# 43 W PFC-SSR flyback demo board with ICL88xx

## Flyback IC for lighting applications

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### Scope and purpose

Two-stage topologies are growing in popularity because of the convenient scalability of power on the primary side as well as the features on the secondary side. High light quality, very low dimming levels, and more complex systems with sensors and MCUs require a stable output voltage enabled by constant voltage (CV) secondary-side regulated (SSR) topology. More stringent standards for flicker and total harmonic distortion (THD) as well as harmonics are also points in favor of SSR topology. The controller used in SSR configuration is suitable for on/off LED drivers and is the best solution for minimum dimming levels down to 0.1 percent and dim-to-off.

### Intended audience

Engineers interested in using ICL88xx as SSR high power factor (PF) flyback with CV output.

## Table of contents

# 1 Introduction

SSR is the best-fit topology for on/off LED drivers and drivers with minimum dimming down to dim-to-off. The main difference between SSR and primary-side regulation (PSR) topology is based on the fact that in the PSR system the main channel secondary-side output voltage is measured indirectly on the primary auxiliary supply winding. This means the coupling between the main secondary and auxiliary windings does affect the regulation accuracy. In contrast, the SSR system directly measures the output, which makes the transformer design easier and less complicated. For the best THD and PF performance the crossover frequency of the feedback loop should be in the range of 5 to 20 Hz. If the crossover frequency is too low, the feedback reaction would be very slow, making it unsuitable for dynamic load changes such as sudden load loss. At the same time, a lower crossover frequency improves THD. It's a compromise between feedback reaction and iTHD. But, if a faster load-jump-dependent loop is required, a fast path can be easily added to the existing feedback loop.

For the secondary-side overvoltage protection (OVP) it is necessary to say that it has a 10 percent tolerance over the production and temperature range; this fact must be considered during the design of the driver. If the overvoltage level is too close to the normal operation voltage, it may lead to accidental triggering of the protection during fast load changes, especially at high input voltages. Here the feedback loop is too slow to react to a sudden load loss, and it can't control the output voltage within the very tight limit anymore. The converter will therefore move to hiccup oscillation. The OVP level must have a proper margin. If it's mandatory to improve regulation accuracy, there are a few options:

- To use a dynamic feedback or dynamic bleeder, which is active only when the voltage reaches a certain point. This adds some complexity and increases cost.
- To increase the size of the output capacitor.

If only dimming to 5 to 10 percent is required and a larger output voltage tolerance (3 to 5 percent) is acceptable then it might be possible to go for a PSR design, where the system costs are lower compared with the SSR solution. The ICL88xx family can be used with all the features in the SSR system as well as the PSR topology. More information about the PSR solution can be found in the **Engineering Report of the PSR reference design**.

As a default setup, the reference design board is assembled with a start-up circuit based on a depletion mode MOSFET BSS126i on a very small adapter board. After the first start, the IC is then supplied from the auxiliary winding and the start-up circuit is disabled. This setup offers the lowest standby losses. If low standby consumption is not necessary as an option, the start-up circut can be changed to a resistive start-up. Here only the resistor R35 in the main schematic (**Figure 2**) with 0 Ω and a protective Zener diode with 22 V needs to be added while the daughterboard gets removed.

This reference design is provided with two regulation circuits. Both circuits are designed as plug and play solutions, but at least one has to be connected to the main board.

The two boards shall show the trade-off between cost; here the TL431 board offers the cheaper solution, and standby performance, while the op-amp board shows an overall 30 mW better performance.

**ICL8800** is a family member, which is cost-optimized and can be perfectly used for on/off drivers and dimming down to 5 percent, as shown in **Figure 29**.

**ICL8810** is a family member with the burst mode (BM) feature. This helps to control the output voltage quite accurately down to a very low output power level and dim-to-off operation. After the limit of ICL8800 shown in **Figure 28**, the IC moves gradually to BM, as shown in section 7.3, and finally to the standby mode shown in **Figure 36**.

**ICL8820** is a family member with a BM and jitter feature. In addition to the BM, this IC offers a jitter function during DC operation. This helps to pass the EMI requirements for DC operation, required for the emergency lighting system. This behavior is shown in sections 7.4 and 11.2.

# 2 Specifications

Input and output specifications of the ICL88xx PFC-SSR flyback demo board are shown in the table below.

**Table 1 Design specifications**

| Specification | Symbol | Value | Unit |
|---|---|---|---|
| Maximum AC input voltage | V AC | 90 to 305 | $V_{rms}$ |
| Normal operational AC input voltage | $V\ AC_{max}$ | 100 to 277 | $V_{rms}$ |
| Normal operational AC input frequency | $F_{line}$ | 47 ~ 63 | Hz |
| Secondary-side regulated CV output set-point | $V_{out,setpoint}$ | 54 | V |
| Steady-state output load current | $I_{out}$ | 0 ~ 800 | mA |
| Steady-state full-load output power | $P_{out,full}$ | 43.2 | W |
| Minimum efficiency at $P_{out,full}$ | $\eta_{min,at,P,out,full}$ | 91 | % |
| Target minimum switching frequency at $P_{out,full}$ | $f_{sw,min,at,P,out,full}$ | 52 | kHz |
| Minimum load for ICL8800 | | 10 percent at 277 V AC/ 5 percent at 230 V AC/1.5 percent at 120 V AC | |
| **Standard compliance** | | | |
| Harmonics | – | EN 61000-3-2 class C | – |
| EMI | – | EN55015 | – |
| **Board dimensions** | | | |
| Size | L x B | Main board: 171 x 27 | mm |
| Size | L x B | PlugIN-TL: 36.5 x 27 | mm |

# 3 Connections

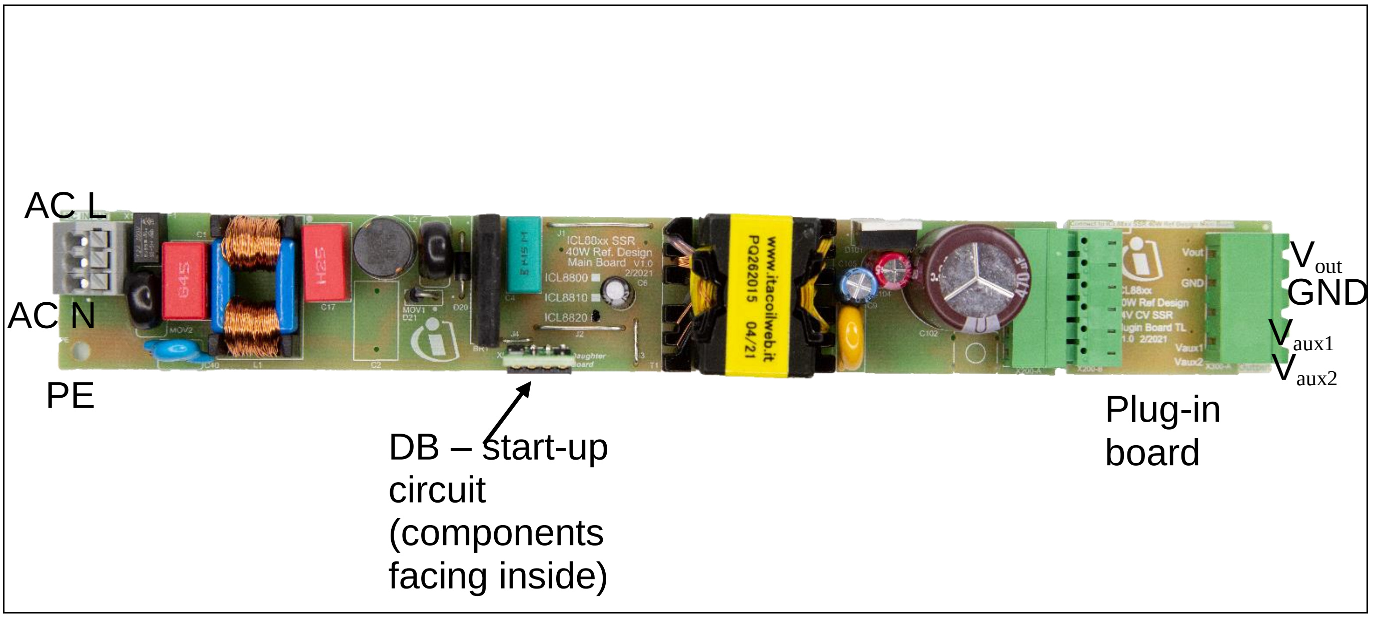



**Figure 1 Top side with connections**

# 4 Schematics

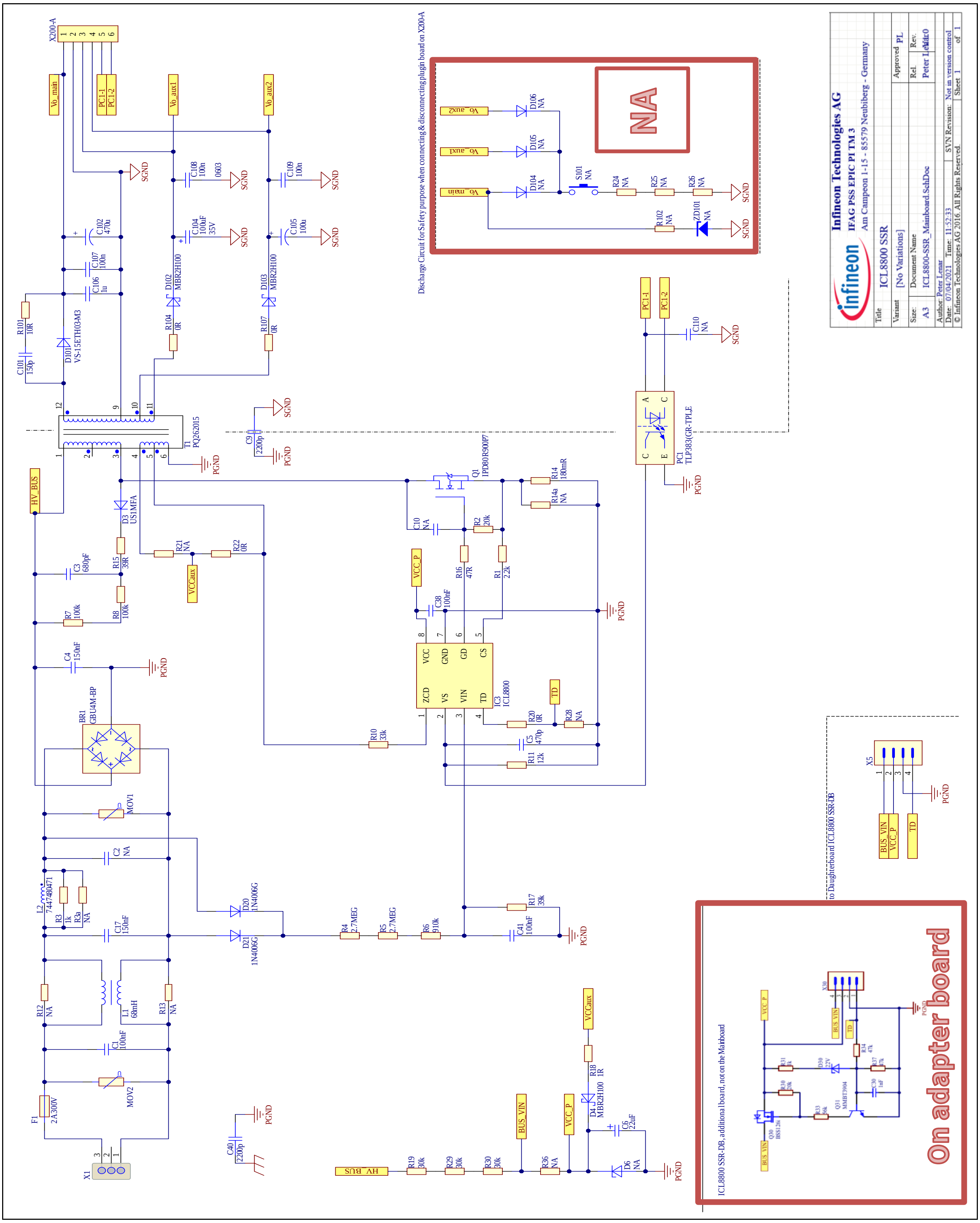



**Figure 2** Schematic of the ICL88xx PFC-SSR flyback demo board

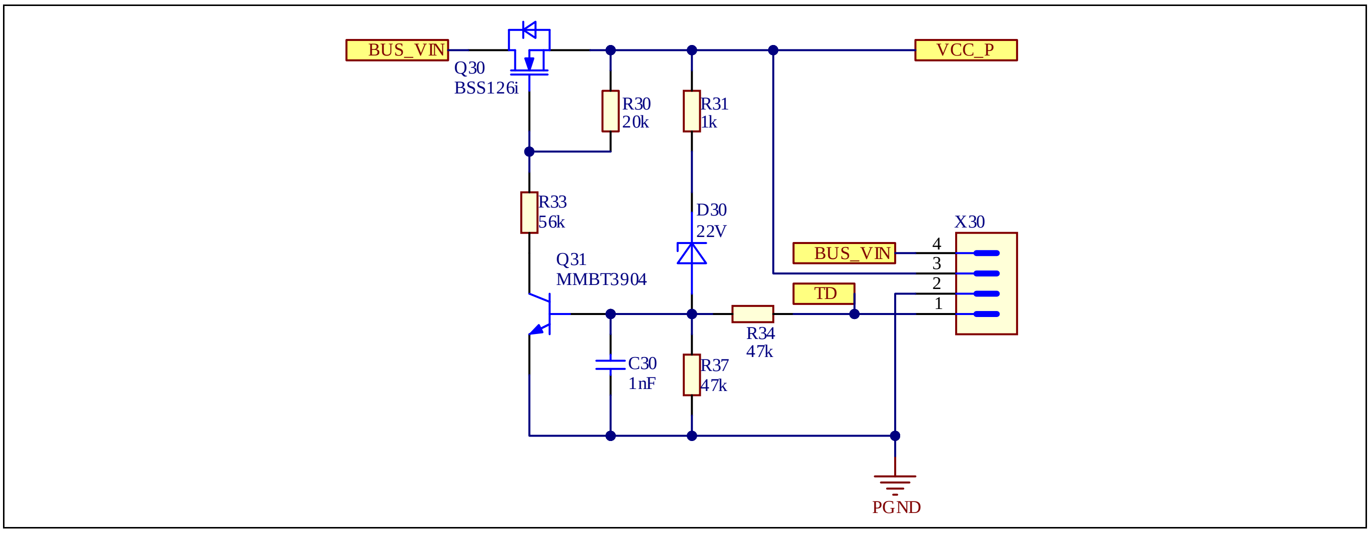



**Figure 3** Schematic of the daughterboard with start-up circuit

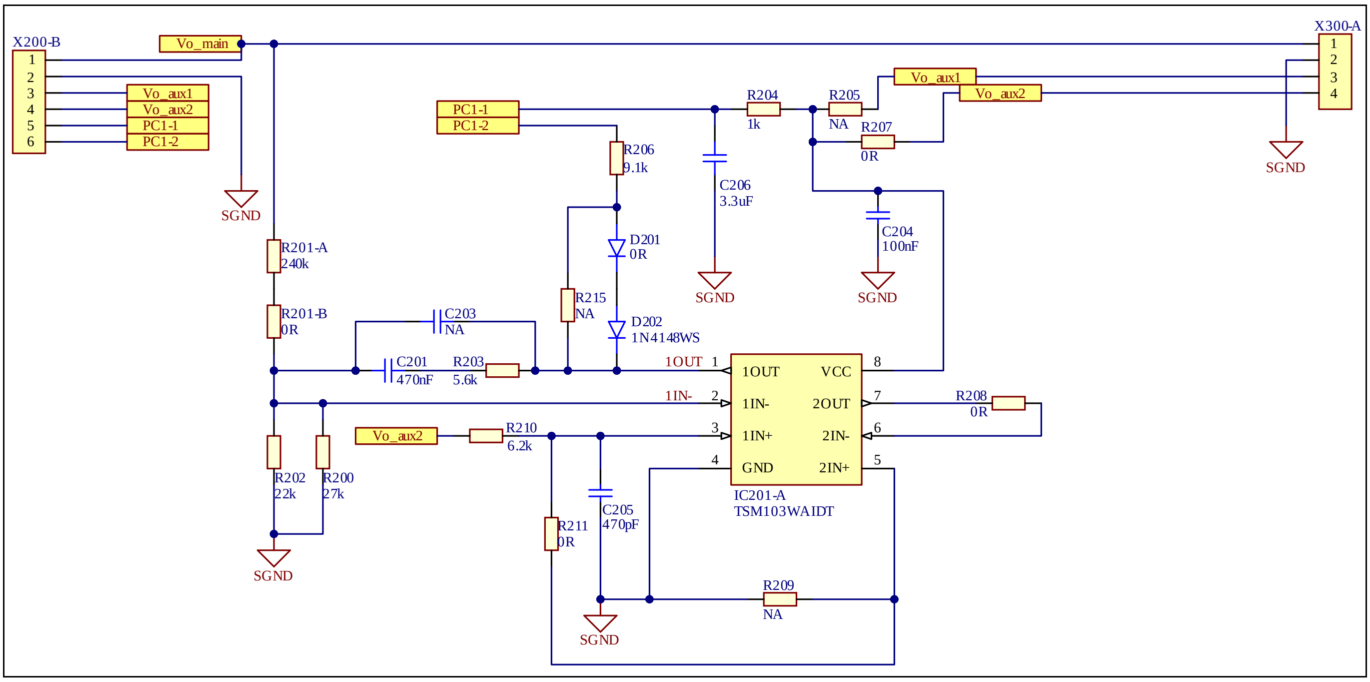



**Figure 4** Schematic of the op-amp plug-in board with the feedback loop

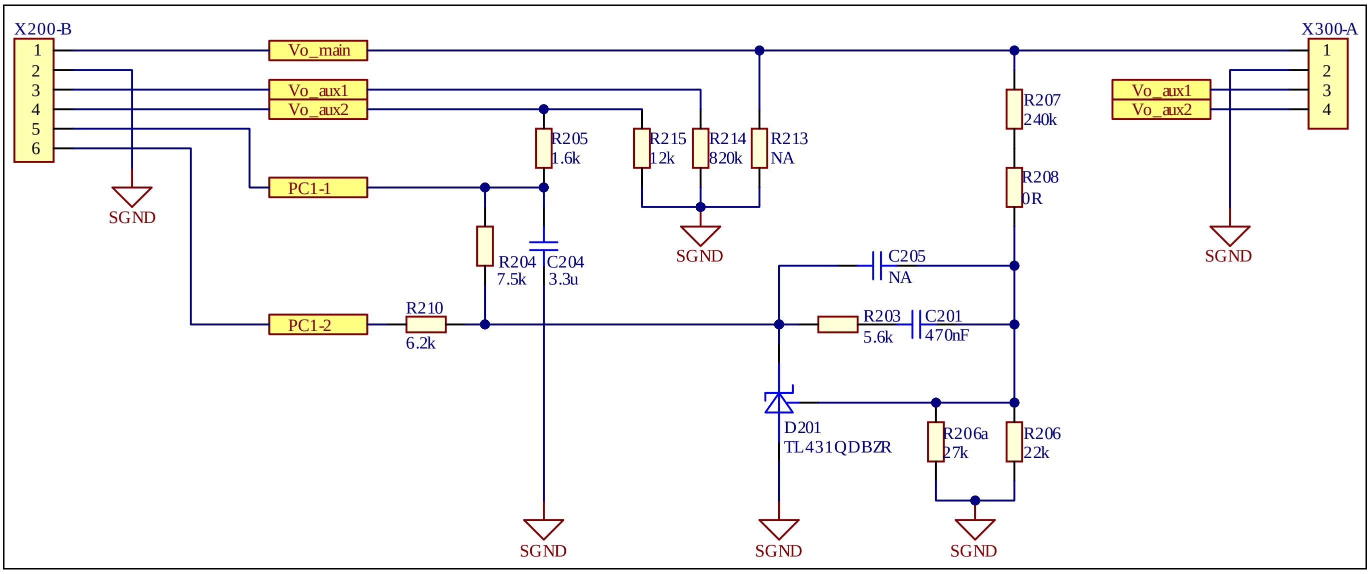



**Figure 5** **Schematic of the TL431 plug-in board with the feedback loop**

# 5 Layouts

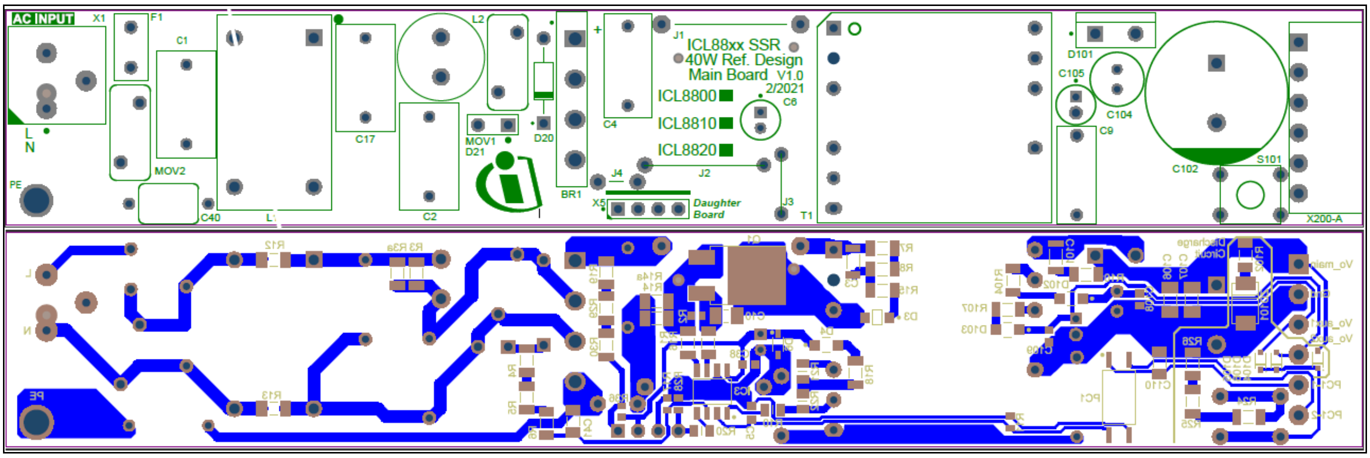



**Figure 6** Layout of the top and bottom side of the main power board

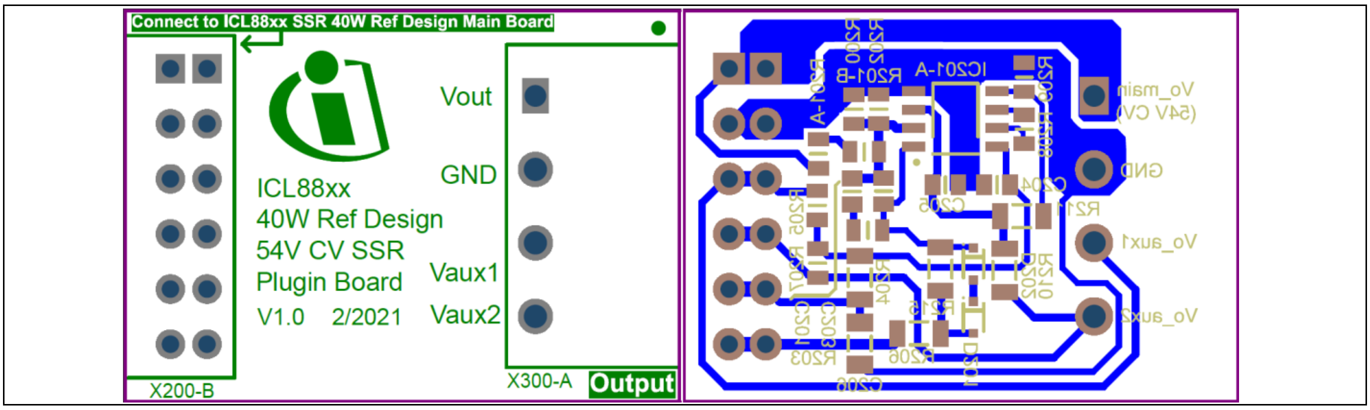



**Figure 7** Layout of the op-amp regulation plug-in board

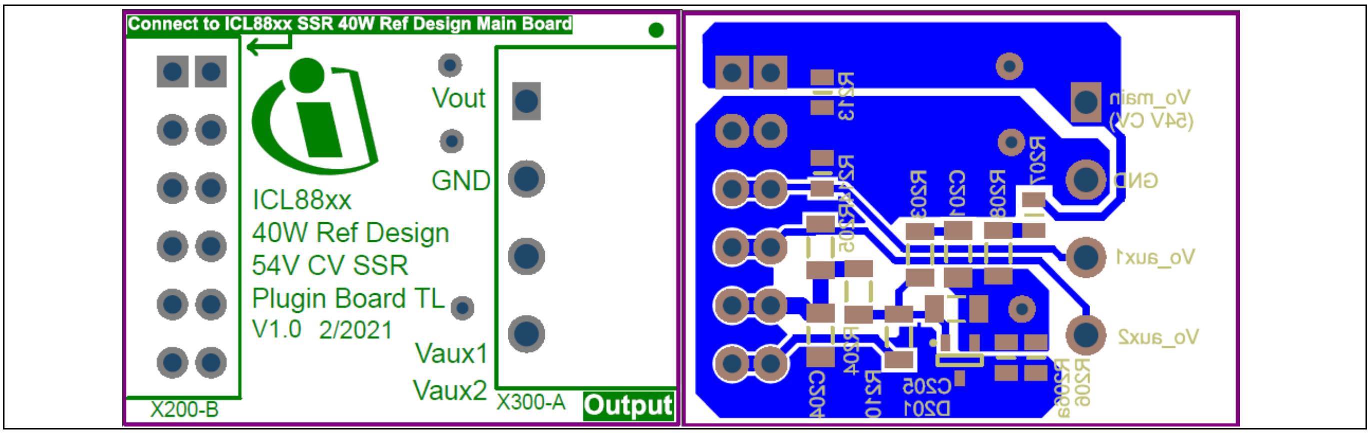



**Figure 8** Layout of the TL431 regulation plug-in board

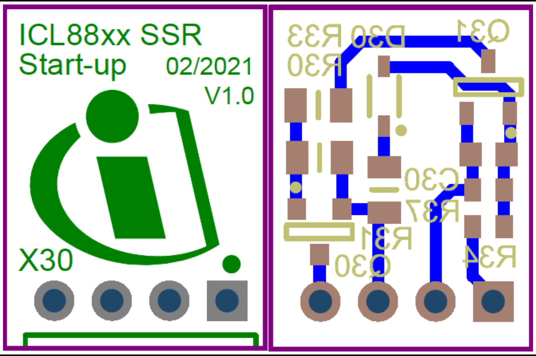



**Figure 9** **Layout of the start-up board**

# 6 Board combinations

Based on the markings on the top side of the board, a different IC out of the ICL88xx family is assembled. The ICs and the boards can be changed without any additional measures. Based on the selected IC, different features are built in.

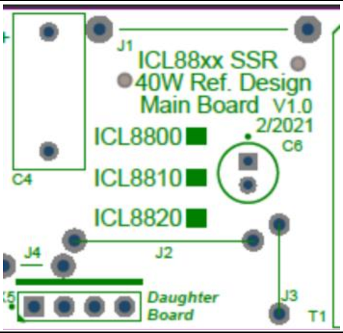



**Figure 10 The soldered-in IC is marked on the powerboard's top side**

## 6.1 Start-up options

As described earlier, the board offers two options for start-up. The resistive circuit is cheap but has constant losses, which are dependent on the input voltage. It is perfect for on/off drivers and dimmable drivers without standby requirements.

The active start-up circuit can provide faster charging of the $V_{CC}$ capacitor. The biggest advantage is the controllable resistive path. In that way the losses are only present during start-up, and if the $V_{CC}$ gets too low. This option is most suitable where standby losses matter.

If testing without the start-up board, the start-up resistors have to be increased to around 200 kΩ, and R36 has to be added, and D6 with 22 V has to be added. This start-up board has to be unplugged.

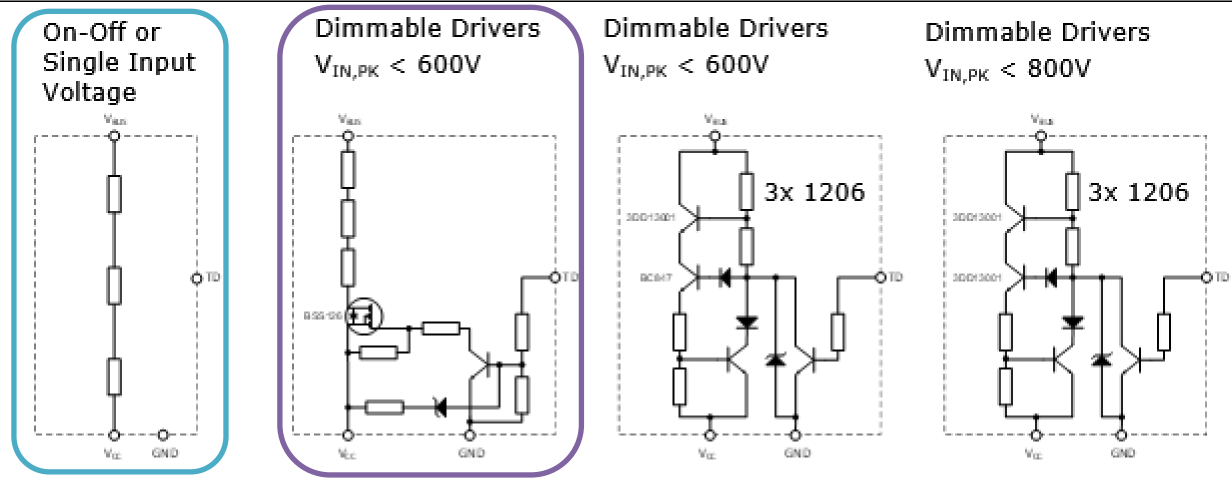



**Figure 11 A selection of start-up options**

## 6.2 SSR circuit

Here, again, two options are offered. The TL431 is the simpler circuit but has higher losses due to the minimum current for the TL431 in order to stay operational.

The choice is between low-cost higher standby losses, and higher-cost better standby performance.

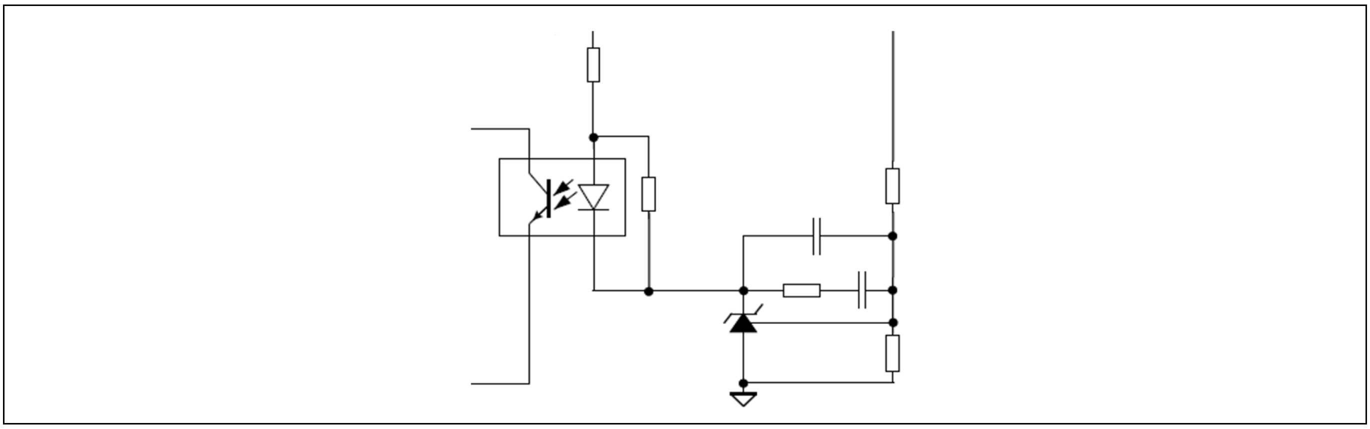


**Figure 12 TL431 circuit**

On the other hand, the op-amp with integrated voltage reference offers the best standby performance.

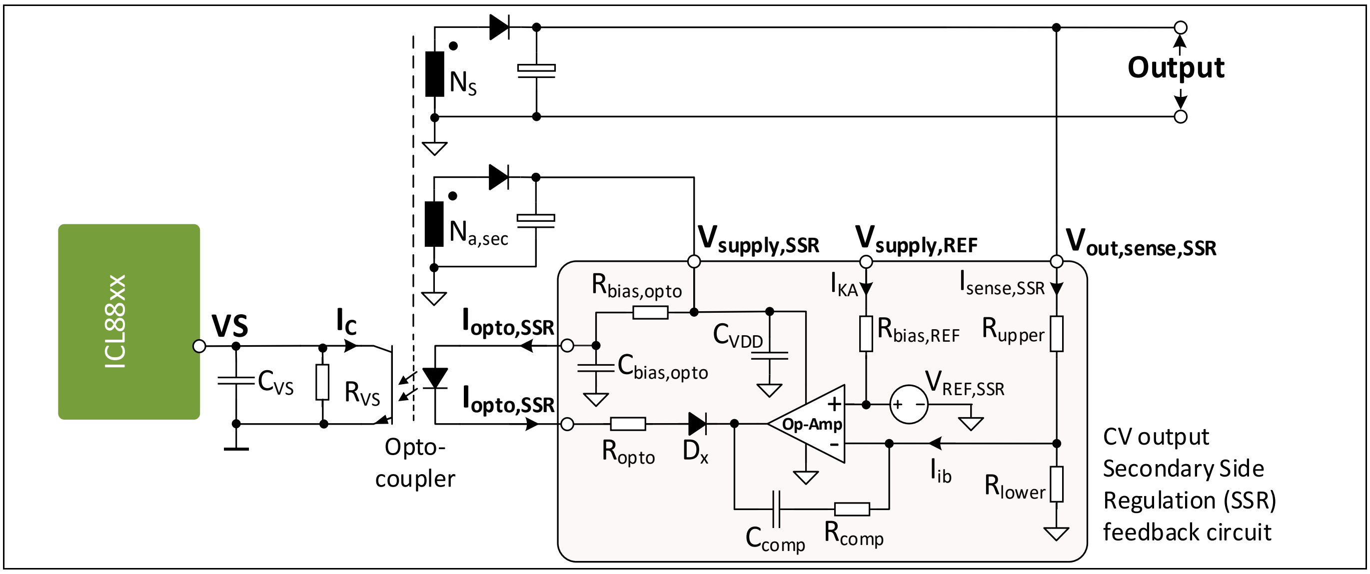



**Figure 13 Op-amp circuit**

Both circuits have their advantages and downsides, and there is no general answer to which circuit is the best. It always depends on the input and output specifications, the focus on cost or performance, and the availability of components.

For test purposes, both boards can be used as plug and play.

***Attention:*** ***Make sure the ouput capacitor is discharged and the AC mains voltage is turned off before changing the feedback board. To make the process easier, the footprint of a discharge circuit is already added on the main PCB. After assembling it the ouput capacitor can be safely discharged by the push of a button.***

# 7 Performance

## 7.1 Performance with op-amp

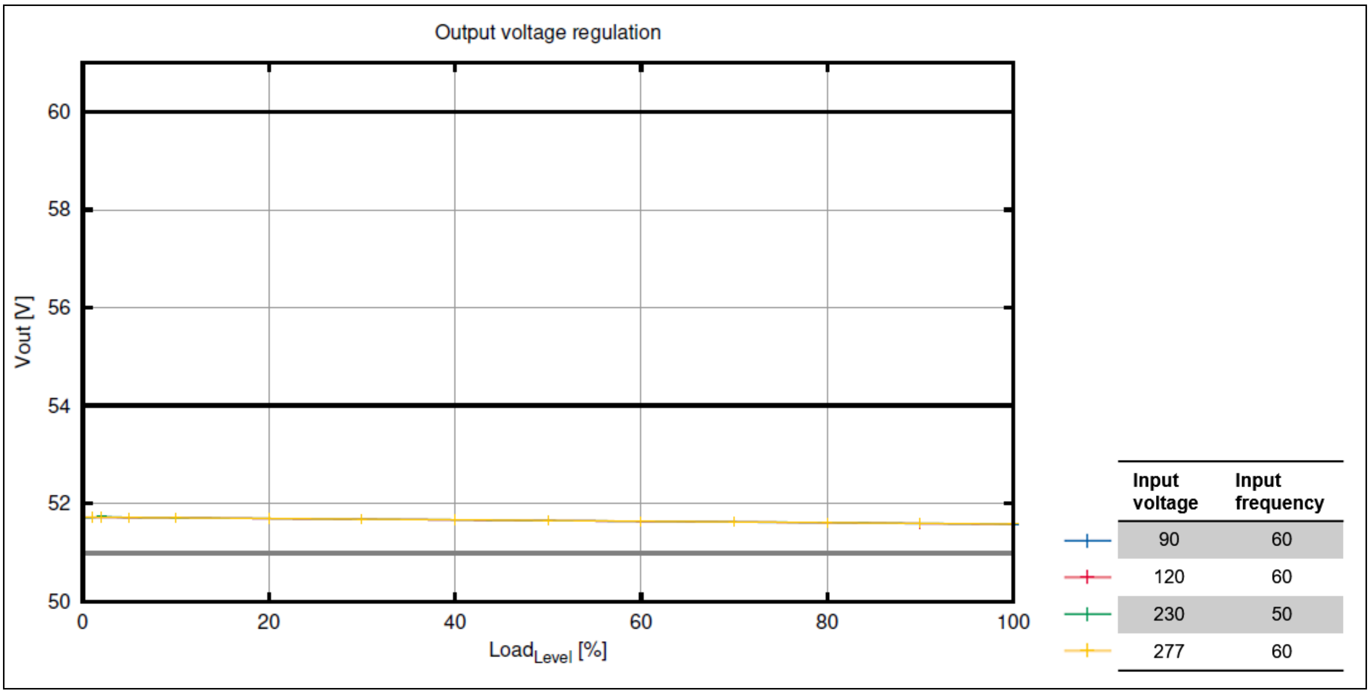



**Figure 14** $V_{out}$ regulation

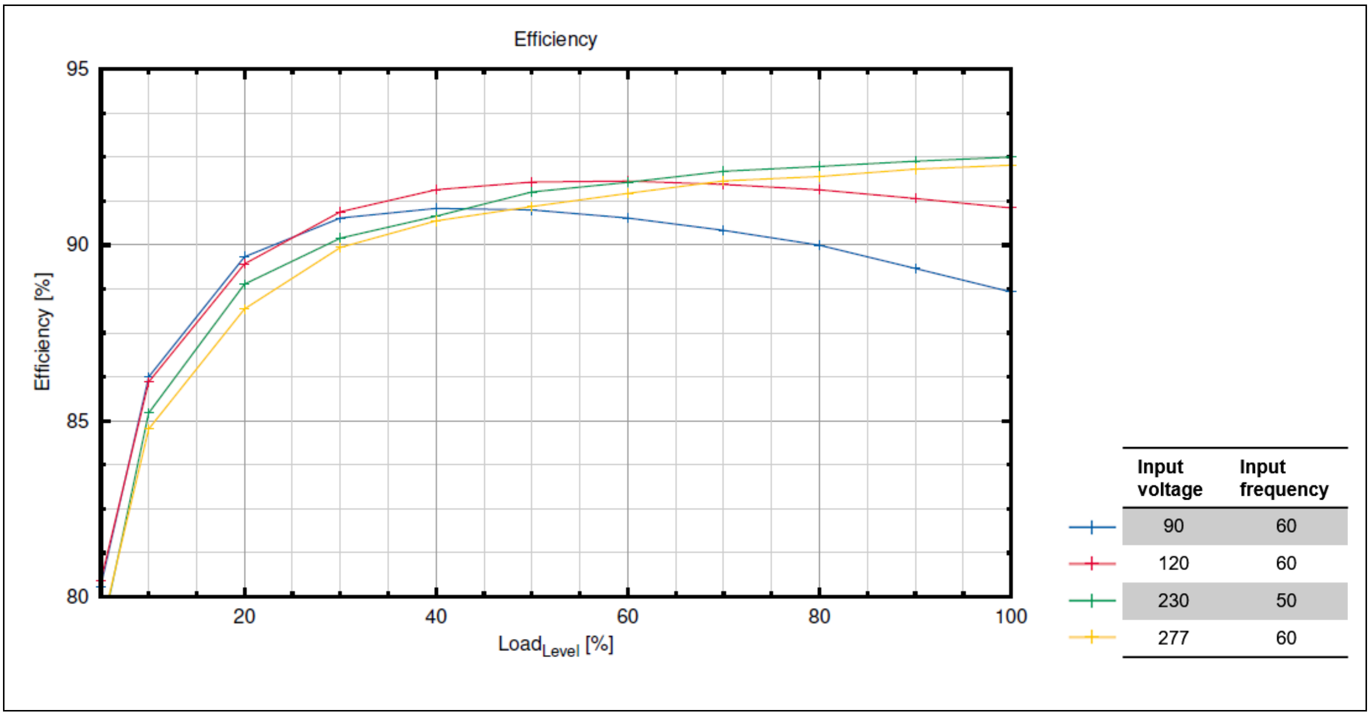



**Figure 15** Efficiency

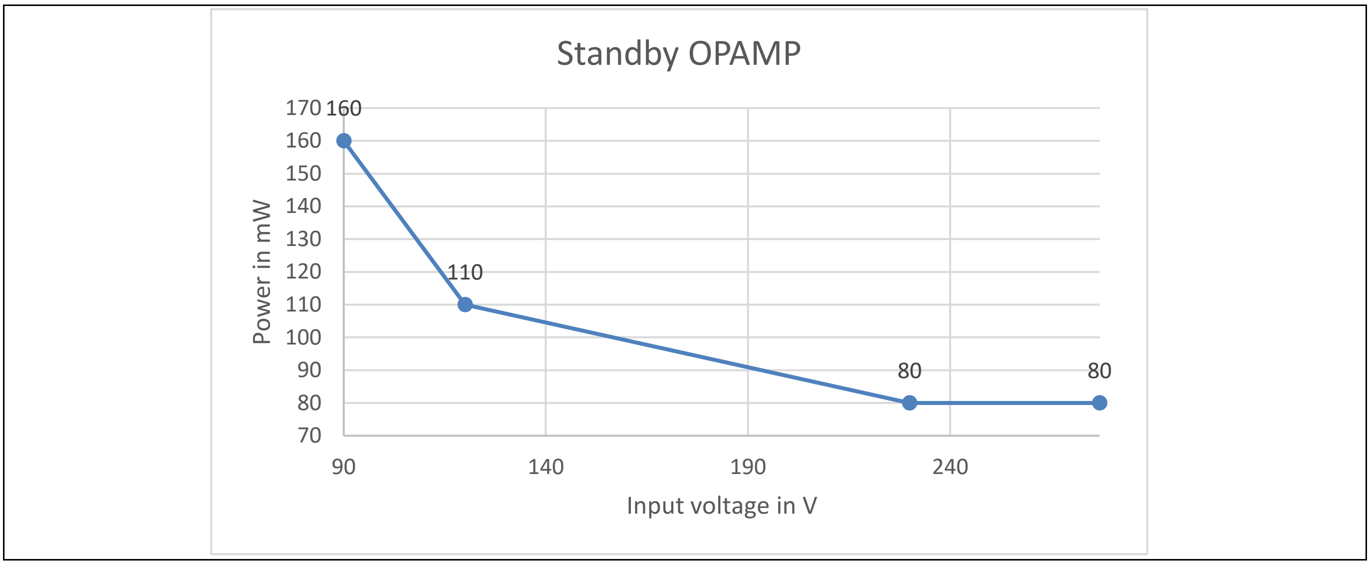



**Figure 16 No-load input power**

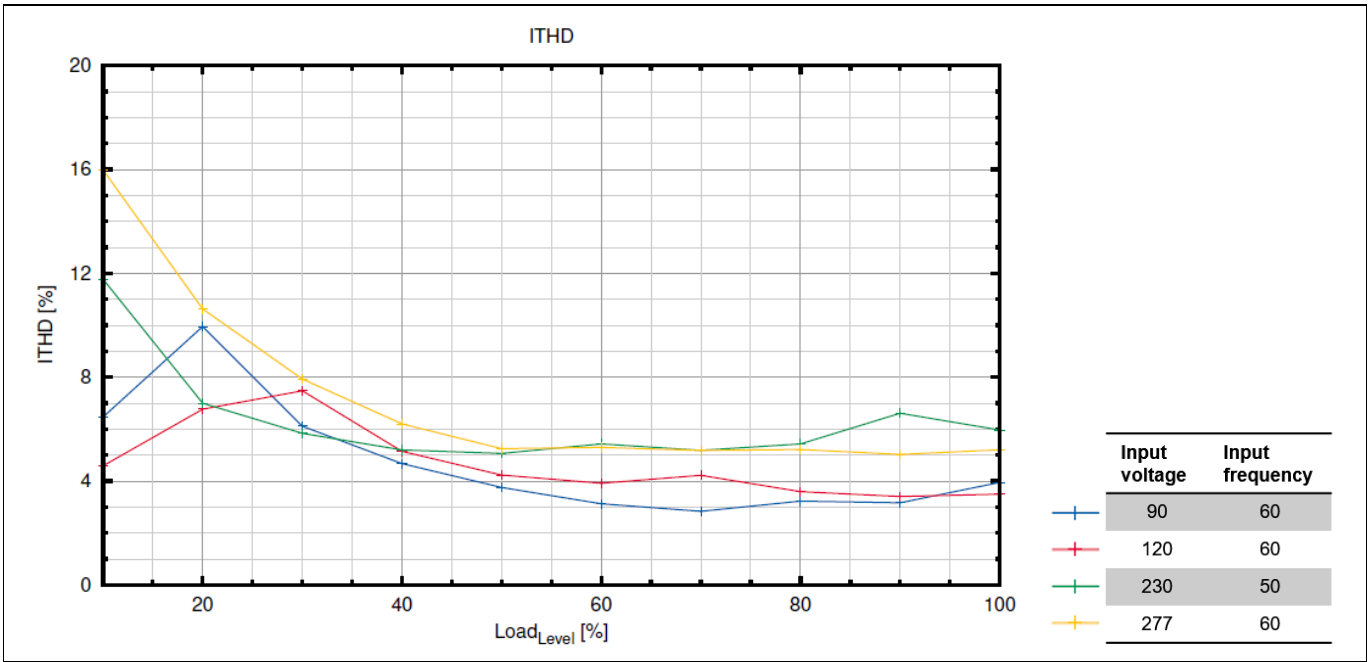



**Figure 17 THD measurement**

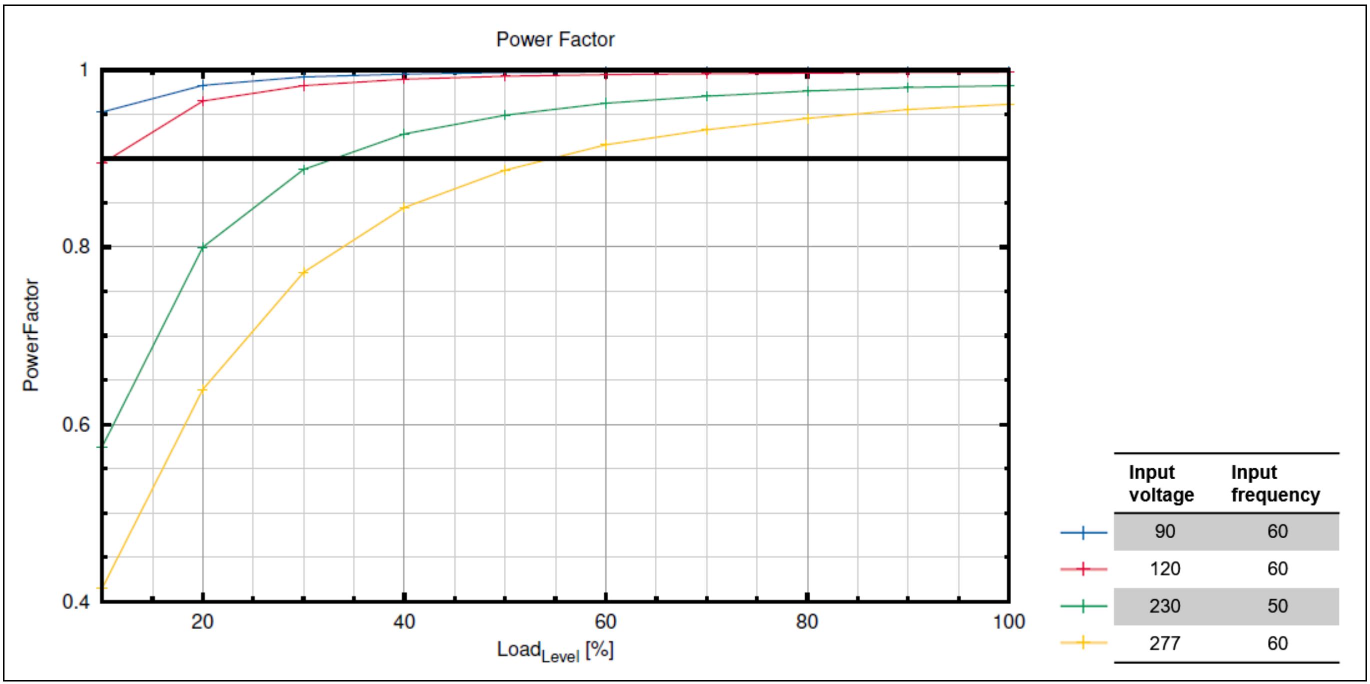



**Figure 18** PF measurement

## 7.2 Performance with TL431

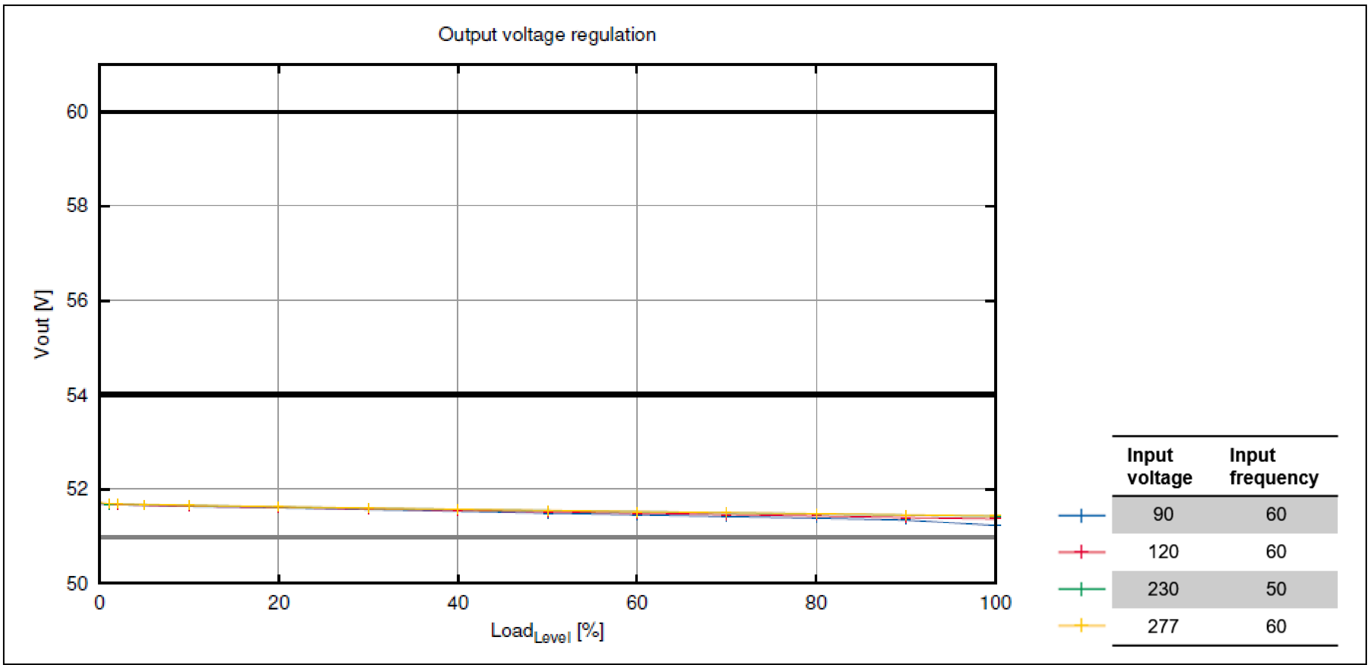



**Figure 19** $V_{out}$ regulation

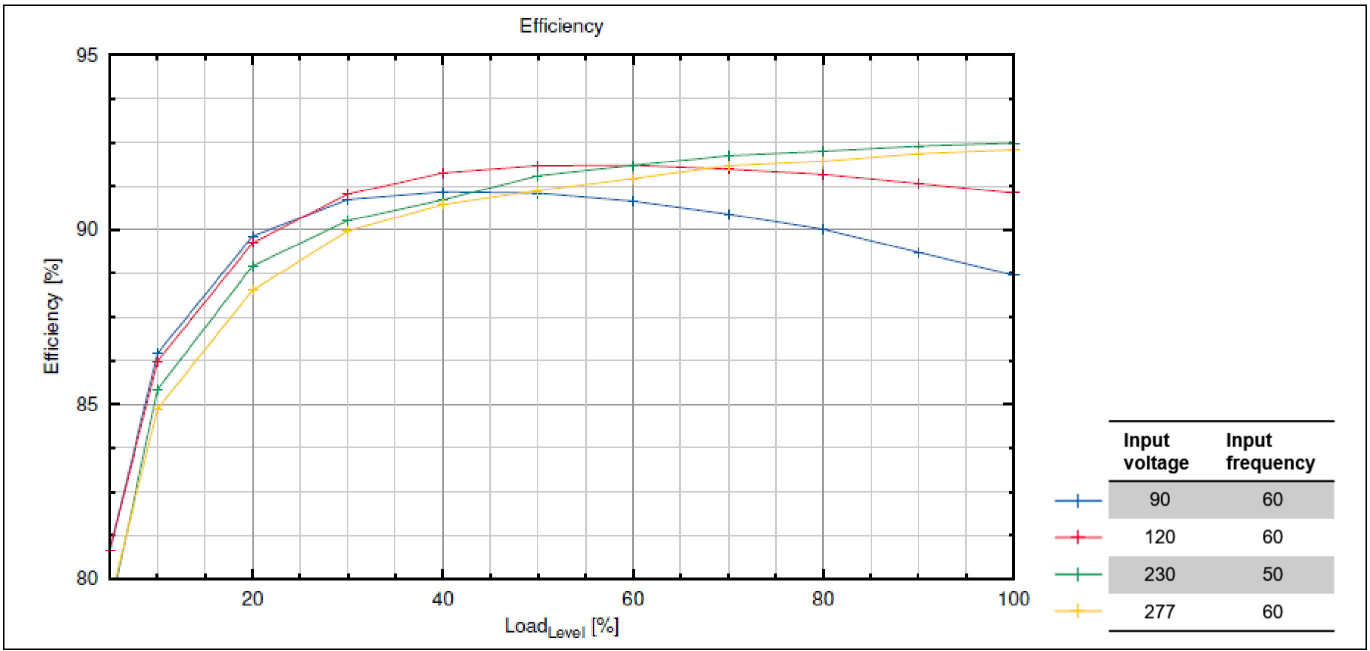



**Figure 20 Efficiency**

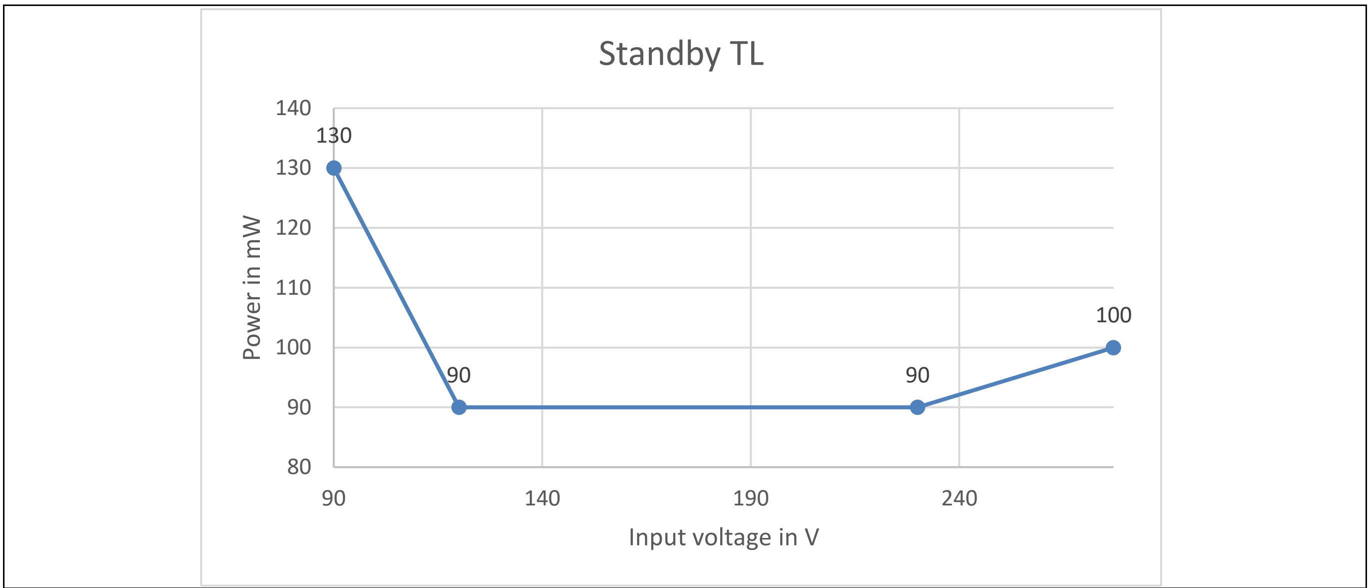



**Figure 21 No-load input power with a very low current optocoupler optimized for efficiency**

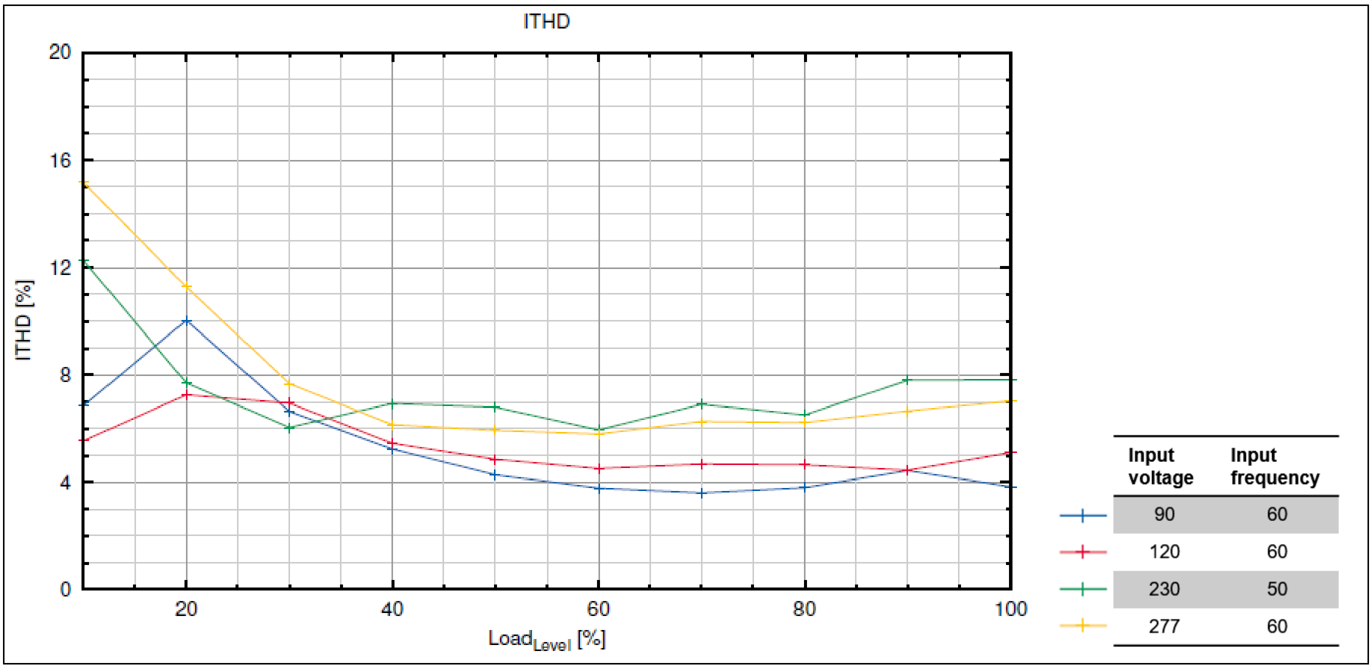



**Figure 22 THD measurement**

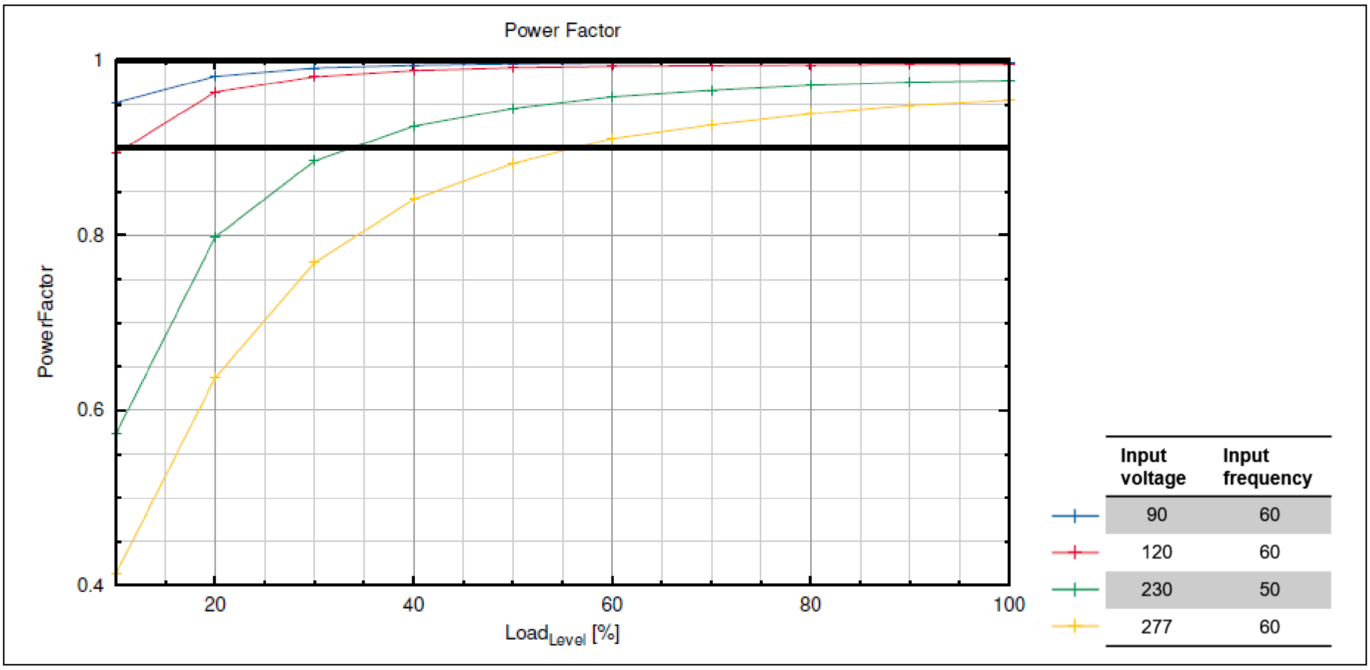



**Figure 23 PF measurement**

# 8 Key waveforms

## 8.1 Start-up

This part shows the start-up behavior of the driver at various input voltages and loads.

The $V_{CC}$ pull-up resistors and $V_{CC}$ capacitor are selected such that the start-up time in the worst case is less than 200 ms.

In order to save energy and make the design-in easier, the gate voltage is reduced during start-up.

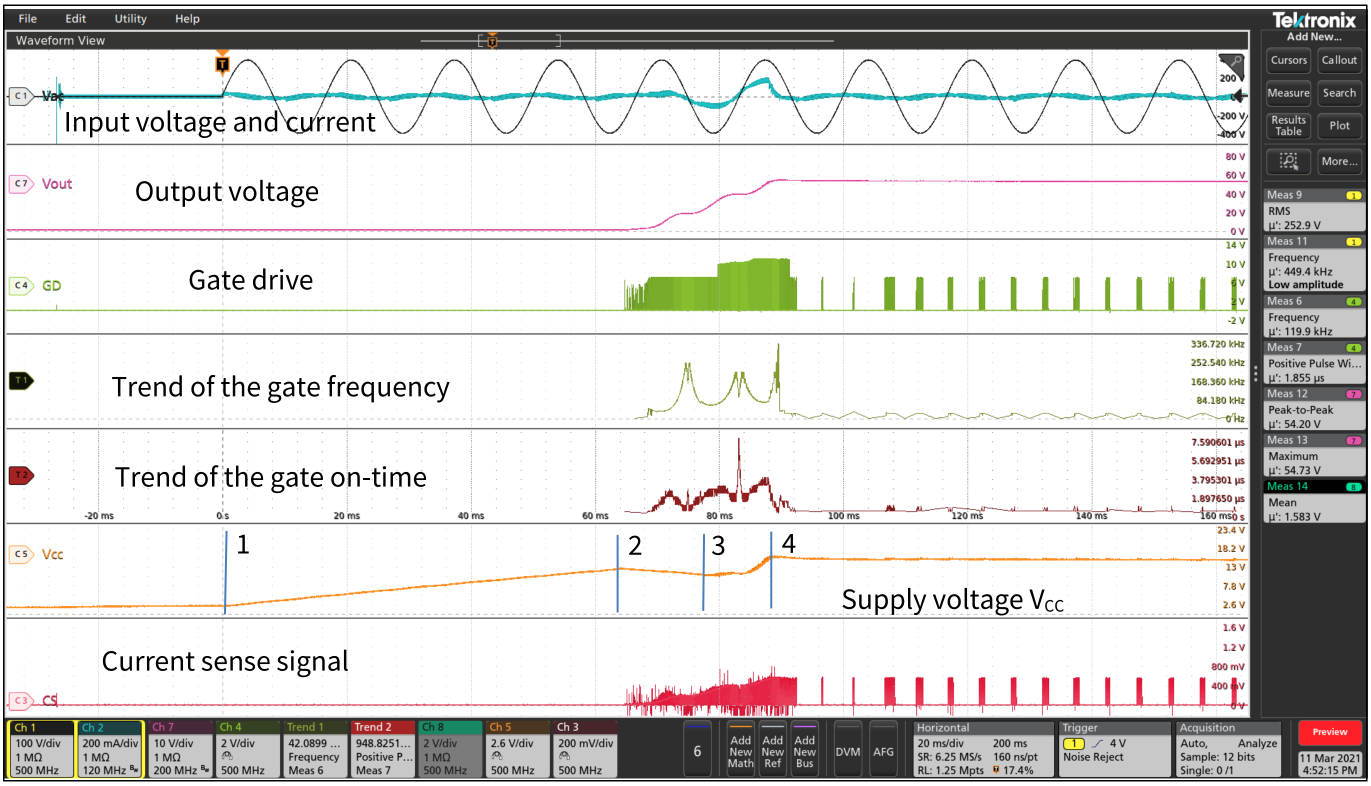



**Figure 24 Start-up at 277 V at no load**

**Table 2 Self-supply during start-up referring to Figure 24**

| Section | Explanation |
|---|---|
| 1 | Start of the AC input voltage and start of the $V_{CC}$ capacitor charging |
| 2 | Start of the IC, supply only from the $V_{CC}$ capacitor |
| 3 | Auxiliary winding delivering power to the $V_{CC}$ capacitor |
| 4 | Normal operation with self-supply |

## Key waveforms

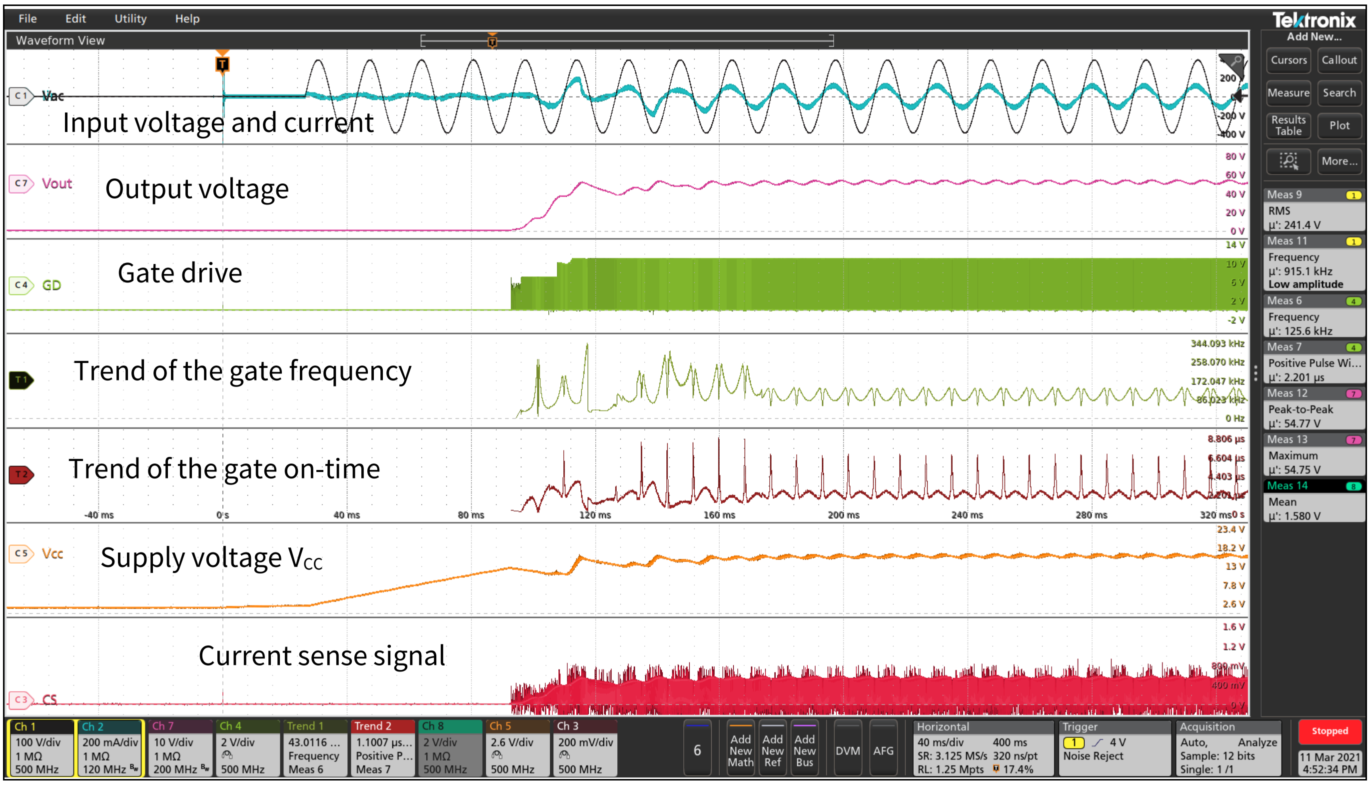



**Figure 25** **Start-up at 277 V at full load**

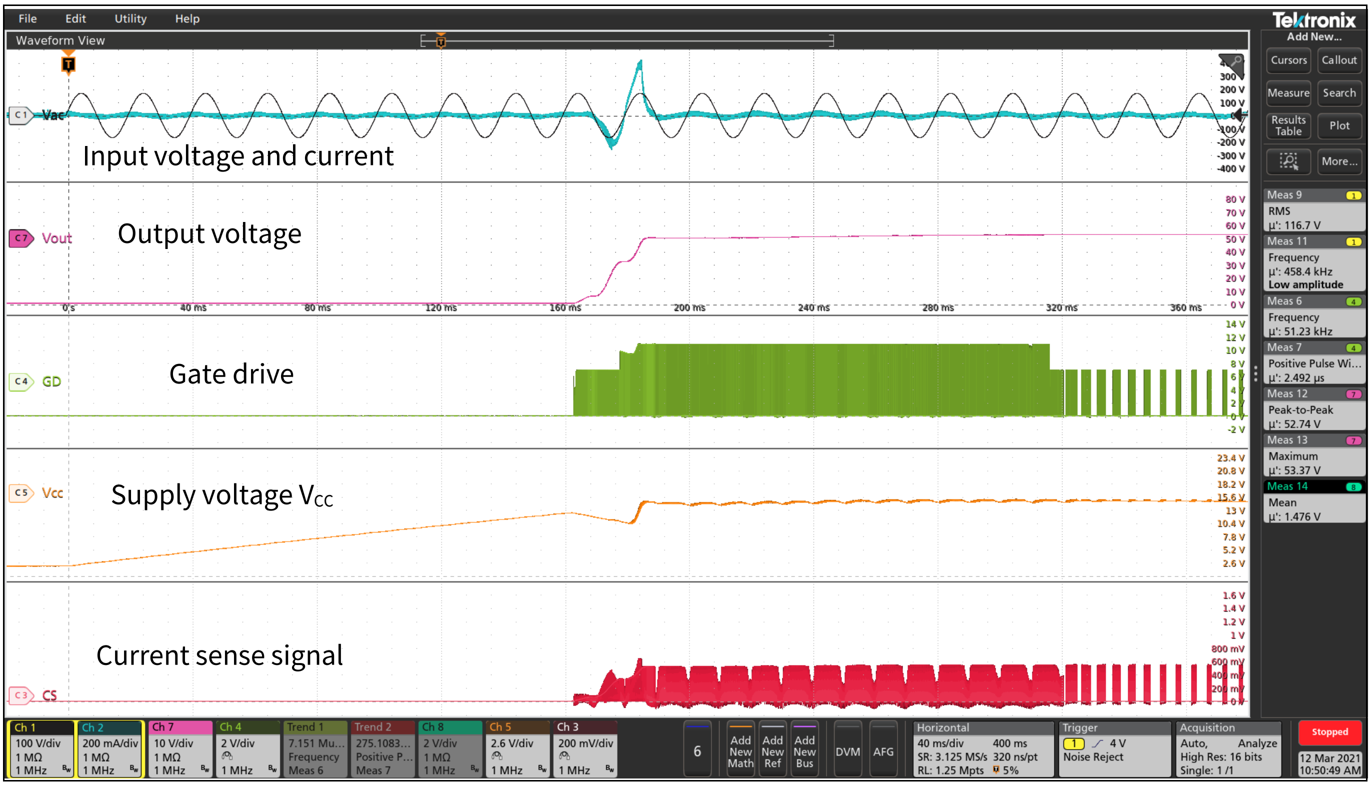



**Figure 26** **Start-up at 120 V at no load**

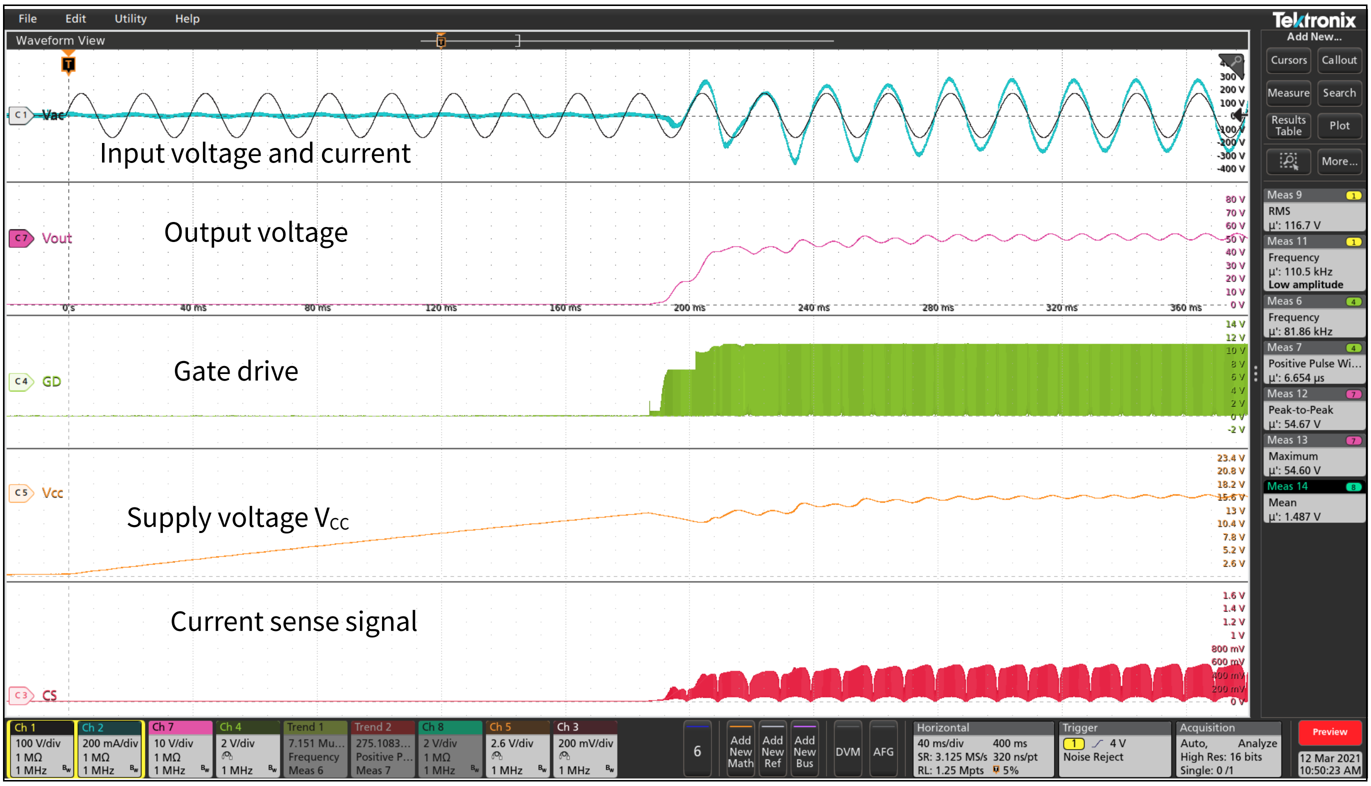



**Figure 27 Start-up at 120 V at full load**

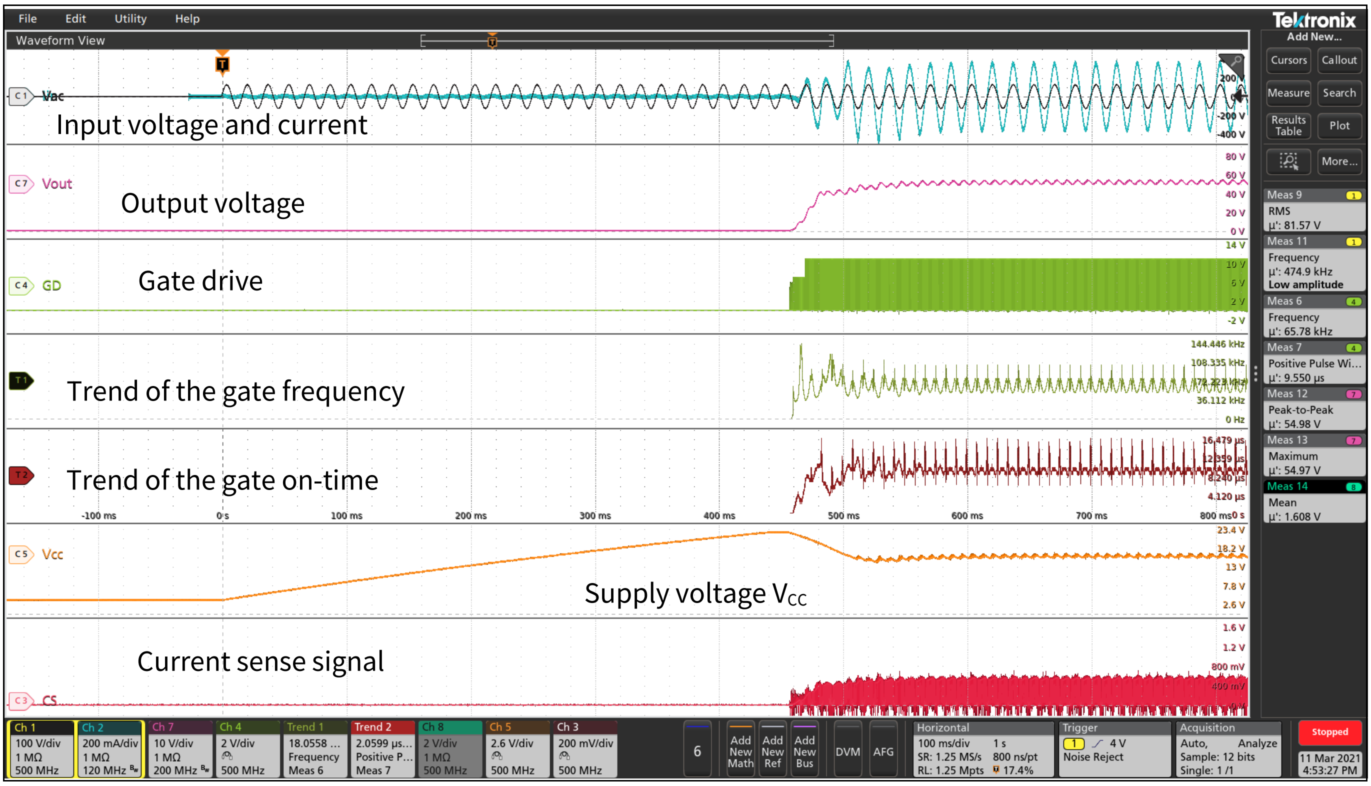



**Figure 28 Start-up at 90 V at full load, delay due to $V_{in}$ pin averaging**

Because the input voltage is internally averaged, it may result in delayed start-ups close to the brown-in voltage.

## 8.2 Steady-state

This chapter shows the switching waveforms in steady-state operation.

Because the ICL8800 has no BM and the minimum on-time is limited, the output voltage will rise to the output OVP if the lowest power limit is reached.

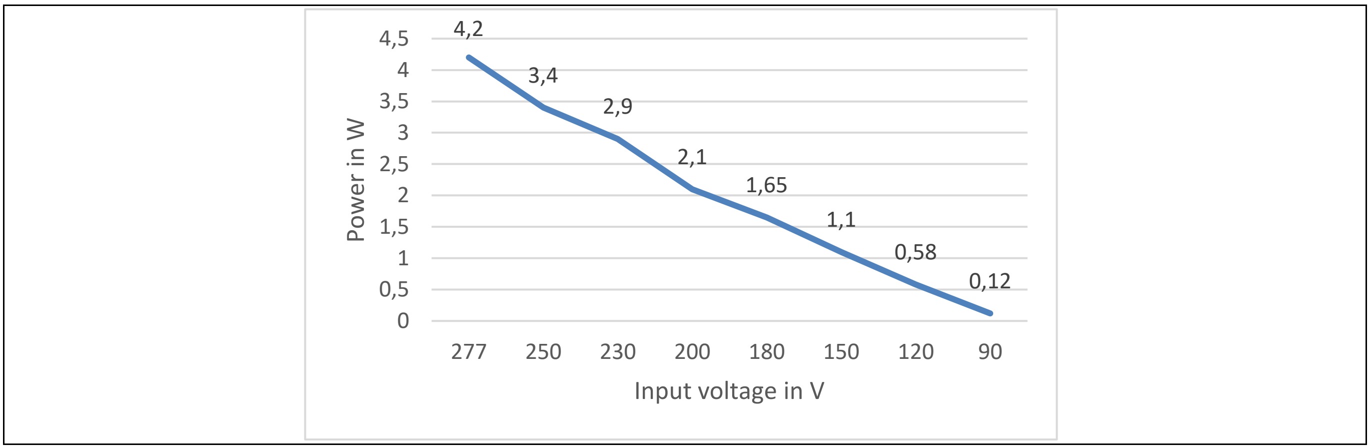



**Figure 29 Lower power limit of the ICL8800 in this design due to missing BM**


**Figure 30 230 V first valley operation ($V_{out}$ ripple pk-pk 5.3 V)**


**Figure 31** 230 V third valley operation ($V_{out}$ ripple pk-pk 3.7 V)


**Figure 32** 230 V ninth valley operation ($V_{out}$ ripple pk-pk 2.5 V)

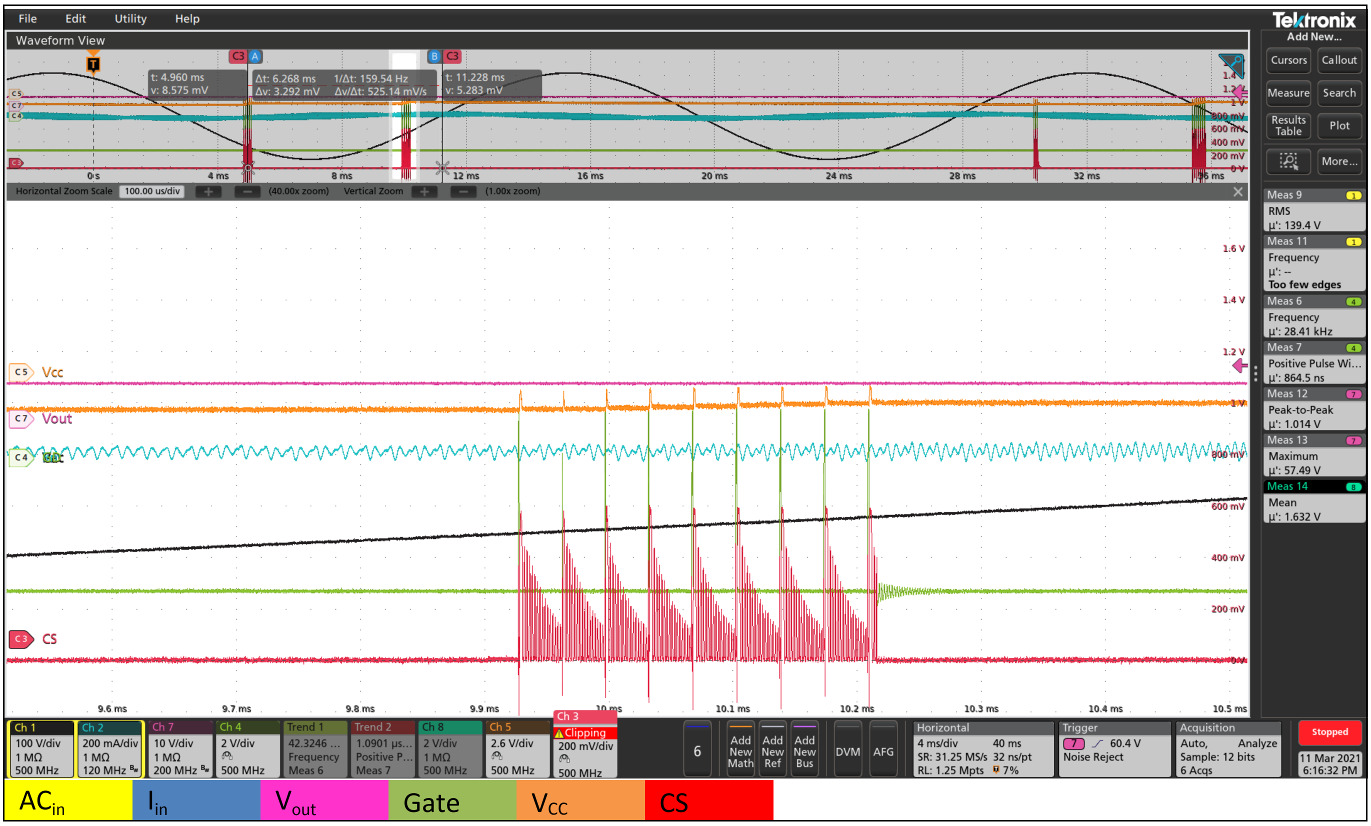



**Figure 33** 230 V burst mode operation ICL8810 and ICL8820 only ($V_{out}$ ripple pk-pk 1.01 V)

## 8.3 Burst mode (only ICL8810 and ICL8820)

The oscilloscope screenshots in this chapter offer an insight into the very smooth and nearly ripple-free BM operation of the ICL8810 and ICL8820.

In order to save energy and make the design-in easier, the gate voltage is reduced in BM. Furthermore, the BM has a very smooth entry and exit. This gradual change of modes is shown in the images below.

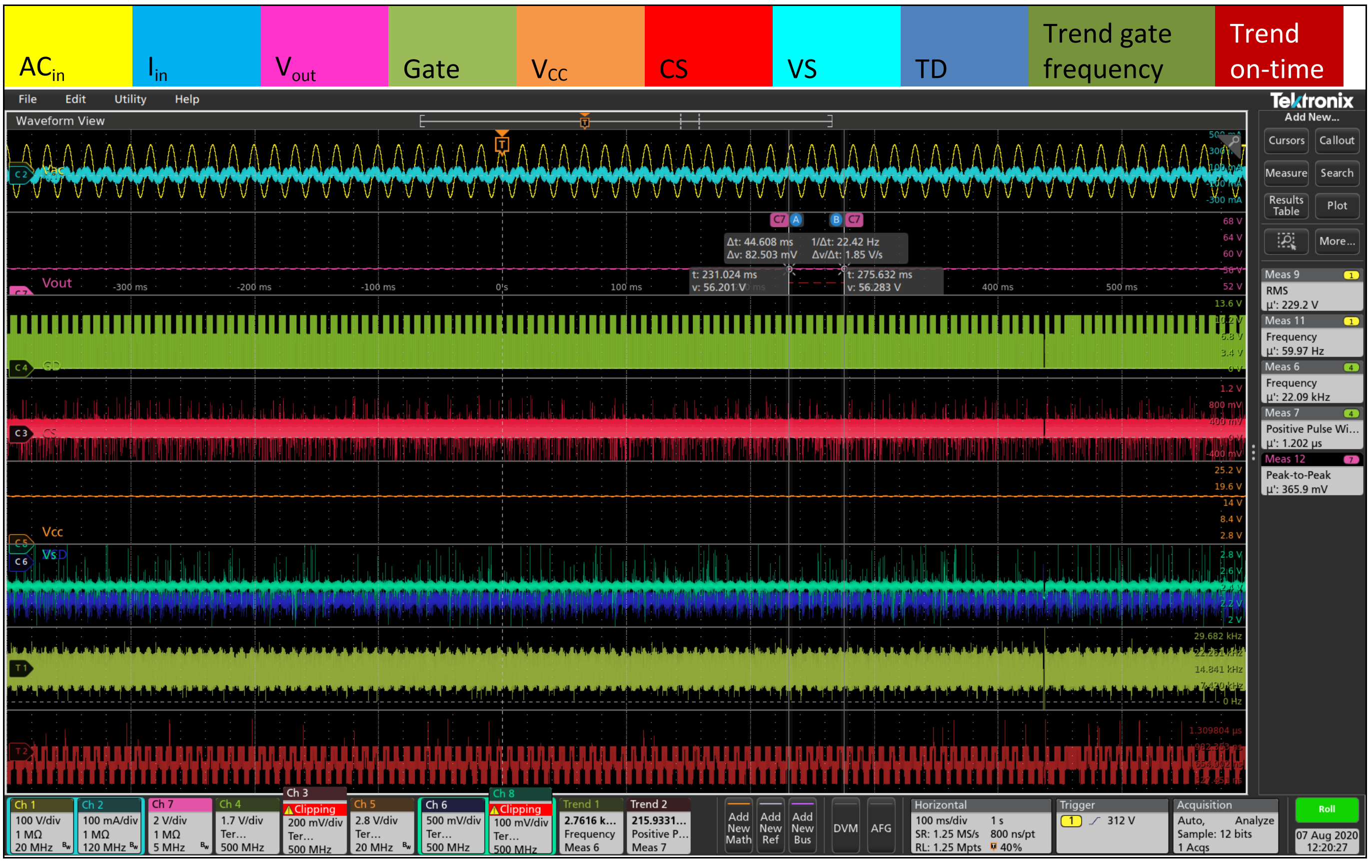



**Figure 34** **Operating point between BM and normal operation, smooth BM entry (365.9 mV pk-pk at $V_{out}$)**

## Key waveforms

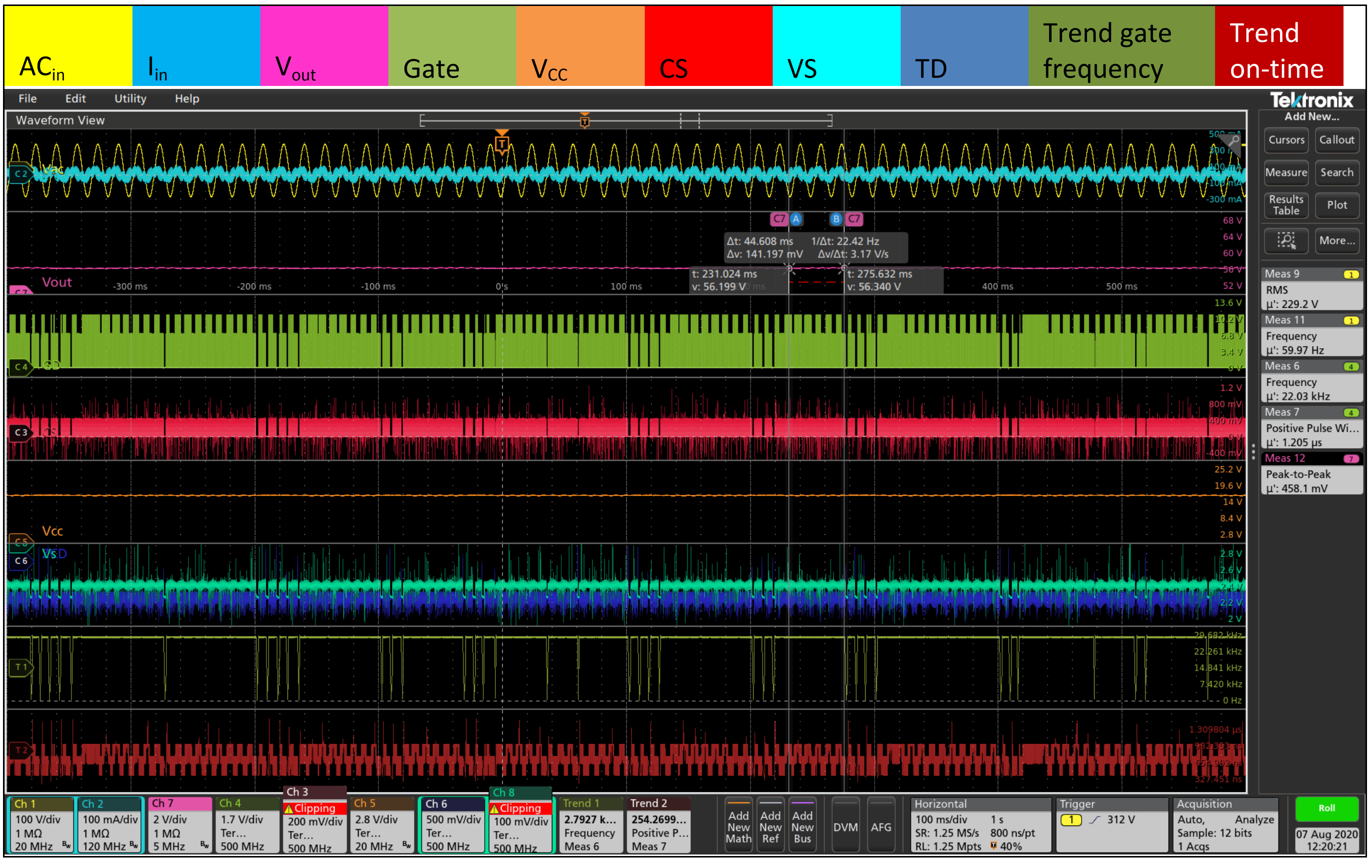



**Figure 35** Operating point with partial IC sleep (458 mV pk-pk at $V_{out}$)

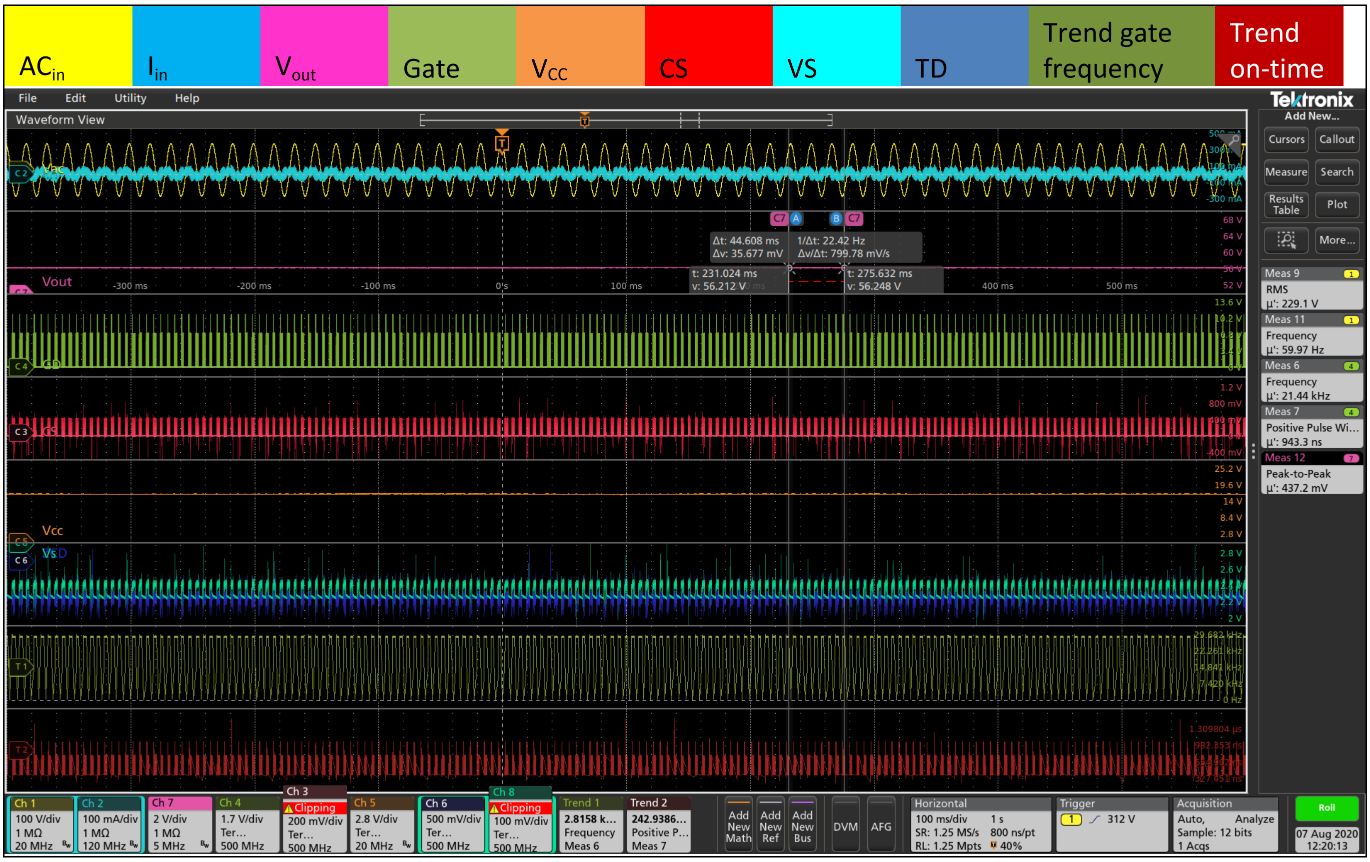



**Figure 36** Operating point fully in BM (437 mV pk-pk at $V_{out}$)

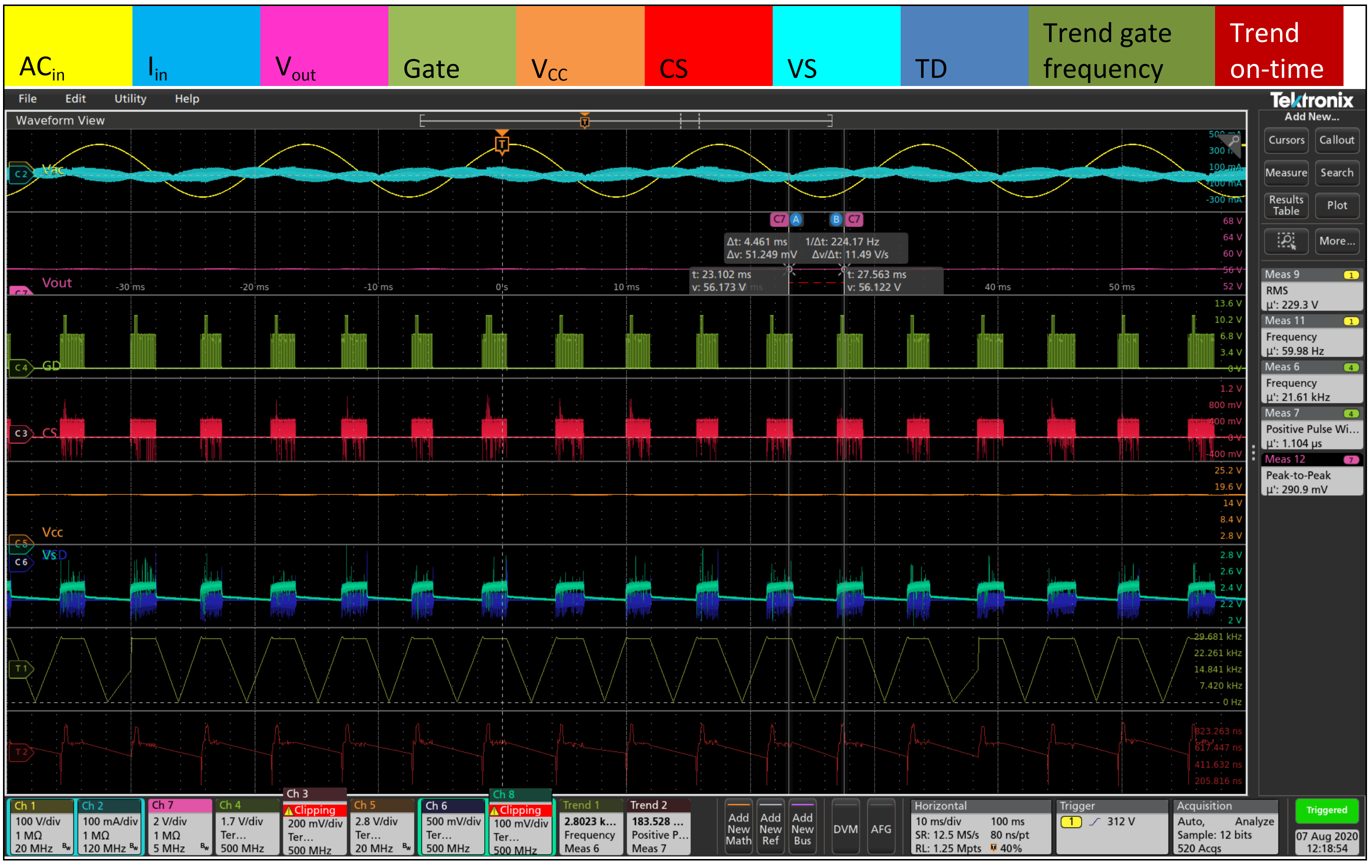



**Figure 37 Operating point in BM**

## 8.4 $V_{CC}$ maintainance mode

Because this IC only generates pulses when the feedback requires it, after a load drop the OVP might be triggered. In this case it will be a long time until the next pulses are generated (this is highly dependent on the system and the size of the $V_{CC}$ capacitor). In BM during the IC sleep the VS pin voltage is zero. To check the power demand the VS pin gets pulled up after the wake-up of the IC. If no pulse is needed, the IC falls back to sleep again. This will happen every 200 Hz.

If the $V_{CC}$ voltage gets too low there are mechanisms to keep the IC operational:

- In addition to the BM wake-up according to the control loop, a higher-priority $V_{CC}$ wake-up threshold may trigger a burst start if $V_{CC}$ drops as low as $V_{VCCwake}$. The controller continues with the burst until $V_{CC}$ increases up to $V_{VCCburst}$ again (this behavior can be seen in **Figure 38**).

- In parallel, the TD pin lowers its voltage to allow an external start-up circuit to charge the $V_{CC}$ capacitor until $V_{VCCburst}$ is reached.

This BM control allows tight output regulation and reduces the standby power, because no unnecessary pulses are generated. In addition, it allows the use of a small $V_{CC}$ capacitor.

This $V_{CC}$ maintainance mode is designed to have minimal inpact on the output voltage. Furthermore, the coupling and the fact that in this case the auxiliary winding has the highest power demand should help with minimizing the impact on the output voltage. This behavior can also help to keep microcontroller functional, and it is shown in **Figure 38**.

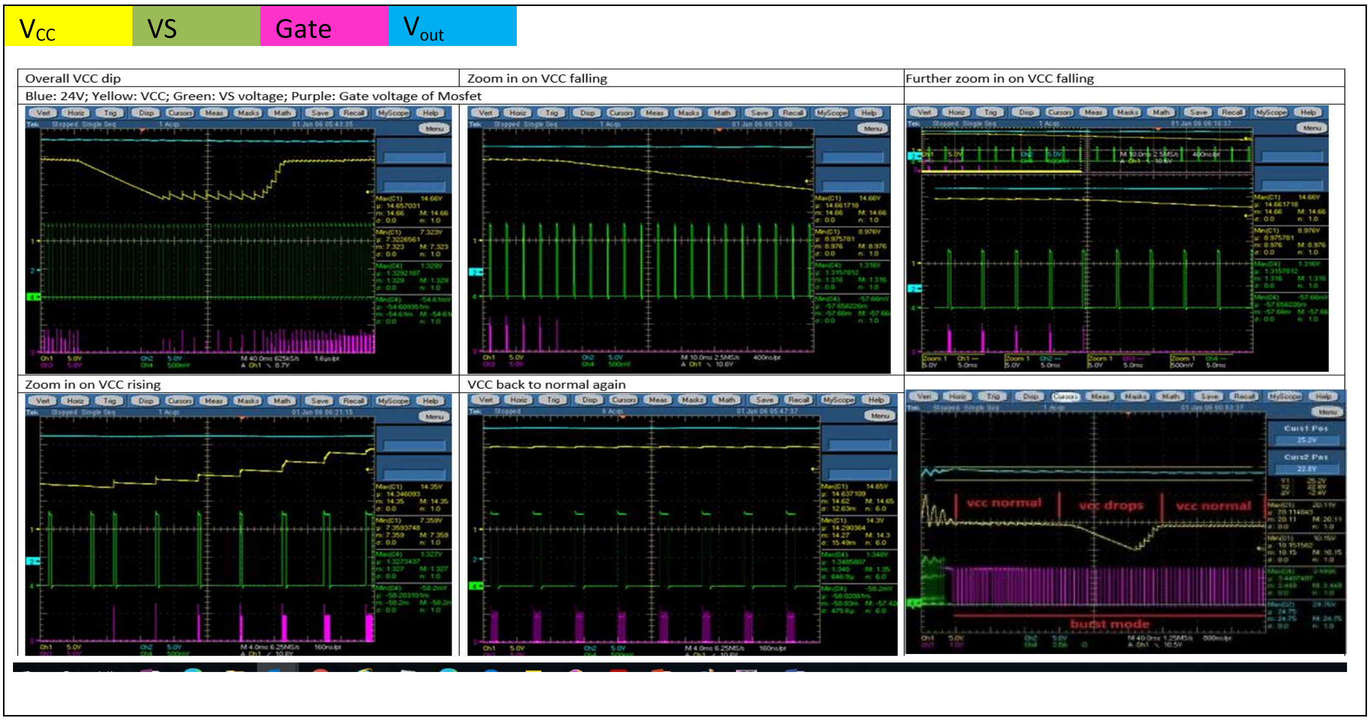



**Figure 38** **$V_{CC}$ maintainance mode if $V_{CC}$ drops too low, with minimum impact on output; VS signal shows wake-ups and gate-only pulses if necessary**

## 8.5 DC jitter (only ICL8820)

The VIN pin automatically detects the AC and DC voltage. If it detects DC, the jitter is added to the ouput of the pulse-width modulation (PWM) generator.

This function eases the design of the emergency lighting driver, as no additional circuit is needed. This feature helps to pass the required EMI standard. The fast restart time of 200 ms also qualifies this IC for designs where a fast restart after the change to DC is required.

Pulling down the VIN pin lets the IC restart even faster. Here the restart conditions are checked every 25 ms. Please refer to the chapter EMI to see the effect of the jitter on the measured spectrum.

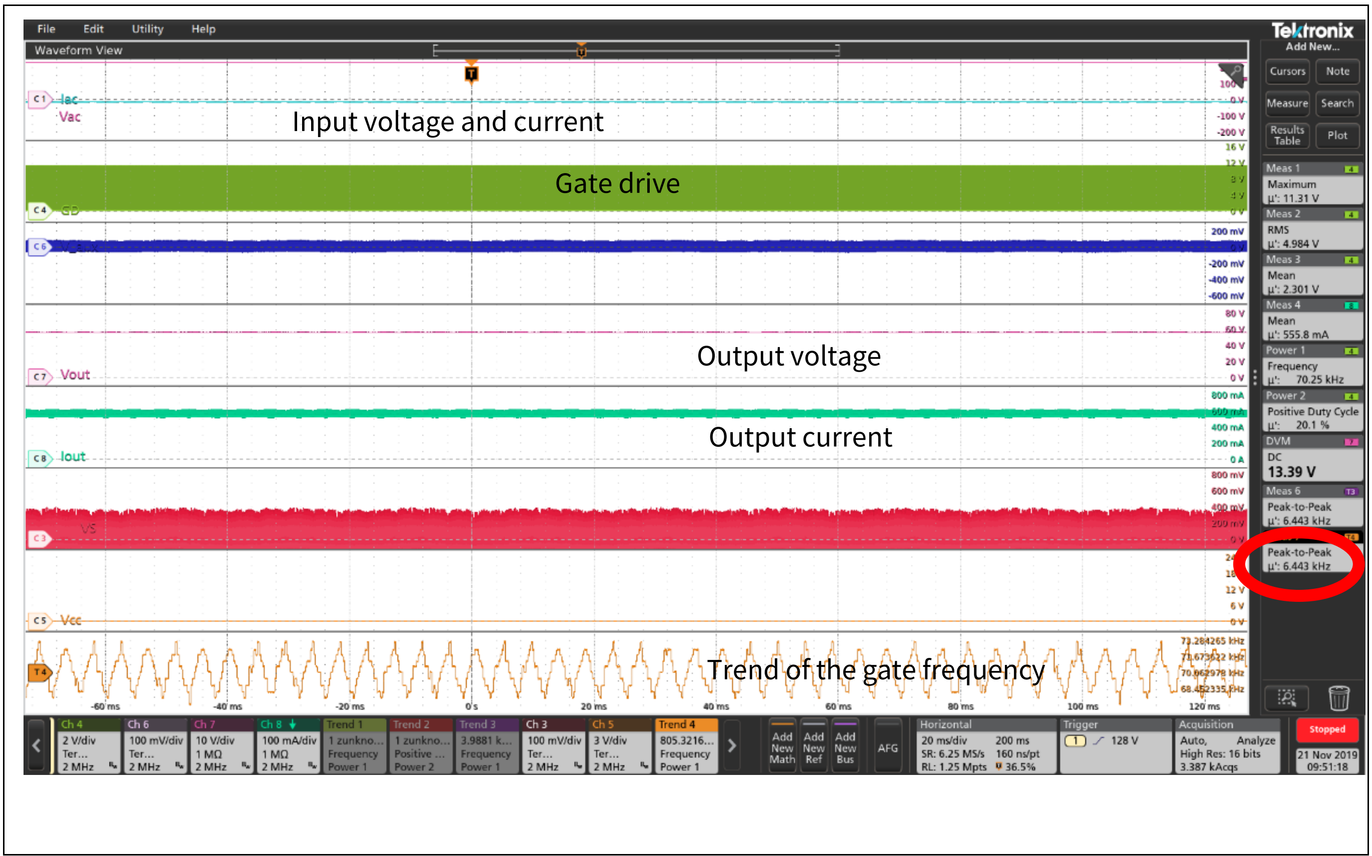



**Figure 39 ICL8820 DC jitter at 30 W, amplitude: 6.443 kHz**

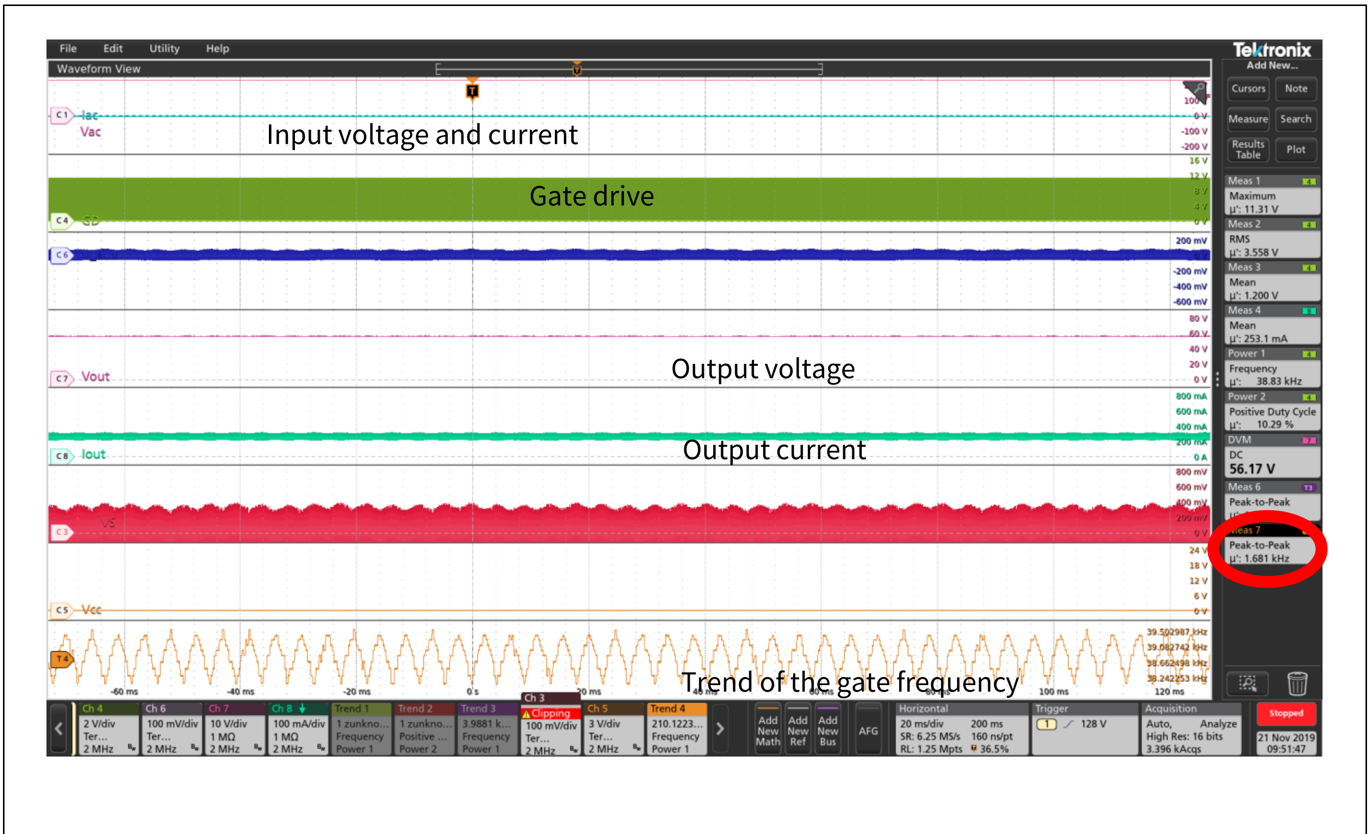



**Figure 40 ICL8820 DC jitter at 13 W, amplitude: 1.681 kHz**

## 8.6 Secondary-side output OVP

The secondary-side OVP is very accurate compared with other products. The IC senses the current flowing into the ZCD pin. This current is internally multiplied with a fixed factor. The resulting current is injected into the CS pin during the off-time of the MOSFET.

This multifunctional use of the OCP offers an 8 percent IC accuracy over the whole temperature range and production variations.

Offering an accurate and cycle-by-cycle-based fast OVP can save cost and eases the design of SELV LED drivers.

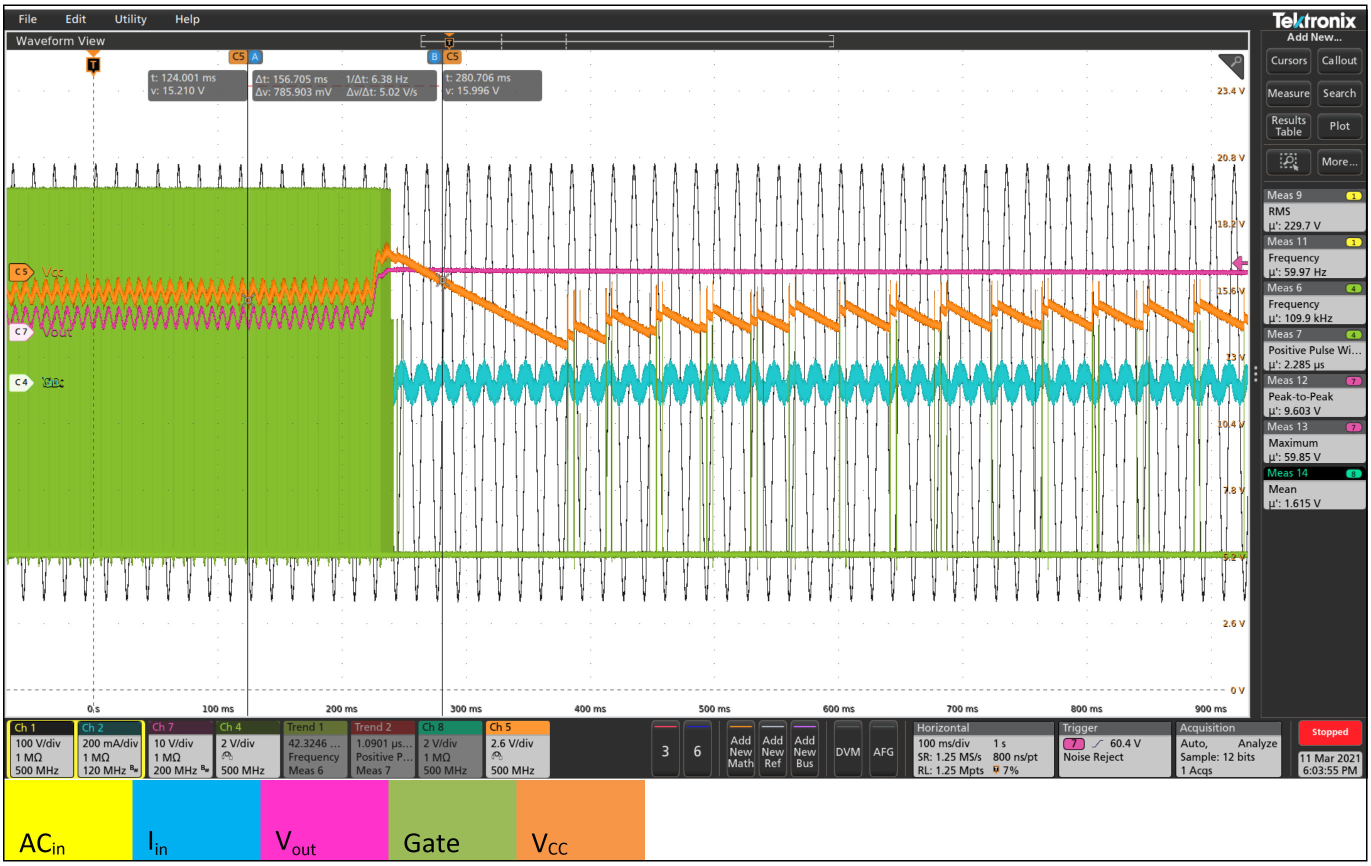



**Figure 41** **Secondary-side OVP at 59.85 V after sudden output open condition following BM entry**

# 9 Thermal images

**Table 3 Thermally measured components**

| | |
|---|---|
| SP1 | CMC |
| SP2 | Diode bridge |
| SP3 | MOSFET |
| SP4 | Transformer |
| SP5 | Output diode |

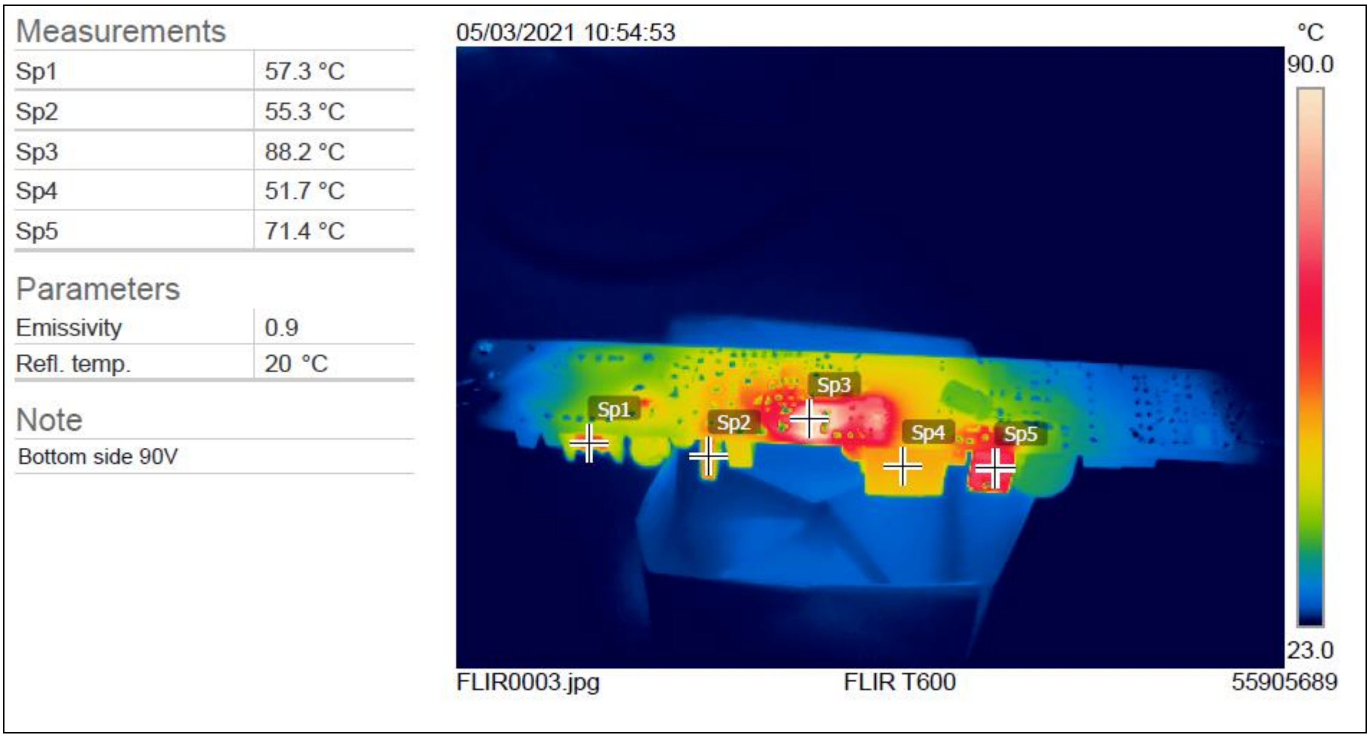



**Figure 42 Thermal image – bottom side 90 V**

| Measurements | |
|---|---|
| Sp1 | 66.4 °C |
| Sp2 | 57.4 °C |
| Sp3 | 84.2 °C |
| Sp4 | 56.2 °C |
| Sp5 | 74.4 °C |

| Parameters | |
|---|---|
| Emissivity | 0.9 |
| Refl. temp. | 20 °C |

| Note |
|---|
| Top side 90V |

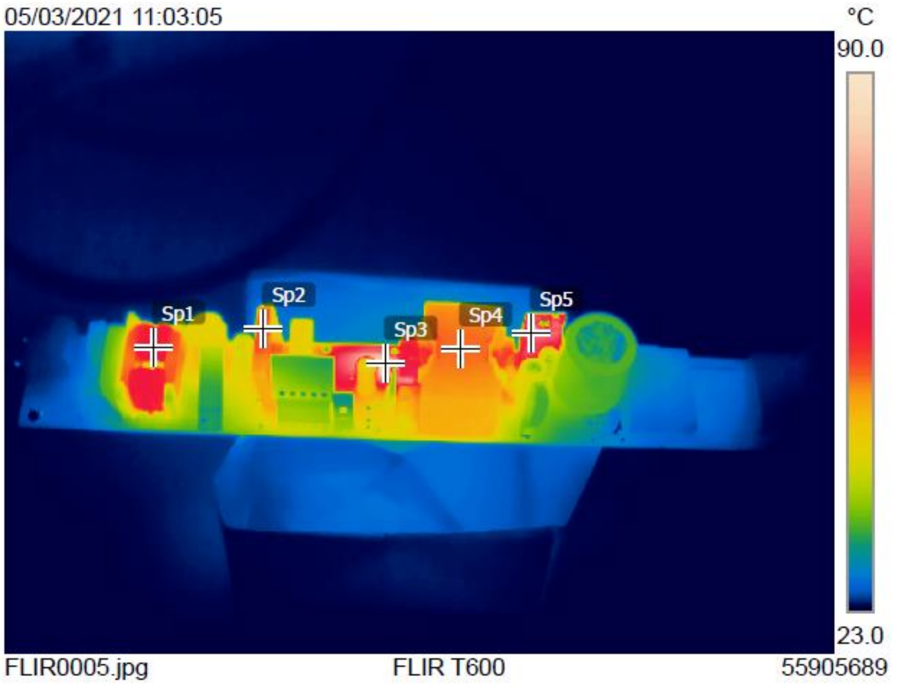



**Figure 43** Thermal image – top side 90 V

| Measurements | |
|---|---|
| Sp1 | 27.8 °C |
| Sp2 | 38.2 °C |
| Sp3 | 71.3 °C |
| Sp4 | 48.9 °C |
| Sp5 | 70.5 °C |

| Parameters | |
|---|---|
| Emissivity | 0.9 |
| Refl. temp. | 20 °C |

| Note |
|---|
| Bottom side 300V |

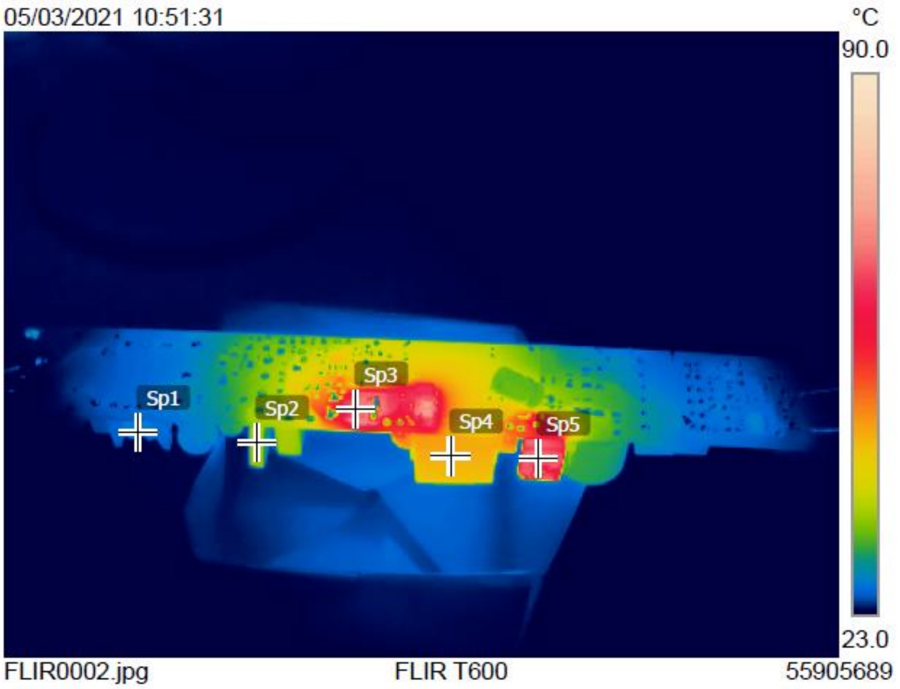



**Figure 44** Thermal image – bottom side 300 V

| Measurements | |
|---|---|
| Sp1 | 41.1 °C |
| Sp2 | 44.5 °C |
| Sp3 | 72.4 °C |
| Sp4 | 55.5 °C |
| Sp5 | 68.6 °C |
| **Parameters** | |
| Emissivity | 0.9 |
| Refl. temp. | 20 °C |

Note

Top side 300V

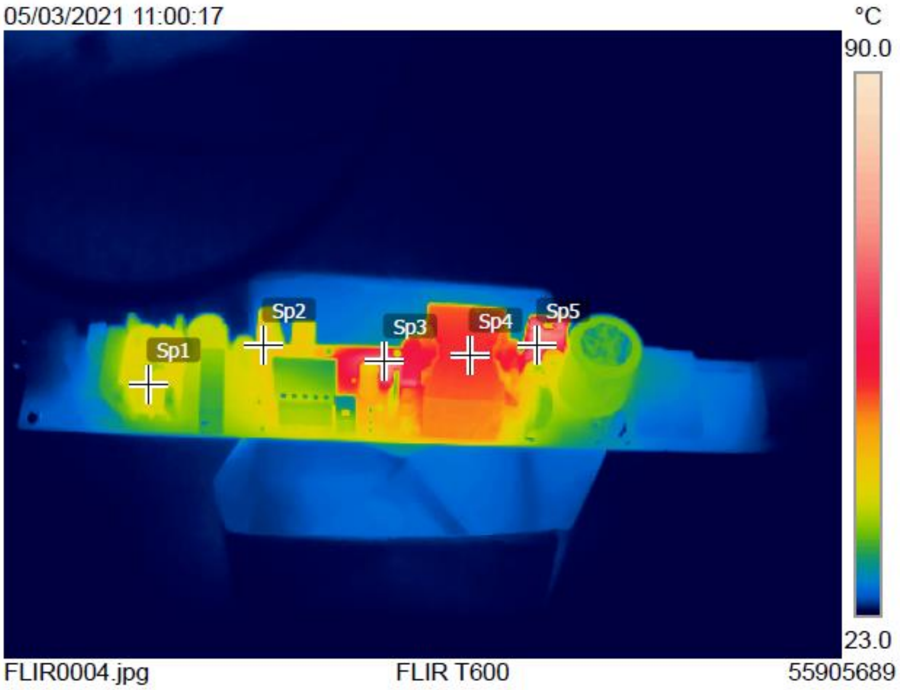



**Figure 45 Thermal image – top side 300 V**

# 10 Set-up and measurement remarks

- AC source: Chroma 61502
- Load: Chroma 63105A in CC mode with $V_{on}$ threshold of 25 V
- Power-up of the board must be done with the adapter boards plugged in
- If testing without the start-up board, the start-up resistors have to be changed – R36 has to be added, D6 with 22 V has to be added
- Because the feedback loops are optimized to deliver a good THD and PF, the crossover frequency of the loop is very low. This compromises the load-jump behavior and favors soft-dimming behavior. For dynamic load changes an additional D-path in the feedback loop is required. This can usually consist of a resistor and a capacitor in parallel to the upper voltage divider resistor. But non-linear feedback with diodes instead of a resistor is also possible. A circuit example is shown in **Figure 46**.
- The fast-reacting second OVP and the slow feedback loop may cause unwanted behavior, where the system is stuck in repetitive restarts. Here the output voltage rises very fast to the OVP level (half-charged output capacitor, fast AC restart, etc.) and triggers the protection while the feedback loop had no time to react. This can occur for multiple reasons, such as a too-small output capacitor or when the output voltage set-point is too close to the OVP level. Solutions include increasing the output capacitor, increasing the threshold for the OVP, lowering the set-point or changing the behavior of the load.

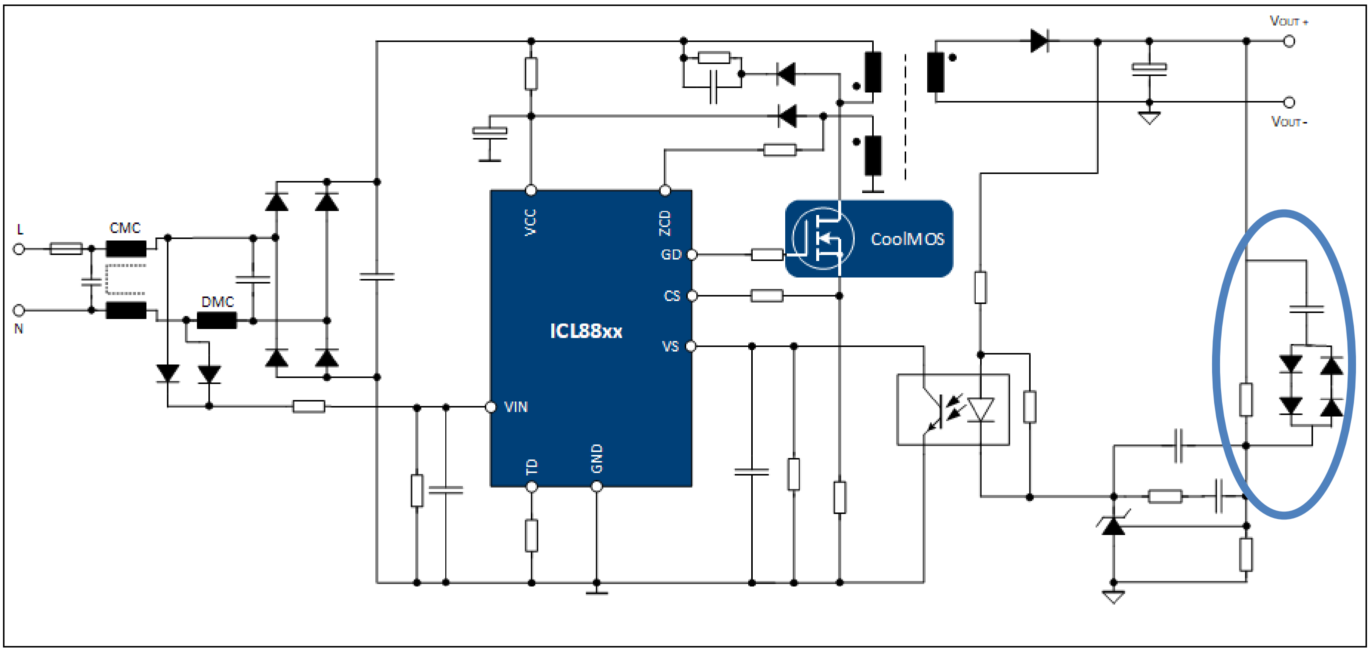



**Figure 46 Non-linear feedback circuit for highly dynamic loads without compromising THD and steady-state performance**

# 11 Harmonics

Because the ICL88xx family are primarily designed for lighting, they can easily pass the harmonic standard.

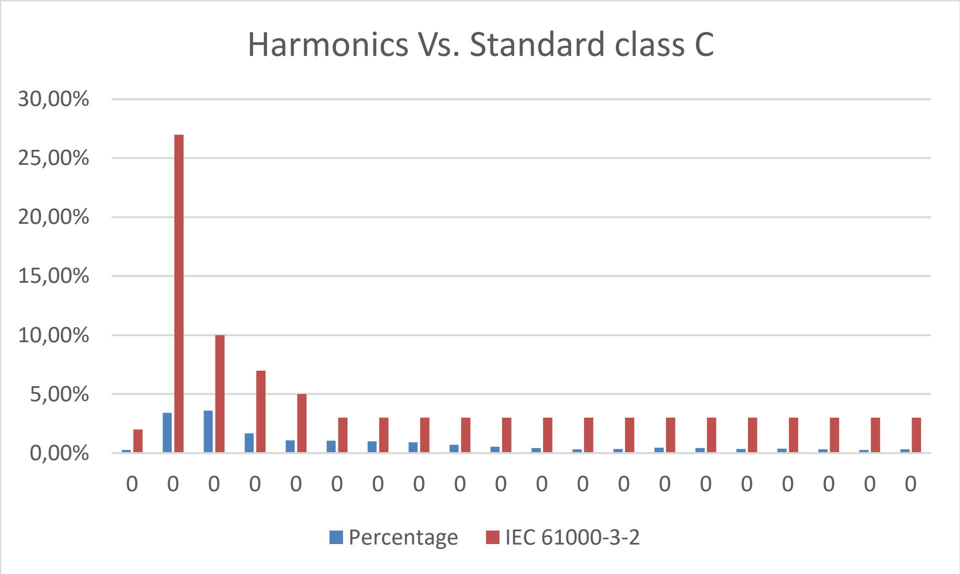



**Figure 47 Harmonics measurement at 277 V full load**

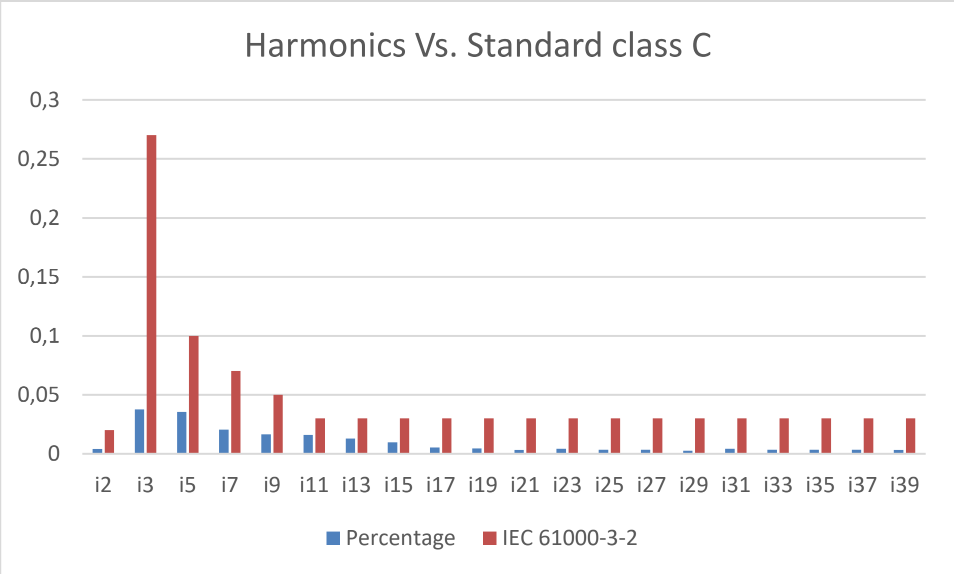



**Figure 48 Harmonics measurement at 230 V full load**

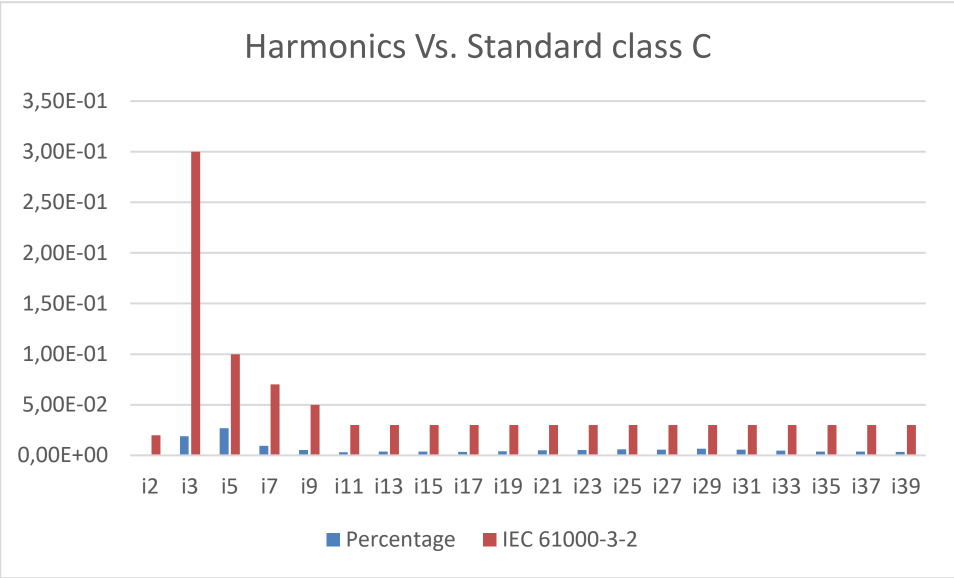



**Figure 49** **Harmonics measurement at 120 V full load**

# 12 EMI measurements

## 12.1 AC input

The SSR reference board can easily pass the EMI standard for AC operation.

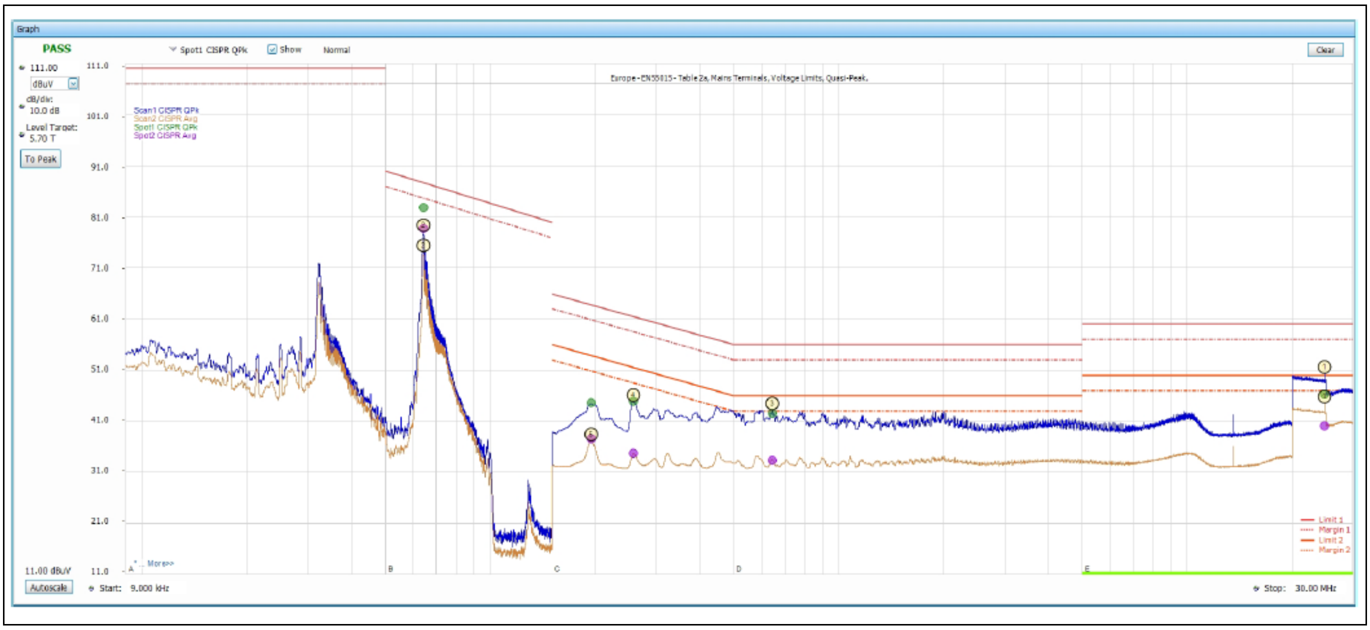


**Figure 50** 120 V L

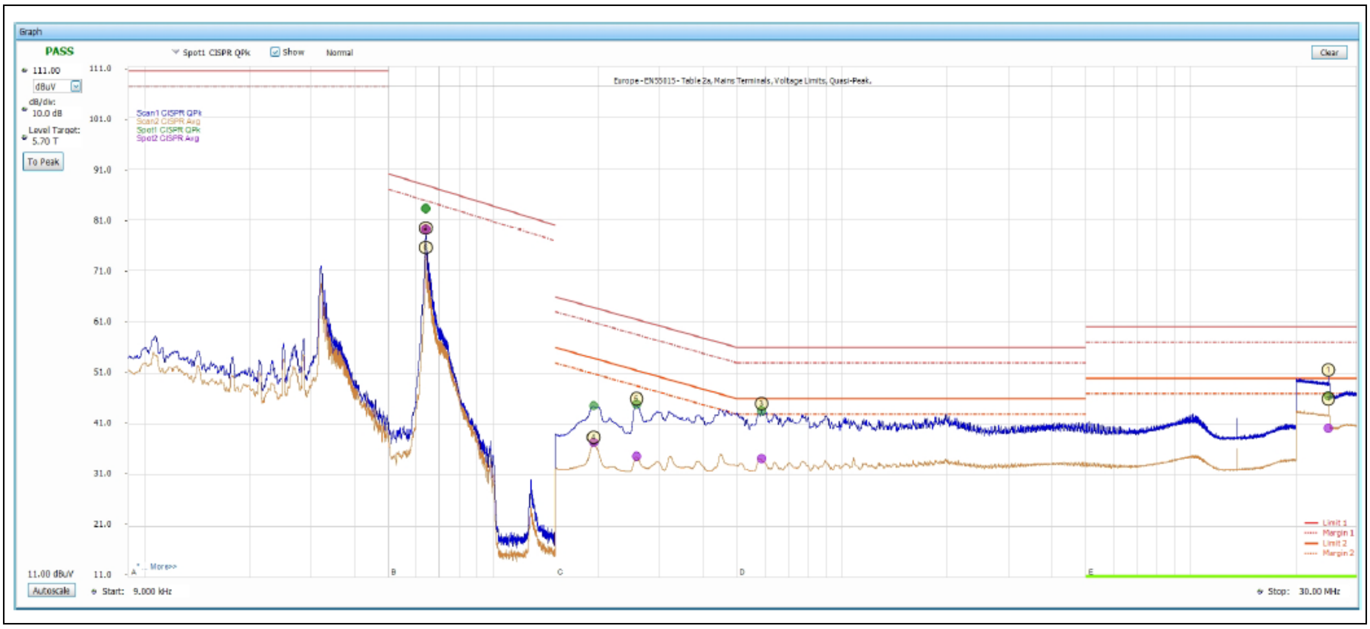


**Figure 51** 120 V N

## 12.2 DC input (ICL8820 only)

The EMI measurements for DC input are given below.

With regard to DC operation, only the ICL8820 can pass the DC test due to the implemented jitter.

The sudden jump at 30 MHz is due to measurement system error and can also be seen with no device connected.

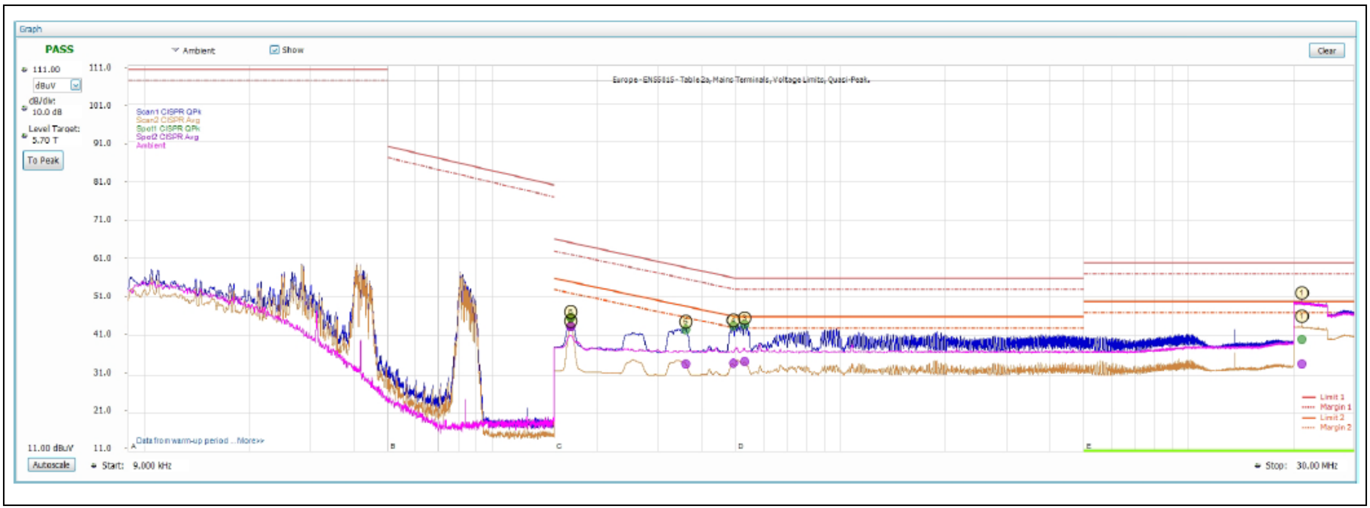



**Figure 52** **120 V DC**

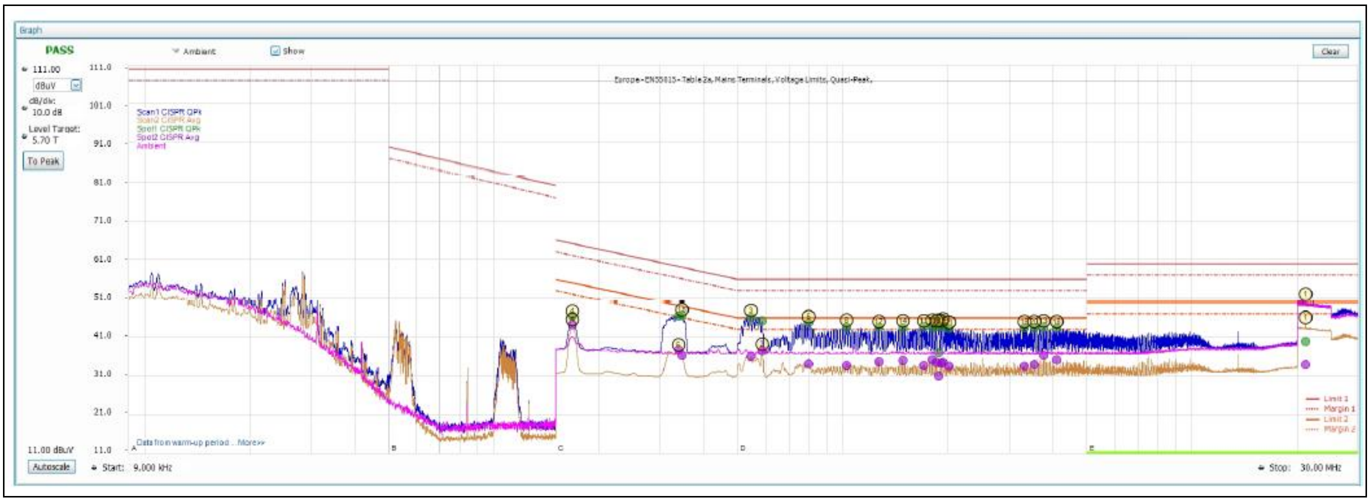



**Figure 53** **160 V DC**

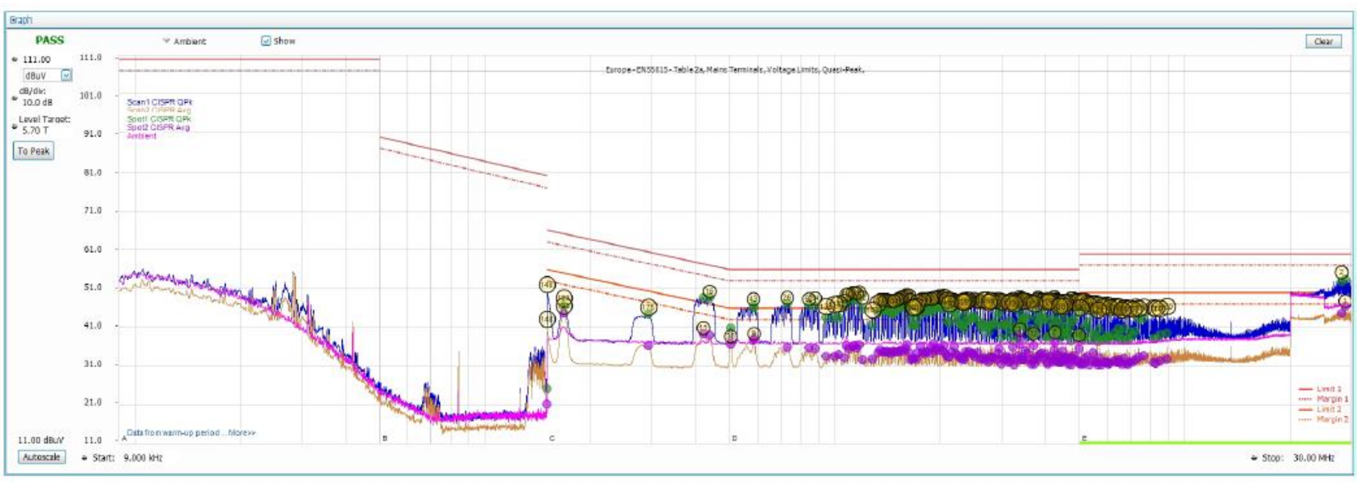
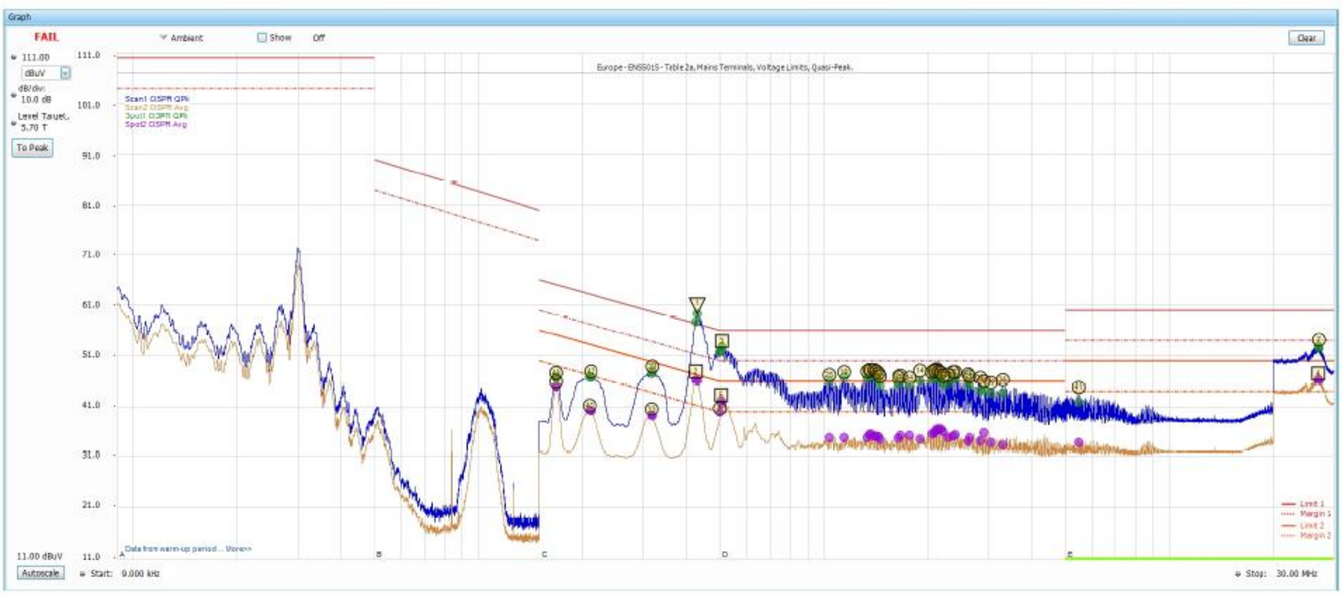



Figure 54 230 V DC




| Enable | Spot # | Range | Freq (Hz) | Scan1 CISPR QPk | | Scan2 CISPR Avg | | Spot1 CISPR QPk | | Spot2 CISPR Avg | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Ampl | Delta (Limit1) | Ampl | Delta (Limit2) | Ampl | Delta (Limit1) | Ampl | Delta (Limit2) |
| √ | 1 | C | 430.984 kHz | 59.38 dBuV | 2.14 dBuV | -- dBuV | -- dBuV | 59.32 dBuV | 2.09 dBuV | 46.00 dBuV | -1.23 dBuV |
| √ | 2 | C | 426.128 kHz | -- dBuV | -- dBuV | 46.67 dBuV | -0.66 dBuV | 57.67 dBuV | 0.34 dBuV | 46.36 dBuV | -0.97 dBuV |
| √ | 3 | D | 507.312 kHz | 52.67 dBuV | -3.33 dBuV | -- dBuV | -- dBuV | 52.71 dBuV | -3.29 dBuV | 41.70 dBuV | -4.30 dBuV |
| √ | 4 | E | 26.939 MHz | -- dBuV | -- dBuV | 46.26 dBuV | -3.74 dBuV | 52.86 dBuV | -7.14 dBuV | 46.38 dBuV | -3.62 dBuV |
| √ | 5 | D | 504.781 kHz | -- dBuV | -- dBuV | 42.08 dBuV | -3.92 dBuV | 52.00 dBuV | -4.00 dBuV | 42.13 dBuV | -3.87 dBuV |
| √ | 6 | C | 500.000 kHz | -- dBuV | -- dBuV | 39.47 dBuV | -6.53 dBuV | 51.77 dBuV | -4.23 dBuV | 39.87 dBuV | -6.13 dBuV |
| √ | 7 | E | 27.037 MHz | 52.92 dBuV | -7.08 dBuV | -- dBuV | -- dBuV | 52.50 dBuV | -7.50 dBuV | 46.17 dBuV | -3.83 dBuV |

Figure 55 Failed test: ICL8800 or ICL8810 without jitter 230 V DC

# 13 Magnetics

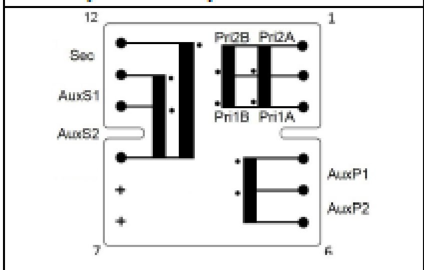
The datasheet of the flyback transformer is shown below.

| itacoilweb | | DATASHEET | 11/07/2019 | | REV | 00 |
|---|---|---|---|---|---|---|
| | | EDITED | Davide Maida | | APPROVED | Dario Radaelli |
| FINAL P/N | PQ262015 | REV | 00 | SAMPLING CODE | PQ262015-240619A | |
| PRELIMINARY P/N | OP1901015 | | | CUSTOMER P/N | | |
| CUSTOMER | INFINEON TECHNOLOGIES AG (Munich) | | | | | |

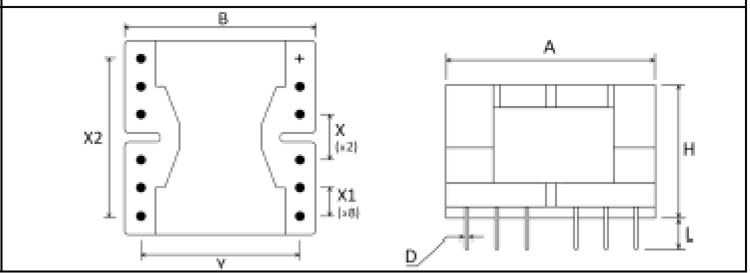
| DESCRIPTION | Flyback Transformer PQ2620 low loss core | |
|---|---|---|
| **TEST/FEATURES** | | |
| Inductance Pri1A+Pri2A | 544,0 µH ±10,0% | 10KHz / 100mV |
| Leakage Inductance Pri1A+Pri2A | 5,0 uH max (short-circuit on Sec+AuxP1+AuxP2+AuxS1+AuxS2) | 10KHz / 100mV |
| Dielectric Strenght | Pri1A+Pri1B+AuxP1+AuxP2+Pri2A+Pri2B / Sec+AuxS1+AuxS2 | 3,0KVac / 2sec. |

| WINDINGS | | |
|---|---|---|
| Pri1A | 16ts - 2x0,20 - gr.2 130° (1UEW) | |
| Pri2A | 16ts - 2x0,20 - gr.2 130° (1UEW) | 1 Ts PE ad.tape 0,06mm 130° yellow |
| Sec | 10ts - 3x0,35 - TIW 130° EN60950 | 1 Ts PE ad.tape 0,06mm 130° yellow |
| AuxP1 | 1ts - 0,16 - gr.2 130° (1UEW) | |
| AuxP2 | 3ts - 0,16 - gr.2 130° (1UEW) | 1 Ts PE ad.tape 0,06mm 130° yellow |
| Pri1B | 16ts - 2x0,20 - gr.2 130° (1UEW) | |
| Pri2B | 16ts - 2x0,20 - gr.2 130° (1UEW) | 1 Ts PE ad.tape 0,06mm 130° yellow |
| AuxS1 | 1ts - 0,20 - TIW 130° EN60950 | |
| AuxS2 | 2ts - 0,20 - TIW 130° EN60950 | 2 Ts PE ad.tape 0,06mm 130° yellow |

**LAYOUT (bottom view)**




**DRAWING**




| DIMENSIONS (mm) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| A | 28,0 max | B | 30,5 max | H | 21,8 max | X | 7,5 typ | X1 | 3,8 typ |
| X2 | 22,7 typ | Y | 25,5 typ | DØ | 0,6 typ | L | 3,0 min | | |

| COMPONENT | THERMAL CLASS | |
|---|---|---|
| Bobbin | 150°C (B) | |
| Copper Wire | 155°C (F) | |
| Tape | 130°C (B) | |
| Tube | 200°C (N) | |
| Varnish | 180°C (H) | |

| NOTES |
|---|
| REACH & RoHS compliant |

# 14 Bill of materials

**Table 4 Start-up board**

| # | Quantity | Designator | Description | Manufacturer | Value |
|---|---|---|---|---|---|
| 1 | 1 | C30 | Capacitor 1 nF/50 V/0603/X7R/5% | Yageo | 1 nF |
| 2 | 1 | D30 | Diode 22 V/22 V/SOD-323 | Nexperia | 22 V |
| **3** | **1** | **Q30** | **BSS126i/PG-SOT-23-3-5** | **Infineon** | **BSS126i** |
| 4 | 1 | Q31 | MMBT3904/SOT-23-3 | NXP Semiconductors | MMBT3904 |
| 5 | 1 | R30 | Resistor 20k/150 V/0805/1% | Vishay | 20k |
| 6 | 1 | R31 | Resistor 1k/150 V/0805/1% | Vishay | 1k |
| 7 | 1 | R33 | Resistor 56k/150 V/0805/1% | Vishay | 56k |
| 8 | 2 | R34, R37 | Resistor 47k/75 V/0603/1% | Vishay | 47k |
| 9 | 1 | X30 | Connector SSW-104-02-G-S-RA/female/4-pin/2.54 mm/90 degrees | Samtec | SSW-104-02-G-S-RA |

**Table 5 Op-amp board**

| # | Quantity | Designator | Description | Manufacturer | Value |
|---|---|---|---|---|---|
| 1 | 1 | C201 | Capacitor 470 nF/50 V/0805/ X7R/10% | Murata | 470 nF |
| 2 | 1 | C204 | Capacitor 100 nF/50 V/0805/ X7R/10% | Yageo | 100 nF |
| 3 | 1 | C205 | Capacitor 470pF/50V/0805/C0G/5% | Murata | 470 pF |
| 4 | 1 | C206 | Capacitor 3.3 µF/25 V/1206/ X7R/10% | Murata | 3.3 µF |
| 5 | 1 | D201 | 0 R/75 V/0603/1% | Yageo/Phycomp | 0 R |
| 6 | 1 | D202 | 1N4148WS/SOD-323 | Vishay | 1N4148WS |
| 7 | 1 | IC201-A | Op-amp IC with reference voltage/SOIC-8 | ST | Op-amp IC with reference voltage |
| 8 | 1 | R200 | Resistor 27k/150 V/0805/1% | Vishay | 27k |
| 9 | 1 | R201-A | Resistor 240k/150 V/0805/1% | Vishay | 240k |
| 10 | 1 | R201-B | Resistor 0 R/150 V/0805/1% | Vishay | 0 R |
| 11 | 1 | R202 | Resistor 22k/150 V/0805/1% | Vishay | 22k |

| | | | | | |
|---|---|---|---|---|---|
| 12 | 1 | R203 | Resistor 5.6k/150 V/0805/1% | Vishay | 5.6k |
| 13 | 1 | R204 | Resistor 1k/200 V/1206/1% | Vishay | 1k |
| 14 | 1 | R206 | Resistor 9.1k/200 V/1206/1% | Vishay | 9.1k |
| 15 | 1 | R207 | Resistor 0 R/150 V/0805 | Vishay | 0 R |
| 16 | 1 | R208 | Resistor 0 R/150 V/0805 | Vishay | 0 R |
| 17 | 1 | R210 | Resistor 6.2k/200 V/1206/1% | Vishay | 6.2k |
| 18 | 1 | R211 | Resistor 0 R/200 V/1206 | Vishay | 0 R |
| 19 | 1 | X200-B | Terminal block/6 pins/3.81 mm pitch/3.81*6 – duplicate – duplicate | Würth | Terminal block/6 pins/3.81 mm pitch |
| 20 | 1 | X300-A | Terminal block/4 pins/5.08 mm pitch/691313510004 | Würth | Terminal block/4 pins/5.08 mm pitch |
| 21 | 0 | C203 | Capacitor NA/50 V/0805/X7R/10% | Murata | NA |
| 22 | 0 | R205 | Resistor NA/150 V/0805/0 R | Vishay | NA |
| 23 | 0 | R209 | Resistor NA/150 V/0805/0 R | Vishay | NA |
| 24 | 0 | R215 | Resistor NA/200 V/1206/0 R | Vishay | NA |

**Table 6 TL431 board**

| # | Quantity | Designator | Description | Manufacturer | Value |
|---|---|---|---|---|---|
| 1 | 1 | C201 | Capacitor 470 nF/50 V/1206/X7R/5% | KEMET | 470 nF |
| 2 | 1 | C204 | Capacitor 3.3 µ/25 V/1206/X7R/10% | Murata | 3.3 µ |
| 3 | 1 | C205 | Capacitor 470 pF/50 V/1206/X7R/5% | Samsung Electro-Mechanics | 470 pF |
| 4 | 1 | D201 | Int TL431QDBZR/SOT-23 | Nexperia | TL431QDBZR |
| 5 | 1 | R203 | Resistor 5.6k/200 V/1206/1% | Vishay | 5.6k |
| 6 | 1 | R204 | Resistor 1k/200 V/1206/1% | Vishay | 1k |
| 7 | 1 | R205 | Resistor 1k/200 V/1206/1% | Vishay | 1k |
| 8 | 1 | R206 | Resistor 22k/150 V/0805/1% | Vishay | 22k |
| 9 | 1 | R206a | Resistor 27k/150 V/0805/1% | Vishay | 27k |
| 10 | 1 | R207 | Resistor 240k/150 V/0805/1% | Vishay | 240k |
| 11 | 1 | R208 | Resistor 12k/200 V/1206/1% | Vishay | 12k |
| 12 | 1 | R210 | Resistor 6.2k/200 V/1206/1% | Vishay | 6.2k |
| 13 | 1 | R214 | Resistor 820k/150 V/0805/1% | Vishay | 820k |
| 14 | 1 | X200-B | Terminal block/6 pins/3.81 mm | Würth | Terminal block/6 |

| | | | | | |
|---|---|---|---|---|---|
| | | | pitch/3.81*6 – duplicate – duplicate | | pins/3.81 mm pitch |
| 15 | 1 | X300-A | Terminal block/4 pins/5.08 mm pitch/691313510004 | Würth | Terminal block/4 pins/5.08 mm pitch |
| 16 | 0 | R213 | Resistor NA/150 V/0805/1% | Vishay | NA |

**Table 7 Power board**

| # | Quantity | Designator | Description | Manufacturer | Value |
|---|---|---|---|---|---|
| 1 | 1 | BR1 | Bridge rectifier/4 A/1000 V/SIP345W114P508L2205H2125Q4B | MCC | Bridge rectifier/4 A/1000V |
| 2 | 1 | C1 | Capacitor 100 nF/310 V AC/radial/10% | Würth | 100 nF |
| 3 | 1 | C3 | Capacitor 680 pF/630 V/1206/C0G/5% | Murata | 680 pF |
| 4 | 1 | C4 | Capacitor 150 nF/630 V/CAP-P10-L13-T6-H12/20% | KEMET | 150 nF |
| 5 | 1 | C5 | Capacitor 470 p/50 V/0603/X8L/20% | Yageo | 470 p |
| 6 | 1 | C6 | Capacitor 22 µF/50 V/CAP-P2-D5-H12/20% | Panasonic | 22 µF |
| 7 | 1 | C9 | 2200 p/500 V AC/Disk/Y5U/20% | Vishay | 2200 p |
| 8 | 1 | C17 | 150 nF/310 V AC/L13_W7_H13_P10_CS | Würth | 150 nF |
| 9 | 1 | C38 | Capacitor 100 nF/50 V/0603/X7R/10% | AVX | 100 nF |
| 10 | 1 | C40 | 2200 p/CAPRR1000W60L750T500H1150B/ | Murata | 2200 p |
| 11 | 1 | C41 | Capacitor 100 nF/50 V/ 1206/X7R/20% | KEMET | 100 nF |
| 12 | 1 | C101 | Capacitor 150p/630 V/1206/U2J/5% | Murata | 150 p |
| 13 | 1 | C102 | 470 µ/80 V/CAP-P7.5-D18-H20/20% | United Chemi-con | 470 µ |
| 14 | 1 | C104 | 100 µF/35 V/WCAP-ATG5_6.3x11 | Würth | 100 µF |
| 15 | 1 | C105 | 100 µ/25 V/CAP-P2-D5-H12/20% | Nichicon | 100 µ |
| 16 | 1 | C106 | 1 µ/100 V/1206/X7R/10% | AVX | 1 µ |
| 17 | 1 | C107 | 100 n/100 V/1206/X7R | AVX | 100 n |
| 18 | 1 | C108 | 100 n/50 V/0603/X7R/10% | Samsung Electro-Mechanics | 100 n |
| 19 | 1 | C109 | 100 n/50 V/0603/X7R/10% | Samsung Electro-Mechanics | 100 n |
| 20 | 1 | D3 | Diode US1MFA/SOD-23FL | ON Semiconductor | US1MFA |

| | | | | | |
|---|---|---|---|---|---|
| 21 | 1 | D4 | Diode MBR2H100/SOD-123FL | ON Semiconductor | MBR2H100 |
| 22 | 1 | D20 | Diode 1N4006G/800V/DO-41 | ON Semiconductor | 1N4006G |
| 23 | 1 | D21 | Diode 1N4006G/800 V/DO-41 | ON Semiconductor | 1N4006G |
| 24 | 1 | D101 | 15 A/300 V/TO-220AC | Vishay | 15 A/300 V |
| 25 | 1 | D102 | Diode MBR2H100/SOD-123FL | ON Semiconductor | MBR2H100 |
| 26 | 1 | D103 | Diode MBR2H100/SOD-123FL | ON Semiconductor | MBR2H100 |
| 27 | 1 | F1 | Fuse 300 V/2 A/ FUSRR508W62L835T430H820B/ | Bussmann by Eaton | Fuse 300 V/2 A |
| **28** | **1** | **IC3** | **ICL88xx/SOIC-8** | **Infineon** | **ICL88xx** |
| 29 | 1 | J1 | Connector 17.5 mm pitch jumper 0.8 mm wire/JP-THT-1.00_2.20_17.5_0.80-2P | PRO Power | 17.5 mm pitch jumper 0.8 mm wire |
| 30 | 1 | J2 | 15 mm pitch jumper 0.8 mm wire/JUMP1.0/15 – duplicate | PRO Power | 15 mm pitch jumper 0.8 mm wire |
| 31 | 1 | J3 | 7.5 mm pitch jumper 0.8 mm wire/JUMP1.0/7.5 – duplicate | PRO Power | 7.5 mm pitch jumper 0.8 mm wire |
| 32 | 1 | J4 | Connector 10 mm pitch jumper 0.8 mm wire/JP-THT-1.00_2.20_10_0.80-2P | PRO Power | 10 mm pitch jumper 0.8 mm wire |
| 33 | 1 | L1 | Inductor 68 mH/B82732F/30% | Epcos | 68 mH |
| 34 | 1 | L2 | 470 µH/1.15 A/7447480471 (WRU) | Würth | 470 µH/1.15 A |
| 35 | 1 | MOV1 | Varistor 510 V/radial type/10% | Panasonic | Varistor 510 V |
| 36 | 1 | PC1 | TLP383 (GR-TPL,E/TLP383) | Toshiba | TLP383 (GR-TPL,E) |
| **37** | **1** | **Q1** | **MOSFET, 0.9 Ω, 800 V, DPAK** | **Infineon** | **MOSFET, 0.9 Ω, 800 V, DPAK** |
| 38 | 1 | R1 | Resistor 2.2k/200 V/1206/1% | Vishay | 2.2k |
| 39 | 1 | R2 | Resistor 20k/75 V/0603/1% | Vishay | 20k |
| 40 | 1 | R3 | Resistor 1k/200 V/1206/1% | Vishay | 1k |
| 41 | 1 | R4 | Resistor 2.7 MEG/200 V/1206/1% | Vishay | 2.7 MEG |
| 42 | 1 | R5 | Resistor 2.7 MEG/200 V/1206/1% | Vishay | 2.7 MEG |
| 43 | 1 | R6 | Resistor 910k/200 V/1206/1% | Vishay | 910k |
| 44 | 1 | R7 | Resistor 100k/200 V/1206/1% | Vishay | 100k |

| | | | | | |
|---|---|---|---|---|---|
| 45 | 1 | R8 | Resistor 100k/200 V/1206/1% | Vishay | 100k |
| 46 | 1 | R10 | Resistor 33k/150 V/0805/1% | Vishay | 33k |
| 47 | 1 | R11 | Resistor 12k/75 V/0603/1% | Vishay | 12k |
| 48 | 1 | R14 | Resistor 180 mR/200 V/1206/1% | Vishay | 180 mR |
| 49 | 1 | R15 | Resistor 39 R/200 V/1206/1% | Vishay | 39 R |
| 50 | 1 | R16 | Resistor 47 R/200 V/1206/1% | Vishay | 47 R |
| 51 | 1 | R17 | Resistor 39k/75 V/0603/1% | Vishay | 39k |
| 52 | 1 | R18 | Resistor 1 R/200 V/1206/1% | Vishay | 1 R |
| 53 | 1 | R19 | Resistor 30k/200 V/1206/1% | Vishay | 30k |
| 54 | 1 | R20 | Resistor 0 R/150 V/0805 | Vishay | 0 R |
| 55 | 1 | R22 | Resistor 0 R/150 V/0805 | Vishay | 0 R |
| 56 | 1 | R29 | Resistor 30k/200 V/1206/1% | Vishay | 30k |
| 57 | 1 | R30 | Resistor 30k/200 V/1206/1% | Vishay | 30k |
| 58 | 1 | R101 | Resistor 10 R/200 V/1206/1% | Vishay | 10 R |
| 59 | 1 | R104 | Resistor 0 R/200 V/1206 | Vishay | 0R |
| 60 | 1 | R107 | Resistor 0 R/200 V/1206 | Vishay | 0 R |
| 61 | 1 | T1 | PQ2620 544 µH/PQ2620 | Itacoil | PQ2620, 544 µH |
| 62 | 1 | X1 | 250-203/WAGO_250-203 | WAGO | 250-203 |
| 63 | 1 | X5 | Connector 826936-4/CON-M-THT-826936-4 | TE Connectivity | 826936-4 |
| 64 | 1 | X200-A | 6-pin pluggable terminal block/3.81*6 – duplicate | Würth | 6-pin pluggable terminal block |
| 65 | 0 | C2 | NA/310 V AC/L13_W7_H13_P10_CS | Würth | NA |
| 66 | 0 | C10 | NA/630 V DC/1206/X7R/10% | TDK | NA |
| 67 | 0 | C110 | Capacitor NA/25 V/1206/X7R/10% | Murata | NA |
| 68 | 0 | D6 | Diode NA/22 V/SOD-323 | Nexperia | NA |
| 69 | 0 | D104 | NA/SOD-323 | Vishay | NA |
| 70 | 0 | D105 | NA/SOD-323 | Vishay | NA |
| 71 | 0 | D106 | NA/SOD-323 | Vishay | NA |
| 72 | 0 | MOV2 | Varistor, 510 V/radial type/10% | Panasonic | Varistor, 510 V |
| 73 | 0 | R3a | Resistor NA/200V/1206/1% | Vishay | NA |
| 74 | 0 | R12 | NA/200 V/1206/1% | Yageo/Phycomp | NA |
| 75 | 0 | R13 | NA/200 V/1206/1% | Yageo/Phycomp | NA |

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| 76 | 0 | R14a | Resistor NA/200 V/1206/1% | Vishay | NA |
| 77 | 0 | R21 | Resistor NA/150 V/0805/0 R | Vishay | NA |
| 78 | 0 | R24 | Resistor NA/200 V/1206/1% | Vishay | NA |
| 79 | 0 | R25 | Resistor NA/200 V/1206/1% | Vishay | NA |
| 80 | 0 | R26 | Resistor NA/200 V/1206/1% | Vishay | NA |
| 81 | 0 | R28 | Resistor NA/75 V/0603/1% | Vishay | NA |
| 82 | 0 | R36 | Resistor NA/75 V/0603/0 R | Vishay | NA |
| 83 | 0 | R102 | NA/1206 | | NA |
| 84 | 0 | S101 | NA/Çá´¥¿ª¹Ø7.6*5.08 – duplicate | Würth | NA |
| 85 | 0 | ZD101 | NA/SMA | Taiwan Semiconductor | NA |

# Revision history

| Document version | Date of release | Description of changes |
|---|---|---|
| V 1.0 | 02-06-2021 | First release |
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