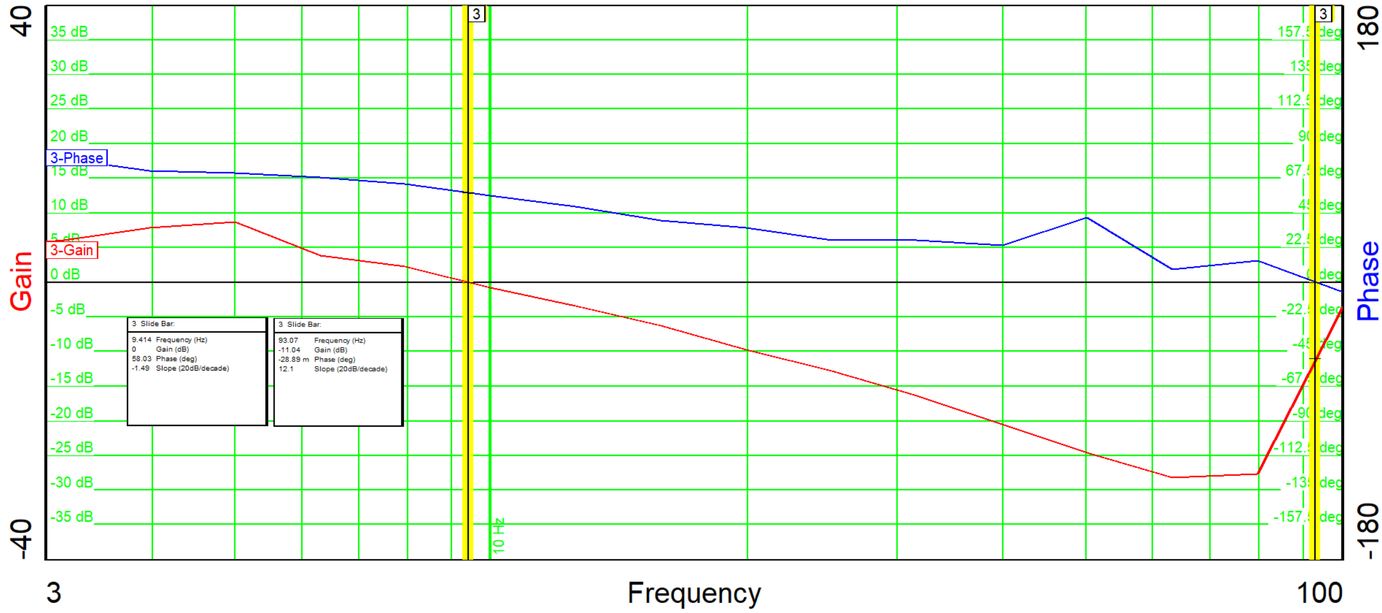
6 Bode Plots

The following graphs and tables show the bode plots of the PFC Boost stage, as well as the DC/DC stage.

6.1 PFC Stage

The Boost stage has been supplied at 230VAC, 50Hz and loaded at 2A in constant current mode.
In the next page is attached the bode plot, associated to the table below, showing the values of crossover frequency, phase margin and gain margin.

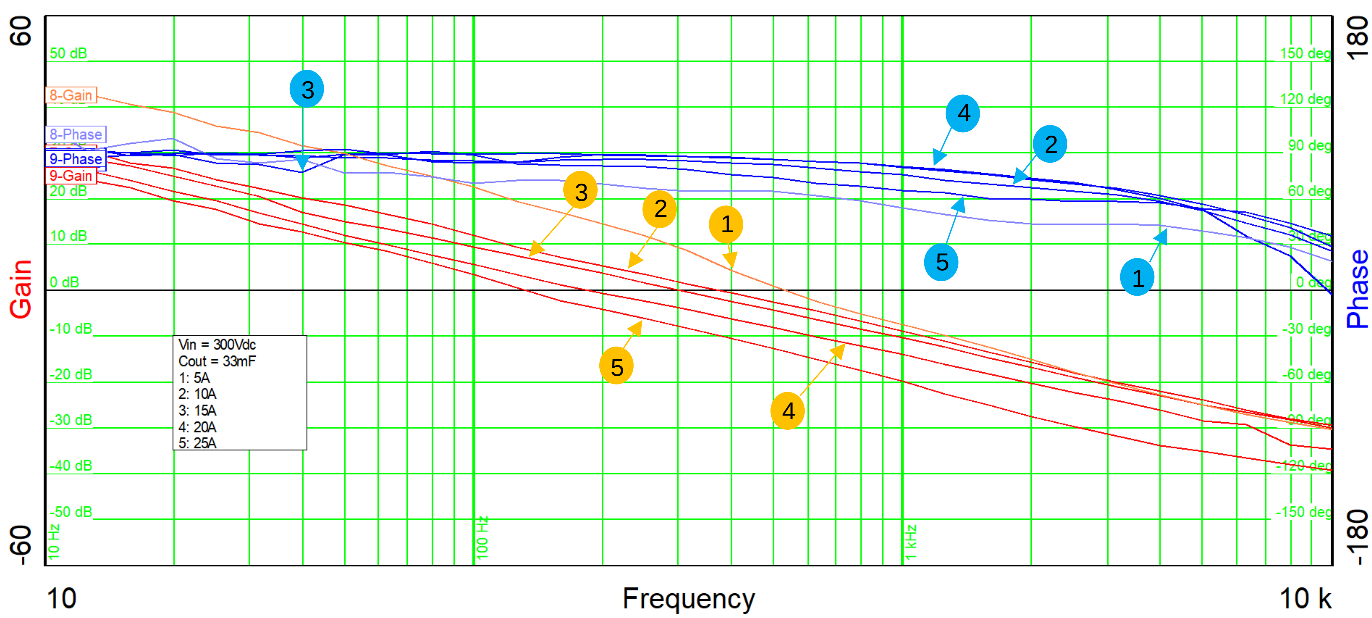
Parameter	Value
Crossover frequency (F_{CO}):	9.414 Hz
Phase margin:	58.03 deg.
Gain margin:	11.04 dB



6.2 DC/DC Stage

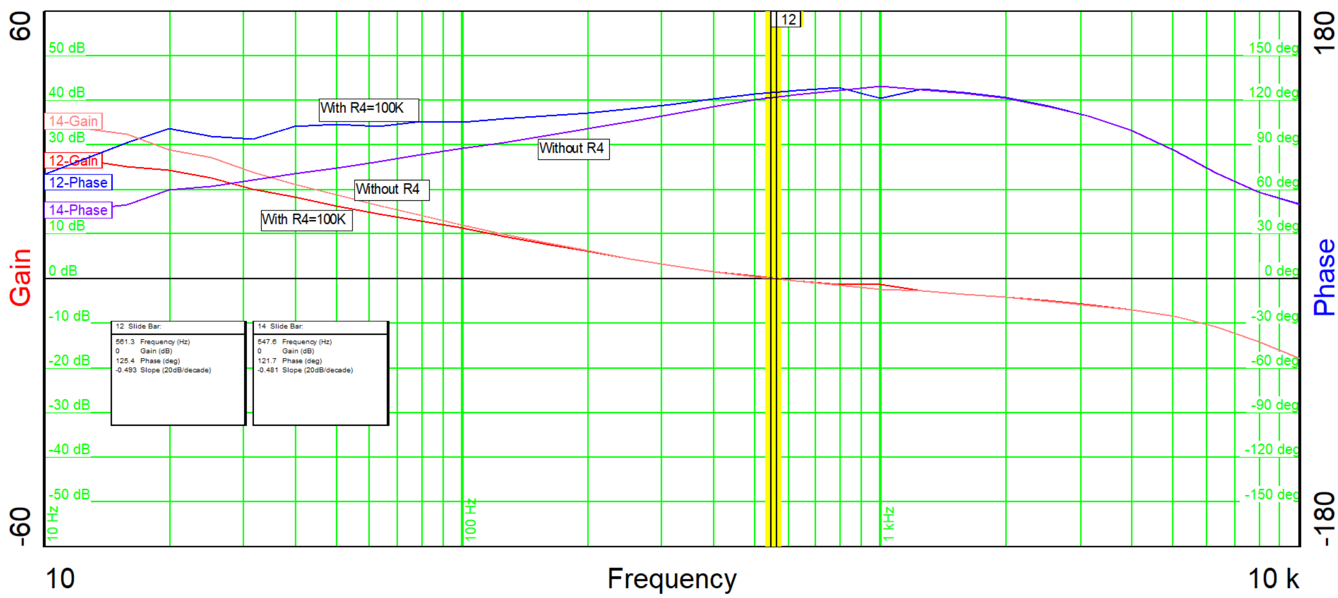
The DC/DC stage has been supplied at 300Vdc and attached to a constant-voltage load, set to 27Vdc, while the charging current has been varied in the range 5A…25A. An extra output capacitor (33,000 µF) has been connected to the output in order to simulate a low impedance battery. Here is a table showing the same parameters of the previous stage:

Parameter	Iout = 5A	Iout = 10A	Iout = 15A	Iout = 20A	Iout = 25A
F_{CO}:	530 Hz	374.3 Hz	302.2 Hz	184.2 Hz	131.3 Hz
Phase margin:	64.05 deg.	83.98 deg.	87.54 deg.	88.44 deg.	82.57 deg.
Gain margin:	> 30 dB	> 30 dB	> 30 dB	34.58 dB	> 30 dB



Another bode plot has been taken by setting the load into con constant-current load. The input voltage was 390Vdc and the extra-output capacitance of 33,000 µF was still connected. The output voltage was set to 22V and the load current to 40A. Two measurements show the difference when the resistor R4 was used or not populated. This resistor increases slightly the output impedance of the converter, simplifying the parallel connection of several modules. This can be seen as “phase lead increase” at low frequency range.

Parameter	With R4 = 100K	Without R4
F_{CO}:	561.3 Hz	547.6 Hz
Phase margin:	125.4 deg.	121.7 deg.
Gain margin:	> 20 dB	> 20 dB



7 Setting up the module

After supplying the module with AC voltage, in the range of 90VAC to 264VAC, the auxiliary power supply will provide all voltages needed at primary and secondary side, as well as the front panel display. Four pushbuttons are used to change the internal parameters as well as switching on and off the module, and also navigate through readout and alarms.

7.1 Switching ON the module

By depressing the red button (“ESC”) for more than 1 second, the converter toggles between on and off state, unless there is an alarm. In this case it will stay off, and the alarm can be visualized according to the alarm menu “ALM”.

7.2 Setting internal parameters (“SET” Menu)

It is possible to set the internal parameters by pressing the green button (“ENTER”) and enter the “SET” menu. By pressing one more time, it enters the menu “M/S Config.”, which is the Master/Slave configuration. Here it is possible to select whether the module runs in “Stand Alone”, “Slave #n” or “Master + n Slaves”.
The following is a description of the difference:

Stand Alone:

In “stand alone” mode, the module doesn’t respond to any command and doesn’t send any request, but it behaves like a normal power supply. All parameters are active, like the voltage levels, current limit, UVLO and OVP etc.

Slave #n:

In this case, it is supposed that there is at least one master that takes the control of the complete system. This slave sets Vout to maximum allowed and output current limit to maximum as well. The master will send to this slave what Vout and Ilim will be. This slave will respond by letting the master know what is its own output current and if there is any alarm or warning. The master collects all information about all slaves and provides on its display this information.

Master + n Slaves:

By setting the number of the slaves, this master will poll all slaves periodically, in order to set their parameters, output voltages and current limits as well as reading their parameters. As described in the “Slave #n” section, the master will collect all information. That means, if the master is on, all slave will be set to on, unless there is any alarm in one slave, which will be set to off by itself.

If we do not press the “ENTER” button, we can scroll all parameters, like “Type of Battery”, “Trickle Level”, “Float Level”, “Minimum Level”, “Charge Current”, “Power Limit”, “Minimum Current for Trickle Charge”, “Mains UVLO”, “Mains OVV”, “Temperature Coefficient”, “Over temperature” and “Backlight always on/off/timer”.
All parameters above are active in this design, except the “type of battery”, “float level”, “minimum level”, “minimum current for trickle charge” and “temperature coefficient”. Typically the charging profile is custom software to be developed according to the final application.

7.3 Reading main electrical values (“READ” Menu)

By pushing the “+” button (under the menu “READ”), It is possible to enter this menu and scroll (with buttons “+” and “-“) several readings, like VAC, internal temperature, status and charge level, as well as fan RPM. In each menu, it is possible to exit from it by pressing “ESC” button.

7.4 Managing alarms and warnings (“ALM” Menu)

The alarm/warning menu can be accessed by pressing the “-” button (under the menu “ALM”). If there is no alarm or warning, it will be shown accordingly.
If there are several alarms, with pushbuttons “+” and “-” it is possible to scroll them. If one alarm is resettable (not all of them are possible) just press the button “ENTER”. After reading them, it is possible to go back to main menu by pressing the “ESC” button.

8 LED indicators

In this module we have three LEDs: green, yellow and red. If there is no abnormal situation, the green LED will light solid (blinking if changing status, for example during startup). In case of abnormality, the red or yellow LED will indicate the following situations:

Red:

There is at least one alarm, which forces the module to off state, and transfers this command to all slaves (if any). If this module is a slave, it will inform the master that there is an alarm.
The table on the left, below, is showing the list of the relative alarms.

Yellow:

There is at least one warning. The converter is still supplying power and will not shut off. It will transfer its status to the master only if it’s a slave. As master there will be no communication.
The table on the right is showing the list of the relative warnings.

#	Alarm Description
0	Mains too low
1	Mains overvoltage
2	Output overvoltage
3	Output shorted
4	Reverse polarity
5	Over temperature
6	Fan failure
7	DC/DC failure

MODULE OFF

#	Warning Description
0	Output current limit
1	Output power limit
2	Input current limit
3	Low battery voltage
4	not used
5	not used
6	not used
7	not used

Yellow LED ON