Application Note

AC-DC CONVERTER TESTING FUNDAMENTALS

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1 Overview

This document is divided in two parts and starts with an introduction in AC-DC conversion principles in general. It will present the most common circuits used for different power levels. The switching mode power supply (SMPS) converter will be the main focus as they are used everywhere in the electronics. Especially the flyback converter design in different flavors are highlighted. Nevertheless, all measurements are also applicable for other SMPS converter designs operating at higher power levels.

In the second part of this document, most relevant testing methods and procedures of an AC-DC converter are highlighted. For each testing section, a fundamental part will be upfront discussed and it is followed by a presentation of a suitable measurement method. In this second part, the device under test (DUT) is considered as black box device and thus the structure is similar. Therefore, the testing parts consists of methods related to input tests, output tests and a combination of both like efficiency. Of course, some test performed at the output of the converter are also relevant for DC-DC converter, e.g. the validation of the output ripple.

2 AC-DC Conversion Fundamentals

Each electronic equipment requires a low DC supply voltage for operation. This supply voltage has to be generated in most cases from the grid, which is an AC supply. Therefore, an AC-DC conversion stage in front of any electronic equipment is needed. For this purpose, different solutions exist to convert the higher AC voltage to a lower and safe DC voltage.

2.1 Linear Power Supply

Linear power supplies have a steel or iron laminated line transformer connected directly to the grid. Therefore, it provides an isolation barrier between the AC input voltage and the lower AC output voltage for safety reasons. The transformer also reduces the AC input voltage from typically 120V/230V to a much lower voltage, e.g. like 24V AC. The lower voltage is then rectified by diodes and smoothed by a large aluminum electrolytic capacitor. That lower DC voltage is then post regulated by a control of a transistor operated in its linear region.

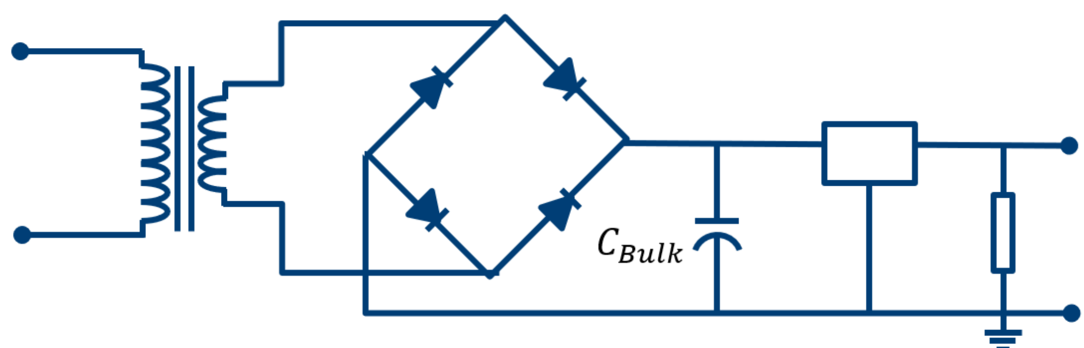


Figure 1 Linear Power Supply

This principle is often used for laboratory power supplies where very low ripple voltage and low noise is mandatory. This concept is typically very bulky due to the line transformer which is designed for low frequency (50/60Hz) operation, the large smoothing capacitor and the required cooling of the linear regulator.

2.2 Switching-Mode Power Supply

In any applications where high efficiency is key, a converter based on the switching-mode principle is a common approach. The selected topology can be a single stage but can also consists of two conversion stages. Which topology suits better depends on several parameters like power capability, efficiency, cost and size.

2.2.1 Lower Power Level (<75W)

In this approach, the AC grid voltage is rectified by diodes and smoothed with large aluminum electrolytic capacitors resulting in a high voltage pulsating DC voltage. This pulsating DC voltage is converted into a lower AC voltage by a high frequency switching principle and transferred to the output via a high frequency transformer. This high switching frequency principle allows the usage of a much smaller transformer. This transformer also provides electrical isolation between AC and DC for safety reasons. The AC signal at the output voltage needs to be rectified and filtered by another set of diodes, capacitors and inductors. Corrections to the output voltage due to load or input changes are achieved by adjusting the pulse width of the high frequency waveform. Typically, this converter needs an additional EMI input filter circuit to limit the noise emission which are generated by the switching elements of the converter stage at higher frequency. A standard converter structure based on the switching principle is illustrated in the picture below:

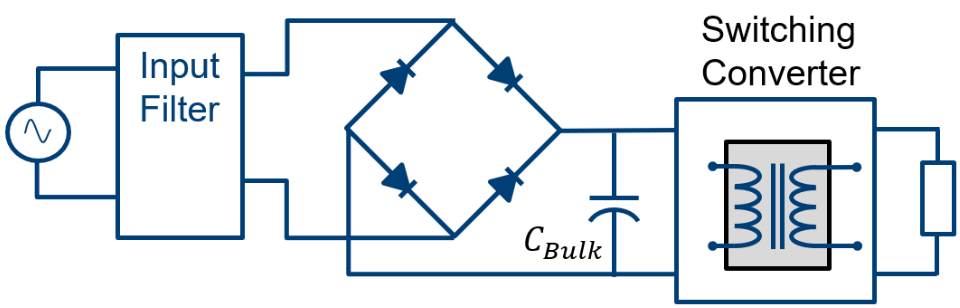


Figure 2 Standard Switching Converter Structure

A very common topology at this lower power level is the flyback converter or forward converter. In a flyback topology, energy is stored in the magnetic field of the transformer during the first half of the switching cycle and then released to the secondary winding connected to the load in the second half of the cycle.

The advantage of this flyback topology is that it can provide efficiencies up to 90% (extended flyback converter with active clamp) at this lower power level and the number of required components is pretty low and leads to a cheap bill of material. A galvanic isolation is provided to fulfill safety requirements as well. Typical applications are notebook power supplies and mobile chargers.

The main disadvantages of this solution are the additional required EMI Input filter and the limited power conversion level due to the energy storage principle of a flyback transformer. Furthermore, this converter causes a low power factor and high current distortion which causes higher transmission losses in the grid. However, if an AC-DC converter is used in standard applications and the power does not exceed 75W, it does not need to comply with power quality requirements regarding EN61000-3-2.

The active clamp flyback topology will be evaluated in the measurement section of this document in more detail.

► Flyback Converter used as Power Factor Correction Circuit (PFC)

For LED lighting solutions there are more stringent rules of the power quality requirements. According to the standard, a driver used for lighting applications with more than 25W input power, a minimum power factor of λ = 0,9 is required. Therefore, several control chip vendors provide tailored controller designs for this specific lighting applications. By using these specific integrated circuits, a flyback converter can operate with a duty cycle modulation that automatically shapes the input current and results in a high PF. In addition, it reduces the harmonic distortion. Beside the control chip change, the large smoothing electrolytic capacitor after the rectifier must be moved to the output of the converter. Only in this case, the line frequency which appears at output will be filtered sufficiently. This converter type is illustrated in the picture below:

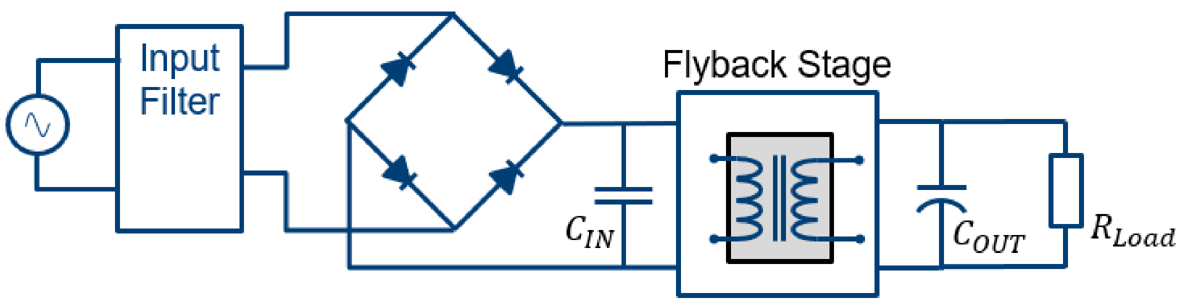


Figure 3 Flyback Topology with PFC Control

Only a small decoupling capacitance after the input must be provided to be able to shape the input current for obtaining a high-power factor. The large capacitor is provided at the output to suppress the line frequency voltage ripple.

This converter topology will be evaluated in the measurement section of this document in more detail.

2.2.2 Higher Power Level (>75W)

An AC-DC converter with focus on higher output power levels requires a different converter topology to achieve higher efficiency and to obtain a compact design as well. For this challenging task, the two-stage converter approach leads to a better technical solution. A very common combination is to use a boost converter after the EMI input filter and bridge rectifier to convert the pulsating rectified DC voltage into a higher DC bus voltage. The higher DC voltage is the input for the second stage. This DC bus voltage will be converted by the second stage to a lower voltage level. A high frequency transformer supports the switching converter to scale down the higher voltage to a lower voltage. Furthermore, the transformer provides the isolation barrier required for safety reason between the AC input rail and the DC output of the converter. Overall efficiencies up to 95% can be achieved with this two-stage concept.

2.2.2.1 Input Converter Stage

At a first view, the details of the input stage design depend on different requirements like power, efficiency and size as mentioned in the previous section. However, it also matters in which region (e.g. US or EU) the converter will be operated. The input voltage can be either at 230V/50Hz for the EU or it can be at 120V/60Hz for the US. The boost converter is a very good fit to cover a very wide input voltage range from 85VAC up to 265VAC.

The main elements of this converter type are shown in the picture below and consists of a bridge rectifier, a boost inductor, a boost diode, a larger bulk capacitor at the output for filtering the line ripple and a switching element, typically a MOSFET.

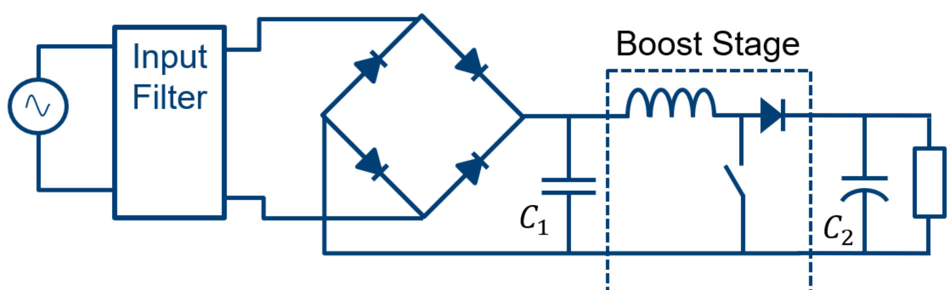


Figure 4 Boost Converter

A standard boost converter operates in a manner that the regulated output DC voltage of the converter is higher than the peak voltage of the AC input voltage. This is very beneficial if the converter is designed to operate as active power factor correction converter. In this application, the converter imitates a resistive load ideally.

► Boost converter as active power factor correction (PFC).

A specific variant of the standard boost converter explained in the previous section operates as active power factor correction to obtain high power factors close to 1 and also fulfils the standard regarding current harmonics (EN61000-3-2). This can be achieved because a boost converter can provide the widest conduction angle for the input current to act as a resistive load for the grid. A simple standard boost converter using a MOSFET as switching devices is commonly used in the industry for active PFC applications. However, depending on power level and desired efficiencies, various circuit extension circuit exists such as interleaved PFC or Totem Pole PFC. This boost PFC variants focus on higher efficiency while they still provide a large power factor and a low total harmonic distortion (THD).

2.2.2.2 Second Stage (DC-DC Conversion)

The design details of the output stage or second stage depends on the application requirements. In case a non-isolated boost PFC is used for the input stage, the second stage has to provide the DC-DC conversion from a higher input DC voltage down to a lower output DC voltage. Furthermore, it provides an isolation barrier for safety reason.

The most common used converter topologies for the second stage are the resonant half bride converter, forward converter and buck converter. Shown below is the circuit of a resonant half bridge converter (LLC).

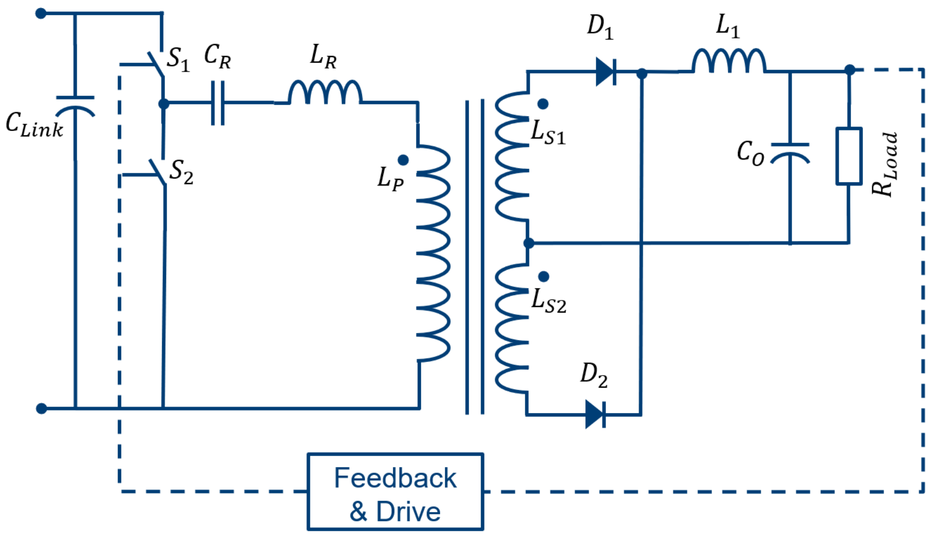


Figure 5 LLC Converter

The LLC converter is a resonant converter with three reactive elements (L_R, L_P and C_R) where the DC input voltage is turned into a square wave by a half-bridge to feed the resonant LLC tank that effectively filters out harmonics providing a nearly sinusoidal voltage and current waveform. This feeds into an isolation transformer that provides also voltage scaling. The power transfer to the output of the converter is controlled by modulating the square wave frequency with respect to the tank circuit's resonance. In an LLC resonant converter, all semiconductor switches at zero-voltage and thus a high efficiency can be achieved.

This second stage is not part of the measurement section within this document because the single stage AC-DC converter is the focus of this paper.

3 AC-DC Converter Testing

A suitable setup to perform all measurement described within this document is required to test the converter accordingly. It consists of a laboratory AC power supply to supply the DUT and an electronic load to set the DUT into the desired operation mode. Especially the laboratory AC power supply is a key instrument to validate the DUT and it need to comply with IEC 61000.

Furthermore, a suitable 4-channel digital oscilloscope is required to measure all relevant parameters listed in the tests below. Of course, enough bandwidth (>1GHz), sufficient memory (400Mpoints) and standard math functions are mandatory.

A voltage measurement with an oscilloscope requires a high voltage differential probe for most of the measurements. This probe should provide a dynamic range of at least ±750V and should provide sufficient bandwidth (>100MHz). Using a differential probe like the RT-ZHD07 helps to avoid ground loops in the system and ensures a proper measurement. This is also beneficial even the laboratory AC-DC power supply ensures isolation to the grid.

A special case does exist if ripple measurement at the output rail needs to be measured. A power rail with high offset capability was used for this purpose.

Current measurements are also required and therefore, a current clamp-on probe was used. Of course, it also requires sufficient bandwidth (> 50MHz).

The following DUT's (device under test) will be used to demonstrate the measurement methods described in this chapter:

- Analog Devices DC1817B: Demo Board for the LT3798 Isolated No Opto-Coupler Flyback Controller with Active PFC
- Texas Instruments UCC28780 EVM-021 Evaluation Module with Active-Clamp Flyback Controller.

3.1 Input Line

3.1.1 Power Quality

The way a switching regulator draws current from the grid can produce an input current which is leading or lagging in relation to the voltage of the AC power source. This leading or lagging of the input current cause an energy transfer between the source and the load which cannot be utilized by the load. The power factor (PF) is a measure how the load draws the power from the source.

Non-linear loads draw current from the grid, which are non-sinusoidal. This causes distortions in the power line voltage. These distortions can trip fuses and circuit breakers at power levels lower than power line capability. The presence of these harmonic can also lead to problems like overheating of neutral conductors and interference with communication circuits connected to the grid. The total harmonic distortion (THD) of the input current is a measure how much the current waveform differs from a true sinusoidal current waveform.

Utility companies have regulatory requirements on the PF and THD of electrical equipment to avoid the problems mentioned above.

3.1.1.1 Fundamentals

In this chapter, the theoretical knowledge will be explained. This knowledge is important to derive the key parameters from the measurements.

3.1.1.1.1 Real Power

The real power is that amount of power delivered from the source to the load which is utilized completely. It can also be expressed as the average of the instantaneous power. The real power is defined by the following equation:

$$P = \frac{1}{T} \int_0^T u(t) * i(t) dt \; [W]$$

Equation 1

3.1.1.1.2 Apparent Power

The apparent power is that amount of power the source has to deliver to the load including the total reactive power. The definition of the apparent power is the product of the RMS (root mean square) voltage and the RMS current. The apparent power can be calculated by the following equation:

$$S = U_{RMS} * I_{RMS} \; [VA]$$

Equation 2

Furthermore, the apparent power can be calculated according to the power triangle by the following equation:

$$S = \sqrt{P^2 + Q_{tot}^2}$$

Equation 3

3.1.1.1.3 Total Reactive Power

The total reactive power Q_{tot} is that amount of power, that the load is not able to utilize. The total reactive power is the geometric sum of the fundamental displacement reactive power Q_1 and the distortion reactive power Q_d. The total reactive power based on the 3-dimensional power triangle can be expressed by the following equation:

$$Q_{tot} = \sqrt{Q_1^2 + Q_d^2} \; [var]$$

Equation 4

The total reactive power can be calculated by rearranging Equation 3 as follows:

$$Q_{tot} = \sqrt{S^2 - P^2}$$

Equation 5

3.1.1.1.4 Power Factor

The power factor (PF) is the ratio of power utilized by the load to the power delivered to the load and is expressed as a number between 0 and 1. A purely resistive loads has a power factor of 1 because it draws current which is exactly in phase with the sinusoidal line voltage. Nevertheless, the reactive elements such as capacitors and inductors of a switching converter draw an additional reactive current which is difficult to measure. Most importantly, this reactive power will cause the delivered power (apparent power) to be larger than the power actually required by the load. This can cause the utility's infrastructure to operate above capacity and can cause damage potential if no measure is taken to protect the infrastructure from being overloaded by the additional reactive power. The closer the PF is to 1, the more closely matched the current and voltage waveforms are. As the PF decreases, more power is wasted in the form of reactive power. A purely capacitive load connected to the grid is illustrated in the picture below:

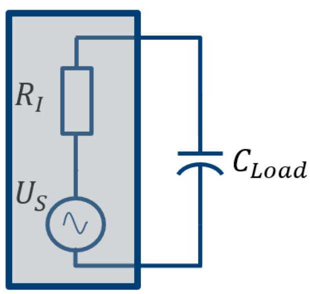


Figure 6 Capacitive Load

The circuit consist of only a reactive element C_{Load} as load. This reactive element causes a leading sinusoidal current. The waveforms, which are shaped by this circuit are illustrated in the picture below:

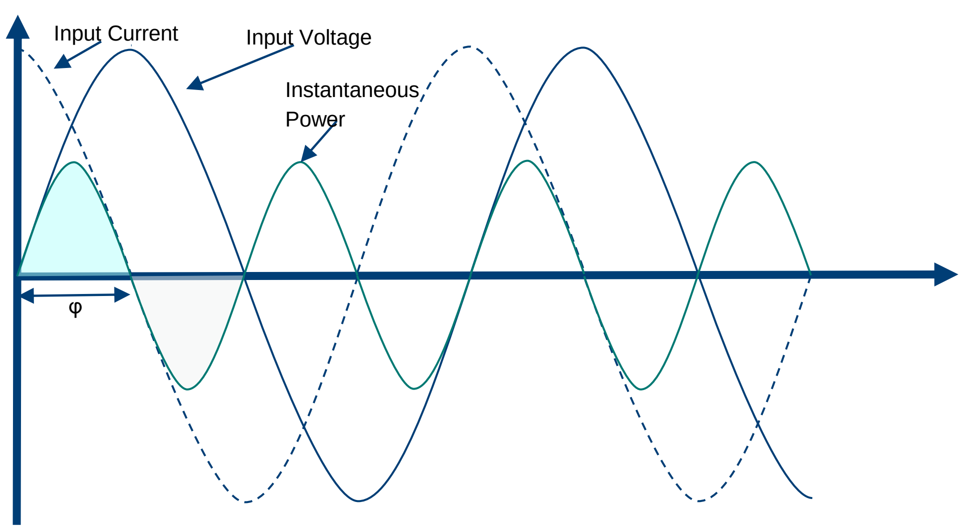


Figure 7 Voltage and Current Waveform of Capacitive Load

The input current is leading and causes a phase angle φ of -90°. The instantaneous power waveform average over one period consumed by the capacitor is zero. However, even the fact that the capacitor does not consume any energy, this energy is flowing from the power source to the load and back to the power source causing losses in the conductors and also in the power source.

The mathematical definition of the power factor is the ratio between the real power P [W] and apparent power S [VA] for all circumstances. This definition is illustrated in the following equation:

$$PF = \frac{P}{S}$$

Equation 6

Remark: The cos(φ) sometimes mention in the literature can only be used for pure sinusoidal waveforms.

For SMPS with power level P < 75W presented in section 2.2.1, the current waveform will result in a power factor of less than 0.5 due to the large input capacitance. However, as already mentioned, a higher power factor is not required according to the standard.

For SMPS with power level P > 25W and used in lighting applications, the power factor should be at least 0,9 depending on the applicable standard. Therefore, circuits with dedicated PFC functions shown in section 2.2.1 will shape the input current to obtain higher power factors.

For power supplies with power levels P > 75W as presented in section 2.2.2, the requirement for a high-power factor will be more stringent.

3.1.1.1.5 Crest Factor

The crest factor describes the quality of an AC waveform. A pure sinusoidal waveform shows a crest factor which is equal to $\sqrt{2} = 1{,}414$. The crest factor defines the ratio between peak value and true rms value and is shown in the following equation:

$$Crest\ Factor = \frac{Peak\ Value}{RMS\ Value}$$

Equation 7

All key parameters described within this chapter 3.1.1 need to be measured to characterize an AC-DC converter regarding power quality.

3.1.1.2 Measurements (PFC Flyback Converter)

The following measurements are typically performed when the design needs to be validated against power quality. In this chapter an active power factor controller is used for controlling the flyback converter. This converter can be used especially in lighting applications where more than 25W output power is required. Therefore, the expectations are that the key parameters characterizing the power quality are comparable values where an PFC controller is used.

3.1.1.2.1 Preparations for Measurements

Before any power measurement with an oscilloscope can be performed, the time delay between a voltage and a current probe pair due to the different probe measurement principles needs to be minimized. This ensures correct power calculation by using the power equation presented in 3.1.1.1.1 where the instantaneous voltage and instantaneous current values are utilized. An auto deskew application, which is part of the oscilloscope, provide the user to apply an auto correction for the deskew method in a very fast and efficient way. It is part of the K31 power option and requires also a deskew fixture hardware to attach the probes. The picture shown below is the start icon to execute the deskew procedure:

Figure 8 Deskew Application

After the deskew process has been performed, the voltage and current probes are aligned horizontally and any measurement to obtain power quality values can be started. Of course, this procedure has to be repeated for the second voltage/current probe pair to measure the power correct.

Remark: It is essential, that the laboratory power supply provides an AC voltage with low distortion and high accuracy. Only in this case, the user can assume that the DUT is the root cause for unexpected results.

Remark: The distortion of the generated sinusoidal voltage by the laboratory power supply is less than 0,3% @ 50/60Hz.

3.1.1.2.2 Results

The power quality measurement illustrated in the picture below is the fundamental measurement of input voltage (C1), input current (C2) and the calculated instantaneous power waveform (M1) This power waveform is the product of C1 and C2.

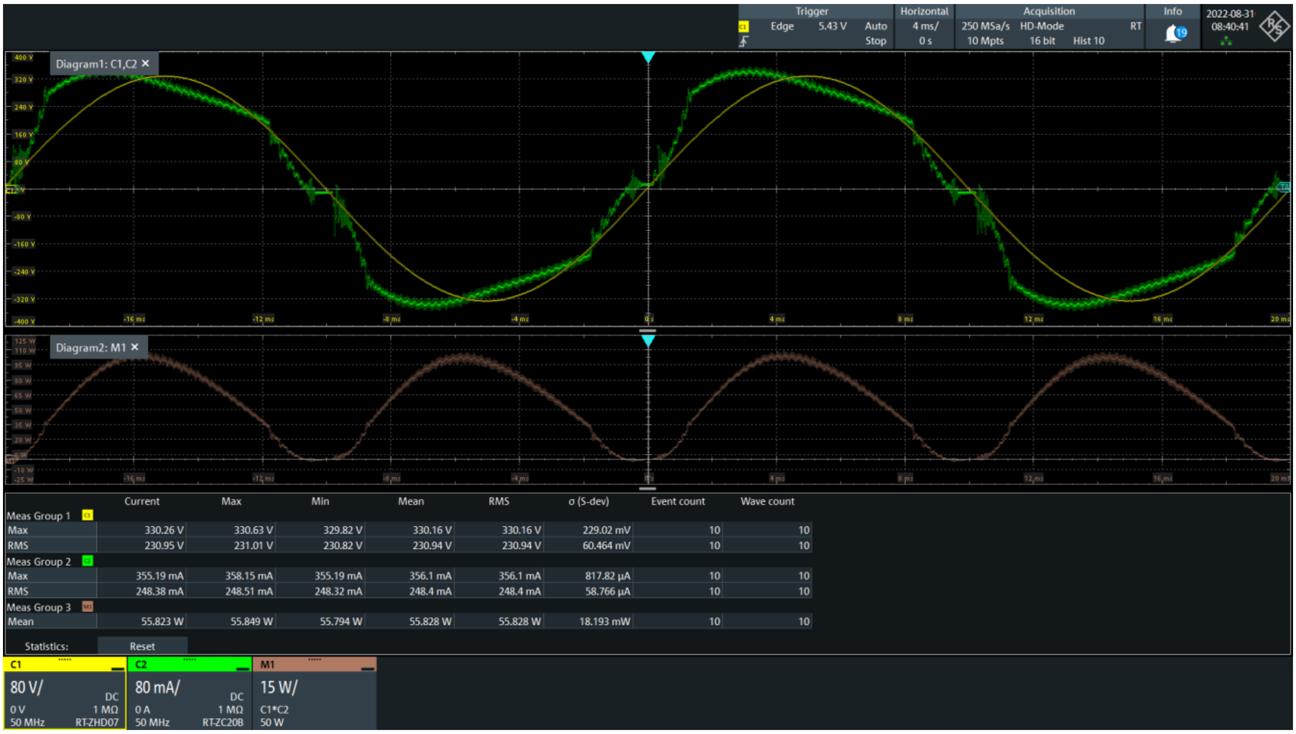


Figure 9 Measured Voltage, Current and Power at Input Terminals

The selected working point for the measurement above is the following:

P_{out} = 48,5W @ V_{in} = 230V/50Hz

The defined measurement groups within the oscilloscope provide the following fundamental values for the input current and input voltage:

U_{Peak} = 330,2 V

U_{RMS} =230,9 V

I_{Peak} = 0,356 A

I_{RMS} = 0,248 A

P_{avg} = 55,83W (2 Periods)

For all measurements, a mean value out of 10 measurements was used to obtain stable values. This can be proven by the standard deviation values.

In the measurement shown above, it is remarkable that the current waveform already shows a trend that it follows the input voltage. This is already an effect of the used active power factor controller. Further calculations and measurements are required to obtain the power quality parameters as describes in the previous chapter.

According to the fundamental equations presented in chapter 3.1.1.1, the following readings or calculations could be performed to obtain additional power quality figures:

► Real Power

This value can be taken from the measurement group directly as it is already defined as average value.

$P = 55{,}83\ W$

► Apparent Power

Using the RMS voltage and RMS current values from the measurement group, the apparent power can be calculated as follows:

$S = 230{,}9\ \mathrm{V} * 0{,}248\ A = 57{,}3\ VA$

► Power Factor

Using Equation 6, the power factor can be calculated as follows:

$PF = \frac{55{,}83\ W}{57{,}3\ VA} = 0{,}97$

► Reactive Power Q

Using the apparent power and measured real power, the reactive power can be calculated as follows:

$Q_{tot} = \sqrt{57{,}3\ VA^2 - 55{,}83\ W^2} = 12{,}9\ var$

► Crest Factor

Using the measured current values of measurement group, the crest factor can be calculated as follows:

$Crest\ Factor = \frac{0{,}356\ A}{0{,}248\ A} = 1{,}435$

All values above show reasonable values for an active power factor correction circuit for the key parameters of the power quality. In the next chapter, these values will be compared to the active clamp flyback stage where no PFC controller is used.

3.1.1.3 Measurements (Active Clamp Flyback Converter)

The following measurements show a power quality measurement of a standard flyback controller in the same manner as already performed in chapter 3.1.1.2 with the PFC converter. Therefore, the expectations are that the key parameters characterizing the power quality are not comparable to the values presented in the previous chapter.

3.1.1.3.1 Results

The power quality measurement illustrated in the picture below is the fundamental measurement of input voltage (C1), input current (C2) and the calculated instantaneous power waveform(M1) This power waveform is the product of C1 and C2.

Figure 10 Measured Voltage, Current and Power at Input Terminals (Non-PFC)

The selected working point for the measurement above is the following:

Pout=40W @ Vin = 230V/50Hz

The measurement groups provide the following fundamental values:

U_{Peak} = 330,3 V

U_{RMS} =230,7 V

I_{Peak} = 3,147 A

I_{RMS} = 0,550 A

P_{avg} = 42,83 W (2 Periods)

In the measurement above, it is remarkable that the current is highly distorted and it is also not in phase with the input voltage. Further calculations and measurements will confirm this in more detail.

According to the fundamental equations presented in chapter 3.1.1.1, the same readings and calculations were performed to obtain the power quality figures for the Non-PFC converter. In addition to the parameters obtained in chapter 3.1.1.2 these values are illustrated in the table below:

Key Parameter	Active Clamp Flyback	PFC Flyback
Real Power (P[W])	42,83	55,83
Apparent Power (S[VA])	126,89	57,30
Reactive Power (Q[var])	119,44	12,90
Power Factor (PF	0,34	0,97
Crest Factor (CF)	5,722	1,435

Table 1 Comparison PFC - Non-PFC Flyback

In this table, the values show clearly that the Non-PFC circuit is not capable to obtain similar values like in the PFC-Flyback. Even though, that the utilized power by the DUT is similar, the apparent power is much higher for the Non-PFC converter. This result show that it is mandatory to add a PFC functionality for higher power levels to limit the amount of reactive power. Remember that this reactive power has to be provided by the source and will generate also losses in the grid.

3.1.2 Total Harmonic Distortion

3.1.2.1 Fundamentals

A standard AC-DC SMPS like a flyback converter draw a current waveform which is not sinusoidal due to non-linear elements such as rectifier diodes. The THD is often mentioned in the same context as the power factor. Voltage and current waveforms created by the standard flyback stage presented in section 2.2.1 are illustrated in the picture below:

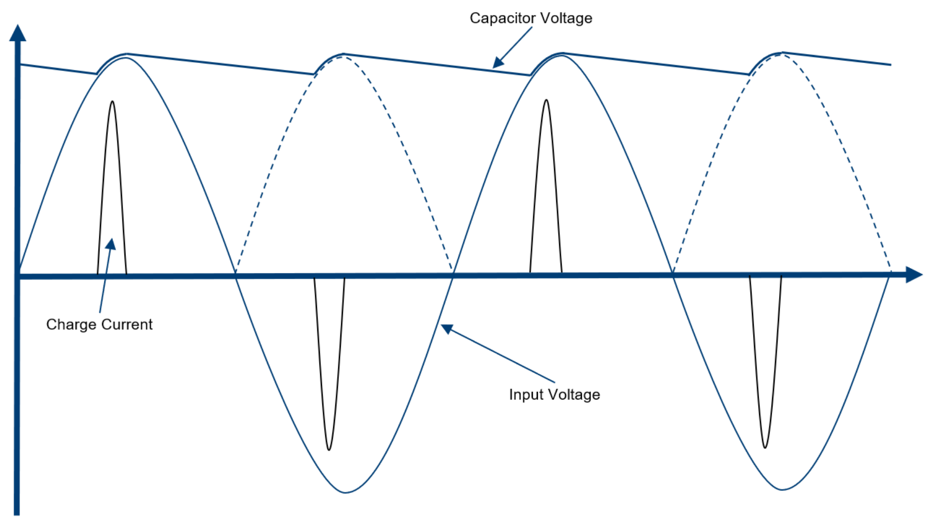


Figure 11 Input Voltage and Current Waveforms

During the power quality measurement of the standard flyback converter presented in chapter 3.1.1.3, this non-linearity of the input current was already clearly visible.

Assuming that the power grid is an ideal power source, the input voltage is still a sinusoidal waveform. Of course, it will be converted to DC pulsating voltage after the bridge rectifier and smoothed by the bulk storage, the electrolytic capacitor. Due to this non-linearity elements, the input current contains several harmonics as the waveform is non-sinusoidal.

Therefore, the current waveform contains harmonics at frequencies higher than the fundamental frequency and can be expressed as follows:

$$I_{RMS} = \sum_{N=2}^{\infty} I_n^2$$

Equation 8

The total harmonic distortion (THD) is represented as a percentage and is defined as follows:

$$THD_i = \frac{I_{RMS}}{I_{1RMS}} * 100[\%]$$

Equation 9

I_{1RMS} = Fundamental component of the current.

This definition with respect to total harmonic distortion assumes that the voltage of the grid stays undistorted. Therefore, it is mandatory to measure the total harmonic distortion at a suitable generator where the distortion is in the order of 1-2% or less. In practice, this current distortion will have impact on the supply voltage waveform. Thus, the grid voltage is often distorted due to the increased number of non-linear loads, that are connected on the grid.

3.1.2.2 Measurements

The current harmonic measurement was only performed with the PFC Flyback Controller because it obvious that the standard Flyback converter will exceed the limits due to the power quality measurement results (current is highly distorted) already presented in chapter 3.1.1.3.

Typically, the harmonics are measured with a power analyzer. This is a good approach but the power option K31 of the oscilloscope provide an application which enables the user to utilize the oscilloscope to measure current harmonics in an easy way. Especially during the design phase, this may improve the efficiency of the development process. The oscilloscope is a standard instrument during development while a power analyze is like not. Nevertheless, in this document, the focus was using the oscilloscope as a standard instrument.

The picture below shows the start icon to execute the current harmonic measurement procedure:

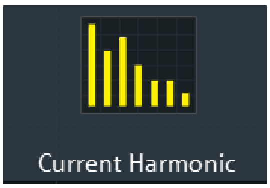


Figure 12 Current Harmonic Application

After setting the DUT in operation, the application can be executed.

3.1.2.2.1 Results

After the application has been executed the harmonic current measurement is illustrated in the picture below. It shows still the time domain waveform of the input voltage (C1), input current (C3) and the instantaneous power(M2) in the top window.

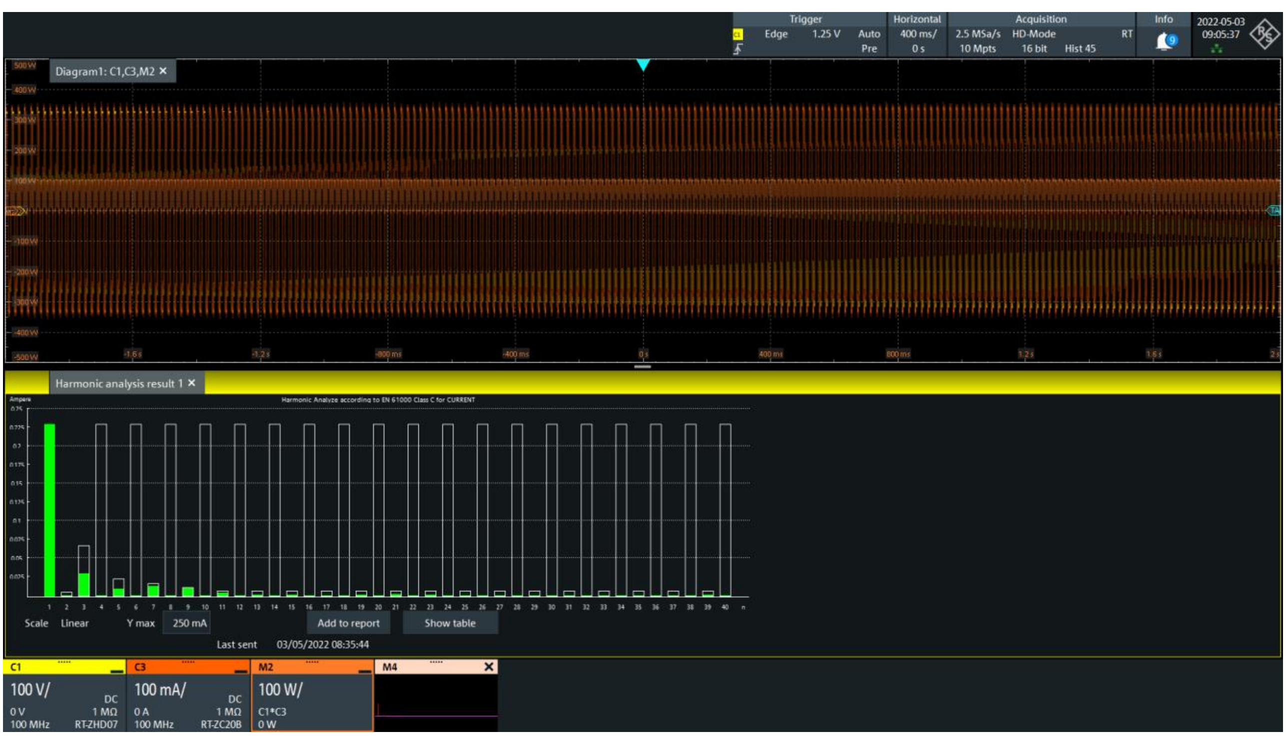
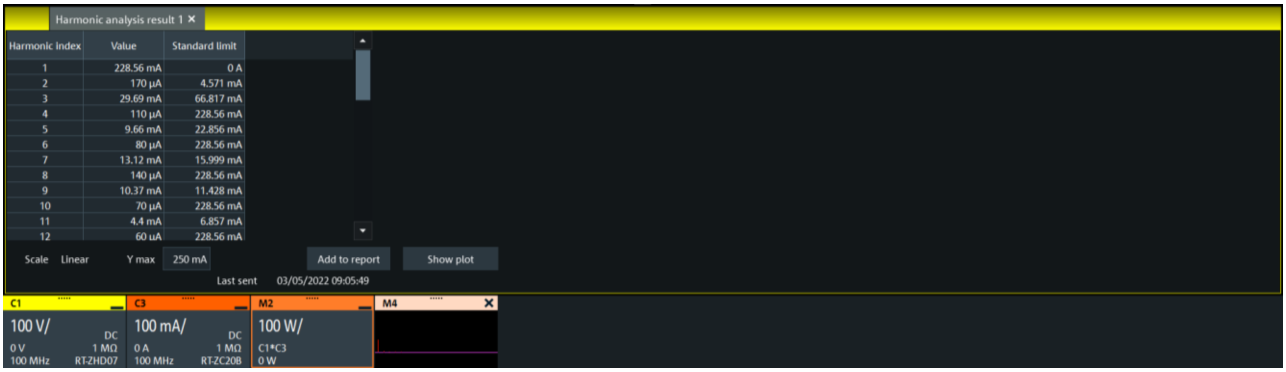


Figure 13 Current Harmonic Measurement Bar View

The bottom window shows the harmonic measurement analysis in a bar graph. In this bar graph, the harmonics are visible up to 40th harmonics. Each harmonic is indicated by a bar and shows either a red bar or a green bar. In case of a red bar, the limit is exceeded according to the standard.

The result shows clearly that no harmonics are exceeding the limits according to the selected standard EN61000 Class C. For class C (Lighting Equipment), it is required to measure also the power factor as the third harmonic needs to be below (PF * 30% of fundamental). Therefore, apparent power (M4) and real power need to be measured. This would imply again a deskew procedure if has not already been performed.

Additionally, the view of showing the harmonics can be changed to a table view. The view with the previous result is shown in the picture below:



Harmonic index	Value	Standard limit
1	228.56 mA	0 A
2	170 µA	4.571 mA
3	29.69 mA	66.817 mA
4	110 µA	228.56 mA
5	9.66 mA	22.856 mA
6	80 µA	228.56 mA
7	13.12 mA	15.999 mA
8	140 µA	228.56 mA
9	10.37 mA	11.428 mA
10	70 µA	228.56 mA
11	4.4 mA	6.857 mA
12	60 µA	228.56 mA

Figure 14 Current Harmonic Measurement Table View

Of course, the result is still the same but it might be more convenient for the user to document the results differently.

3.1.3 Inrush Current

3.1.3.1 Fundamentals

The current flowing from the grid into the AC-DC converter during the switch-on event is called inrush current and is a critical parameter of the power supply. This high peak current is only limited by the impedance of the grid itself and the input impedance of the converter. The grid impedance and converter input impedance are typically very low. Nevertheless, it is not reasonable to increase the impedance of the grid, but the converter design can be done in different ways to increase the input impedance during switch-on period. The input impedance of the converter at the switch-on event is typically dominated by the smoothing capacitor after the bridge rectifier. Depending on which converter topology is used, the inrush current can be very large and can cause disturbances, trip fuses or circuit breakers.

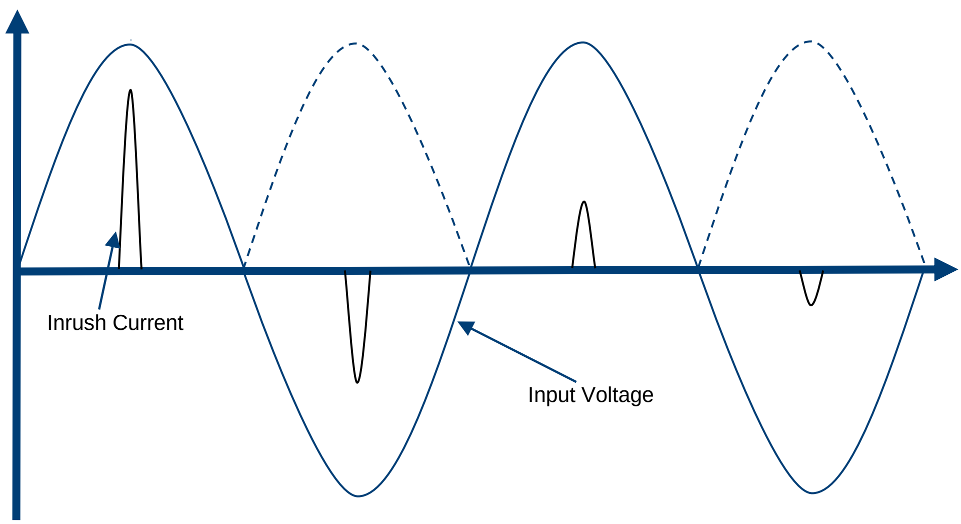


Figure 15 Inrush Current Over Time

Very important to evaluate is that the maximum inrush current is also depended at which phase angle the converter is connected to the mains voltage. The worst-case scenario the designer has to consider, is at 90° degree where the highest peak voltage will cause the highest peak current.

3.1.3.2 Measurements

The inrush current measurement was only performed with the Active Clamp Flyback Controller. In fact, this converter type will show a high current peak because of its input structure. It provides a structure which is similar to the circuit presented in Figure 2 (chapter 2.2.1).

An inrush measurement is typically performed with an oscilloscope but in some cases, a power analyzer can be used as well. However, inrush current is analyzed in the time domain and therefore, the oscilloscope with sufficient memory is the best choice. Furthermore, the K31 power option of the oscilloscope provide an application which enables the user to utilize the oscilloscope to measure inrush currents in an easy and fast way. Especially during the design phase, this may improve the efficiency of the development process. The oscilloscope is a standard instrument during development while a power analyze is not a standard measurement device.

The picture below shows the start icon to execute the inrush current measurement procedure:

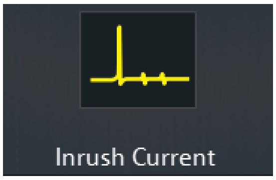


Figure 16 Inrush Current Application

After the application has been executed, the next task is to configure the inrush current application within the dialogue to match DUT operation parameter. This includes to specify the expected maximum peak current, the trigger level of the current and the gates where the oscilloscope should measure the multiple peak currents.

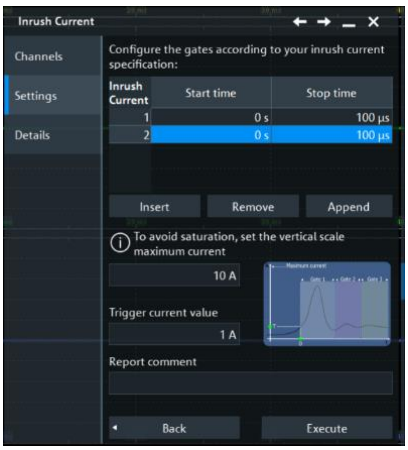


Figure 17 Inrush Current Configuration

It might be that this configuration needs to be changed after the first measurement as the details of the current peaks are unknown. After the execution of this application configured correctly, the inrush current application of the oscilloscope measure peak current, the area of the current which is the charge Q and the rise time automatically.

After setting all relevant values, a laboratory AC-Power Supply can be used to switch-on the power while the inrush current will be measured with the oscilloscope.

As already mentioned the phase angle should be varied by means of the laboratory power supply to cover the worst-case condition.

3.1.3.2.1 Results

The inrush current result is shown in the picture below:

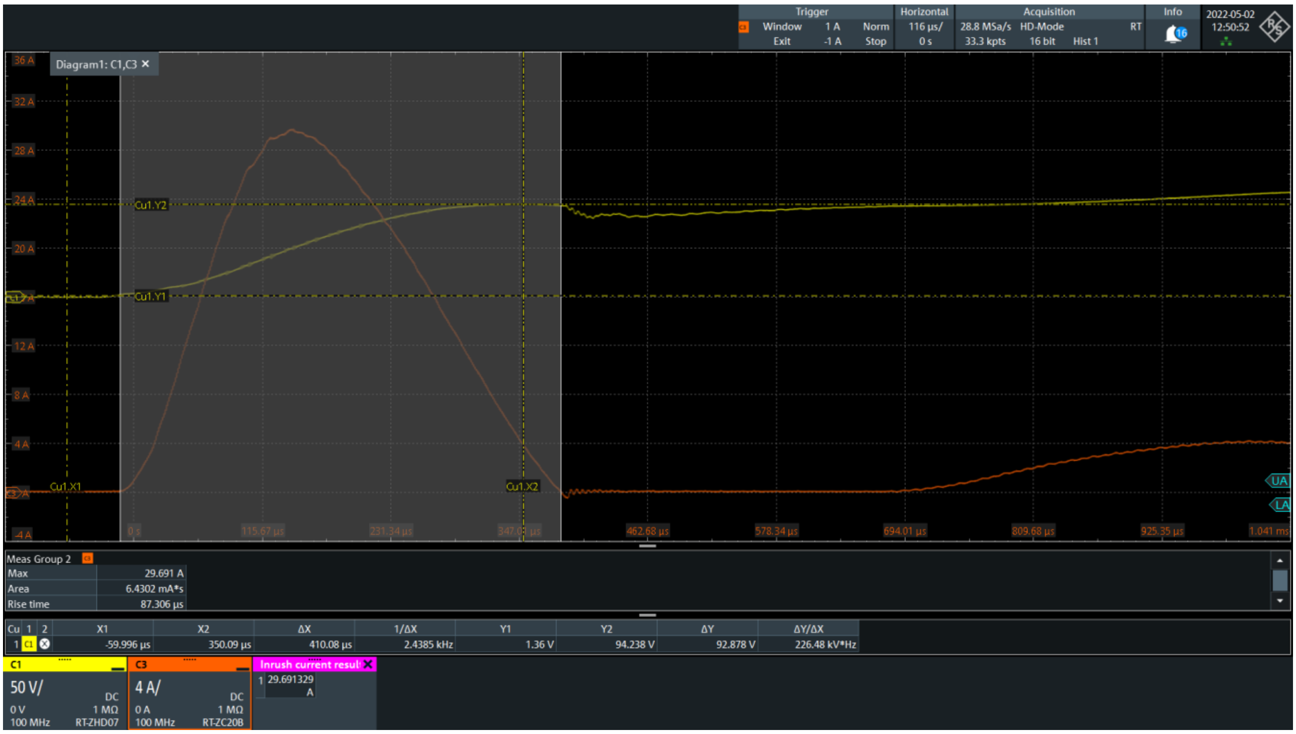


Figure 18 Inrush Current Measurement

In the inrush current application shows the first peak current measurement of almost 30A on channel 3. Of course, the user has to ensure that no clipping occurs and the current probe is capable to measure the max peak currents caused by the DUT. In addition to the input current, the input voltage on channel 1 is illustrated to show a valid reference. In this measurement, a rise time of the current peak of almost 90 µs was measured. This measurement is only possible if the probe including the oscilloscope provides enough bandwidth. This measurement example was performed at 0-degree phase angle which is not the worst scenario.

In case, that the inrush current exceeds the specified limit, several common techniques are used to overcome this problem. A negative temperature coefficient thermistor is often used to limit the current at switch-on because it provides a high resistance at low temperature. After heating up, the resistance value changes to a lower value and continuous current can flow without large power losses. In some applications, a relay is used across the thermistor to increase efficiency. The relay will be switched on when the inrush current event has finished.

3.1.4 Conducted Emissions

The conducted emissions at the input line of an AC-DC power supply need to be tested at the end of a development cycle and it is usually covered by spectrum analyzer or EMI test receiver where the standard limits are used to evaluate the pass/fail criteria. Especially when these types of instruments are used in a proper environment (anechoic chamber), the result will be close or equal to the final compliance measurement which is required to release the product to the market. These pre-compliance tests or even compliance test require a lot of resources and are rarely performed during the design phase. However, an early feedback during the design phase can be very beneficial to avoid redesigns close to the end of a design cycle. This can be obtained by using a suitable instrument to perform the task "Debugging Conducted Emissions".

3.1.4.1 Fundamentals

3.1.4.1.1 Setup

Debugging conducted emissions will be often performed in a standard development environment. In this case, no EMI chamber is available. Nevertheless, conducted emissions can be performed when the user follows some rules listed below:

- Artificial Mains Network (AMN) or Line Impedance Stabilization Network (LISN) is required to obtain results which are independent from the connected power source. Only in this case, the results are comparable and repeatable. Furthermore, it provides a defined impedance for the DUT and RF ports are provided to connect the measurement device.
- Ground plane is highly recommended. The conducted emissions created by the converter and measurable at the input terminals always consists of common mode noise and differential mode noise. Especially, the common mode noise propagates between the earth ground and the two input terminals (Line, Neutral). If the ground plane does not exist like required in the standard, it is difficult to analyze the measurement in a proper and reliable way. The goal is always to be as close as possible to the setup defined in the standard.
- Anechoic chamber is not required, but it will improve the measurement. This highly depends on the radiated emissions created by other equipment within the lab environment.

The minimum recommended setup for debugging EMI emissions is illustrated below:

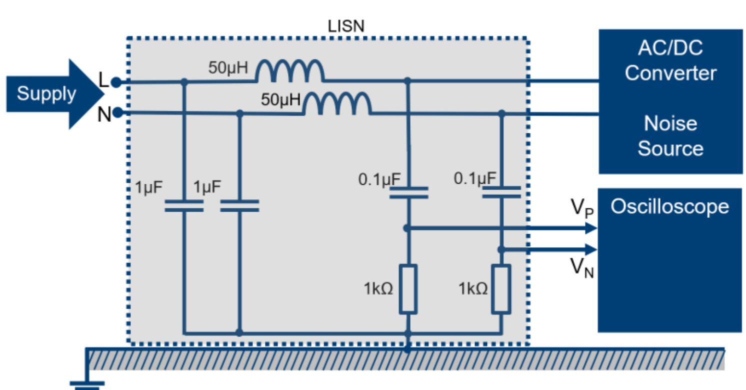


Figure 19 Conducted Emission Setup

This measurement setup is recommended to use if the task debugging conducted emissions will be performed.

3.1.4.1.2 Instrument

The oscilloscope is the standard instrument for all relevant time domain measurement tasks in the lab. Nowadays, a suitable oscilloscope allows also measurements in the frequency domain. Therefore, the oscilloscope can be used to allow optimization regarding EMI conducted emissions early in the lab Furthermore, an oscilloscope in combination with an additional external tool can simplify conducted emissions measurements.

An oscilloscope should provide the following features to support the task performing EMI Debugging in the laboratory:

► Multiple FFT to enable the user to perform a smart CM/DM (Common Mode/Differential Mode) separation technique. A single FFT can be used as well but it can only measure the combined noise sources.

► Low Noise Frontend. Depending on the standard, the emission limits are sometimes quite low (10-20 dBµV average in CISPR25)

► Powerful oscilloscope hardware to provide fast measurements (high update rate while the FFT is enabled).

In addition to the basic FFT functionality, the oscilloscope can be used to gain the knowledge between the FFT and the correlated time domain signals. This is a huge benefit of using an oscilloscope for debugging conducted emissions of a power supply.

3.1.4.2 Measurement with Precompliance Tool

A measurement of the conducted emission performed with the RTO6 in combination with the RTx Precompliance Tool is shown below:

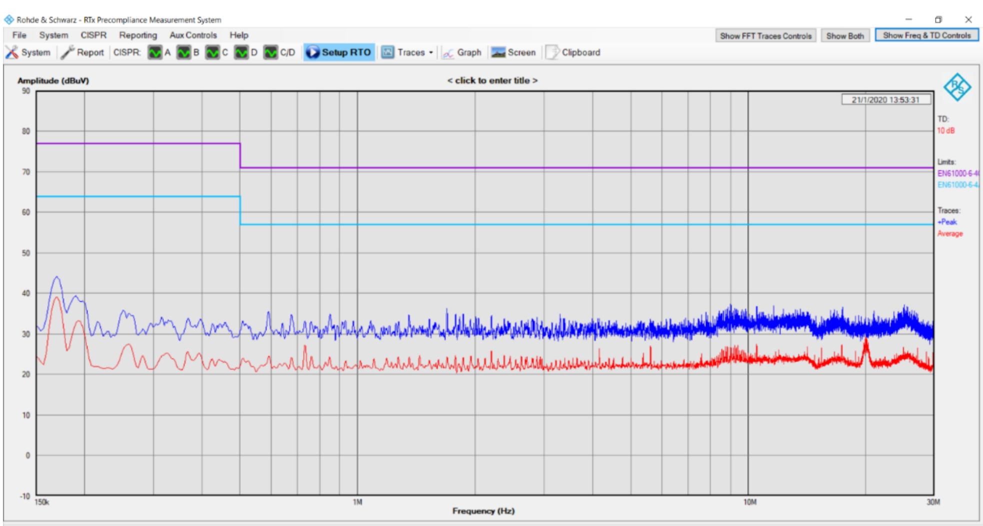


Figure 20 Conducted Emission Measurement (Oscilloscope)

This measurement includes a result which was already optimized (EMI Input Filter) regarding EMI Emissions. Therefore, all limits are well below the selected class B which ranges from 150kHz to 30MHz. The measurement result includes the peak and the average curves.

The precompliance tool can be downloaded for free by using the following link:

www.rohde-schwarz.com/emi

3.2 Output Line

3.2.1 Output Ripple Voltage

3.2.1.1 Fundamentals

The output ripple voltage is also part of the validation process of an AC-DC converter. However, usually the measurement does not differ form a ripple voltage measurement of an DC-DC Converter. Minimizing output ripple and limited switching transients are essential in most applications. Especially noise sensitive devices like an AD-Converter have stringed limits in terms of ripple voltage. In general, the output ripple voltage can be divided in two parts:

► Output ripple (Low-frequency periodic deviation)

The output ripple peak-to-peak describes the AC output voltage part, which is related to the switching operation of the converter. Its fundamental frequency is the same as the regulator switching frequency.

► The switching transients ripple peak-to-peak (high-frequency periodic deviation)

Switching transients are high frequency spikes or oscillations that occur during switching transitions. Its amplitude is defined as maximum peak-to-peak value. These switching transients will be superimposed on the output ripple peak-to-peak. Often, this part is difficult to measure accurately since it is highly dependent on the test setup. Furthermore, a proper probing is essential to measure a correct transient.

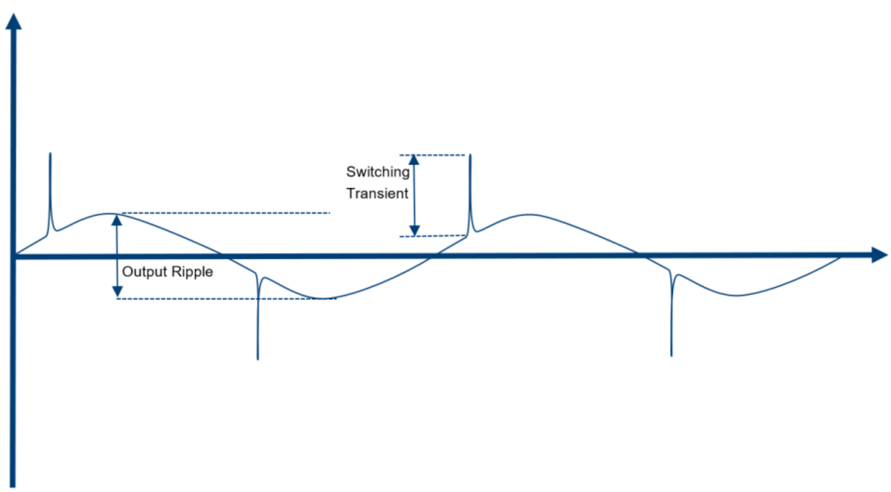


Figure 21 Output Ripple Definition

The output ripple definition is illustrated in the picture above. The waveform clearly shows the two components of the output ripple described above.

3.2.1.2 Measurement

Measuring these undesired voltages requires great care because a poor measurement setup can lead to a result which does not match to real waveforms. Loops formed by the oscilloscope probe signal and ground leads introduce parasitic inductance. This increases the amplitude of switching transients that are associated with the fast switching transitions. Therefore, proper connections and good measurement techniques in a wide bandwidth measurement is essential.

A specific power rail probe with very accurate offset capability will provide great results as very small AC signals can be measured even at higher output DC voltage. A measurement of the output rail of the active clamp flyback converter is illustrated below:

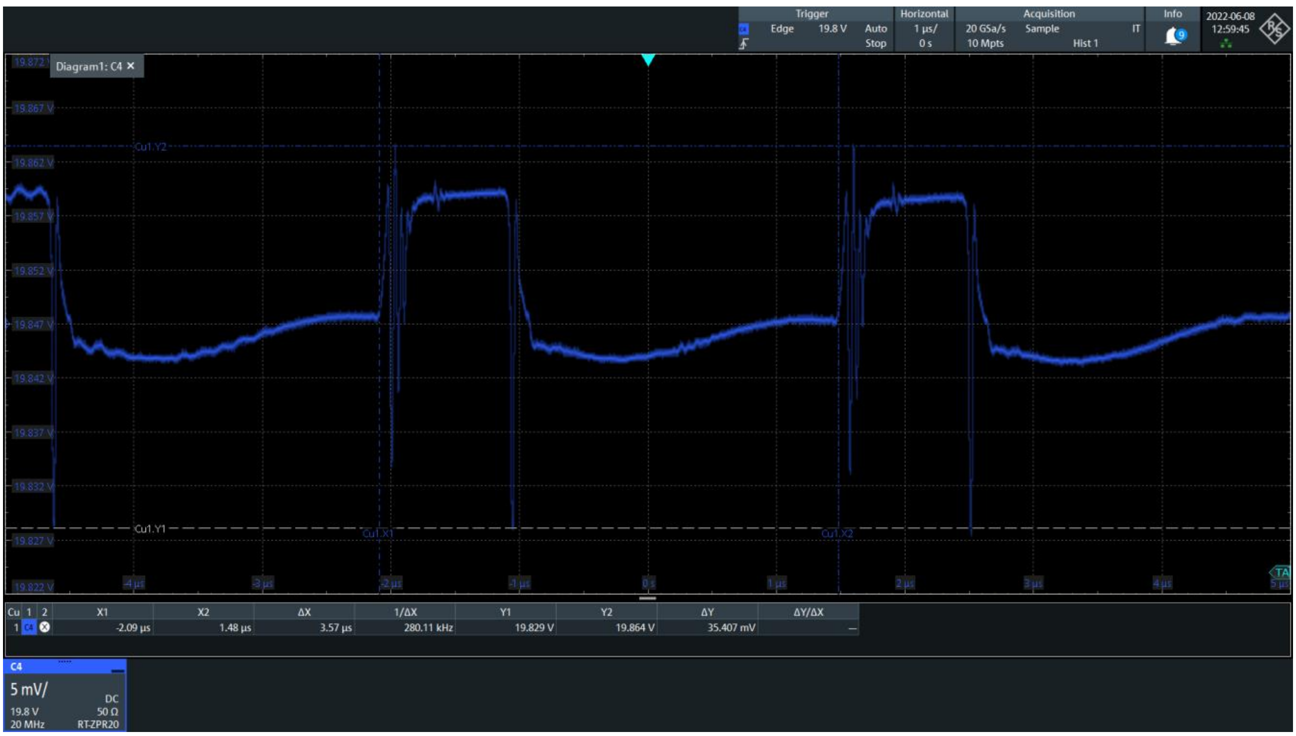


Figure 22 Ripple Voltage @ Full Load

The output ripple voltage is measured on channel 1 and an offset of 19,8V (output DC voltage) was applied to be able to set the vertical scale to 5mV/DIV. This increases the resolution tremendously and very small details within the waveform are visible. This waveform shows an overall peak to peak voltage ripple of 35mV measured by means of curser functionality. As described in the fundamental section, it consists of the low frequency portion (15mV@285kHz) and the high frequency oscillation (approximately 35mV@10MHz). According to the specification of the converter design, the nominal output ripple voltage is given by V_{ripple} = 28mV.

Frequently, some controller integrated circuits provide different methods to control the output voltage depending on the load condition. Therefore, the controller sometimes changes its operation mode from a continuously switching operation (standard at highest load) into the so-called "burst mode". In this burst-mode, the controller switches only several times continuously and after the switching sequence it stops for a certain period of time to save power. This approach is mainly implemented to set the converter into a more efficient mode at lower output power. However, these different operating modes may cause a higher ripple voltage.

The burst mode was measured and is illustrated in the measurement below.

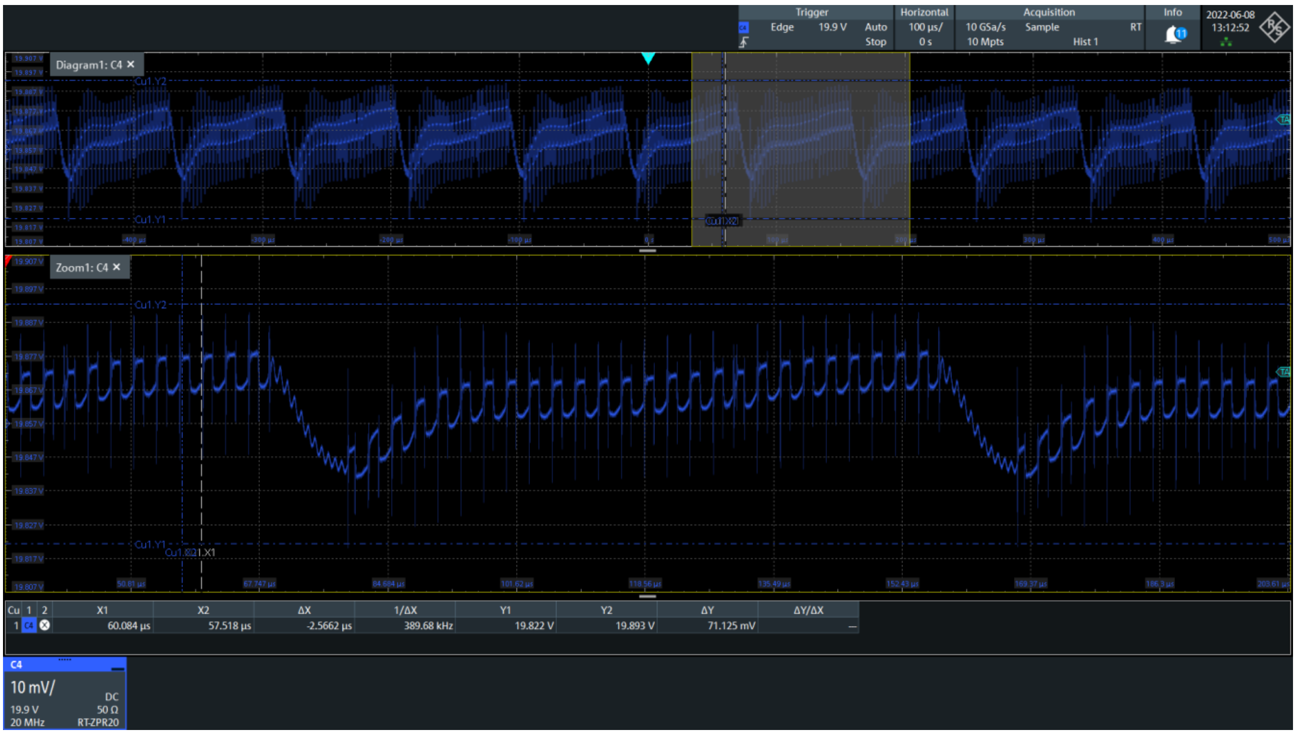


Figure 23 Ripple Voltage @ Burst Mode Operation

The ripple voltage increases to about 72mV due to this burst mode operation. However, this special case has to be measured separately and needs to be defined within the specification because the customized controllers can offer various different modes and thus the maximum ripple may be different.

3.2.2 Transient Load Response

Transient response test is a measure how quickly and effectively the power supply can adjust to sudden changes in current demands.

3.2.2.1 Fundamentals

This test is still applicable for many power supply applications even though, the frequency response analysis test is more and more used for stability testing. In very critical applications like aerospace and defense, both stability testing methods are performed. An example of such a transient load response test is illustrated in the picture below:

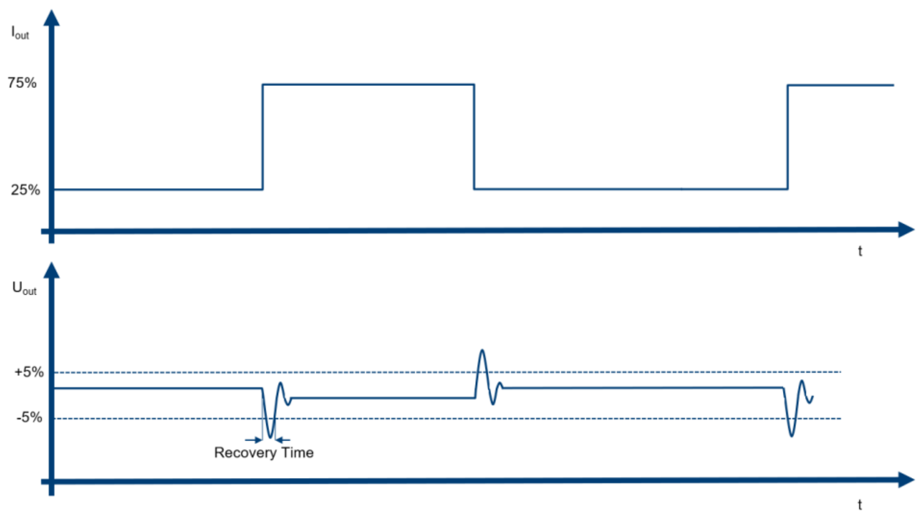


Figure 24 Load Transient Response

The waveforms show a current transient during a load step between 25% and 75% in the top window and the resulting output voltage waveform in the bottom window. It is clearly visible that there exists a certain recovery time for the regulator to adopt to the new load condition. However, if the recovery time needs to be short, the tradeoff will always end in a larger overshoot during the load transient. This optimization process is an essential part of any power supply design and needs to be validated.

A current step generator circuit to generate this fast load step should be fast enough (high di/dt) to test the power supply in a realistic scenario. Therefore, the connection between the current transient generator and the output of the power supply is critical. A long wiring could already limit the di/dt due to the inductance and thus limit the test capability.

Recommendations for the setup:

► The current step generator should be on the same printed circuit board as the power supply itself (A-Model) to minimized the parasitic inductance. In this case, the worst-case condition for the regulator circuit can be applied.

► In case an external current step generator is used to generate the current steps, it is essential to minimize the distance between output of the power supply output terminals and the external step generator (electronic load) as much as possible.

► Avoid connectors because they insert additional inductance.

3.2.2.2 Measurement

A transient test result is illustrated in the picture below:

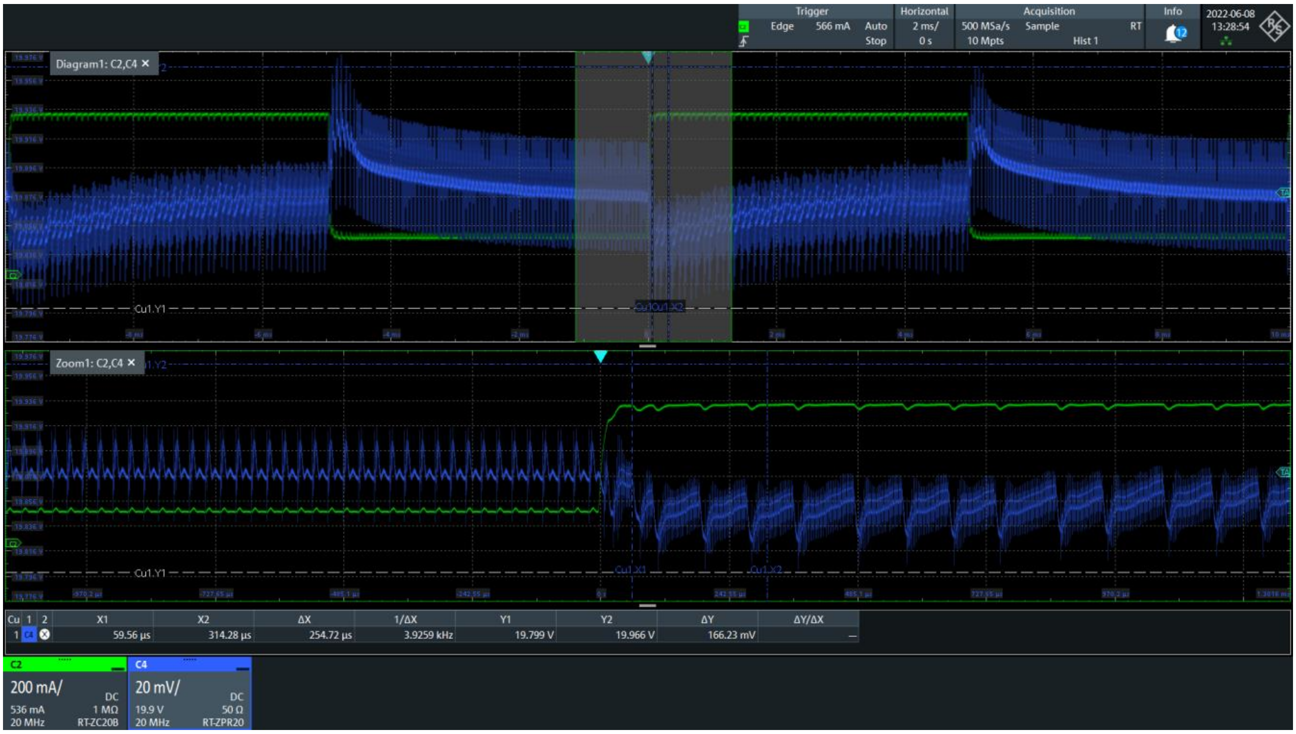


Figure 25 Active Clamp Flyback Transient Test

Channel 2 shows two cycles of the applied current steps between 250mA and 1000mA. Channel 4 shows the correlated voltage waveform, where voltage drops of approximately 65mV are visible. The applied offset voltage of 19,9V is set by the power rail and therefore, it is possible to identify the switching ripple and also the different operating modes like the burst mode. The recovery time was not measured because the transient pulse does not exceed the tolerance band of ±5%.

Furthermore, it is remarkable, that due to the applied load step, the operating mode of the controller changes during this event. This measurement details are only visible when a voltage probe with high offset voltage capability is used.

3.3 Efficiency

Nowadays, the efficiency is one of the most important key parameters to characterize a power supply. Of course, this is also true for an AC-DC power supply if it is only operating at lower power (<100W). Therefore, this test is a major part of every test plan to release the power supply to the market.

3.3.1 Fundamentals

Very often, a power analyzer is used to measure the input power to get very accurate values. This is for sure, the best choice to obtain values with highest accuracy. However, efficiency needs to be measured already during the design phase of the power supply because almost every part or component of the circuit will have impact on this critical measurement.

Typically, the oscilloscope is the workhorse of a designer during development. Therefore, it would be beneficial also to measure input power and output power with an oscilloscope to be able to calculate the efficiency. In this case, the designer is able to optimize the circuit in a very efficient way because of the fast feedback. Furthermore, the oscilloscope provides higher bandwidth than a power analyzer which could be also beneficial during efficiency measurements.

Efficiency is defined as the ratio of output power to input power and is defined in the equation illustrated below:

$$\eta = \frac{P_{out}}{P_{in}} * 100[\%]$$

Equation 10

Using the same fundamentals illustrated in chapter 3.1.1.1.1, the input power and output power can be measured.

3.3.1.1 Setup

The overall setup for an efficiency measurement is illustrated below:

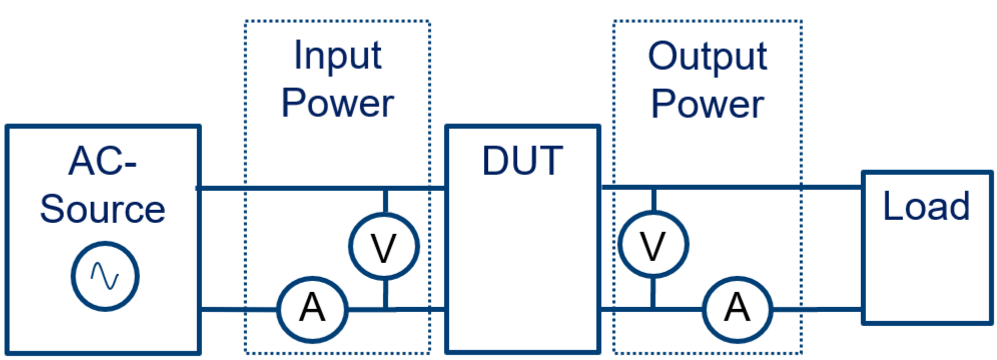


Figure 26 Efficiency Measurement Setup

It is important that the voltage probes are connected towards the device under test if the test will be performed at higher power. This ensures best accuracy as the voltage drop caused by the amperemeter is excluded from the measurement. Of course, this does not apply to current measurements performed with a current clamp-on probe.

3.3.2 Measurements

Before every power measurement can be performed with an oscilloscope, the deskew process is mandatory to obtain correct and reliable results. This deskew process is already described in chapter 3.1.1.2 and is also applicable for the channels to measure output voltage and output current.

The oscilloscope power analysis option K31 provide also an application for this efficiency measurement. The application icon is illustrated below:

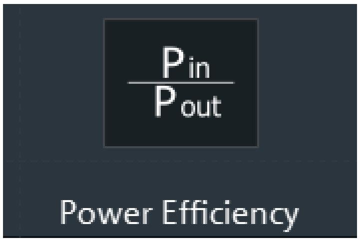


Figure 27 Efficiency Application

After the device under test is set to the desired working point, the application can be executed and the measurement window will appear. It includes all selected channels and in addition the calculated efficiency.

Figure 28 Efficiency Measurement

C1 = Input Voltage

C2 = Output Voltage

C3 = Input Current

C4 = Output Current

M2 = Input Power

M3 = Output Power

The efficiency value for this operating point is shown in the power efficiency box next to the channels.

Usually, this efficiency will be measured over the input voltage range. The result is illustrated in the table below:

Input Voltage (RMS)	η[%]
115	85,7
135	86,5
155	86,8
175	86,9
195	86,9
215	86,8
230	86,6
250	86,5

Table 2 Efficiency over Input Voltage

After collection all measurement points, a graph representation can be shown. This is illustrated in the picture below:

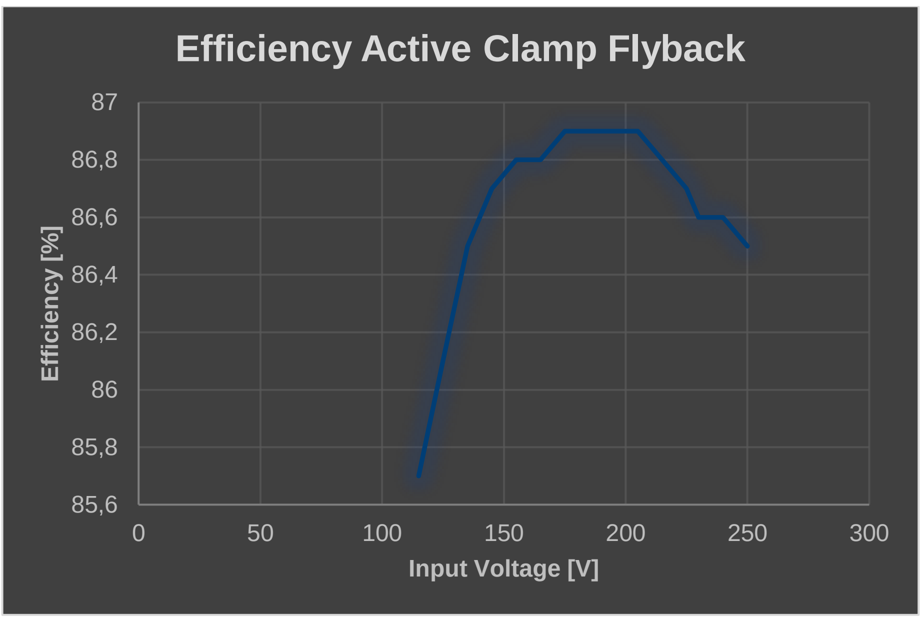


Figure 29 Efficency of Flyback ACF Over Input Voltage

A similar efficiency chart is typically shown, where the efficiency over output current will be illustrated to characterize the power supply at different load conditions. However, this test was not performed as it follows the same procedure like the efficiency of voltage.

3.4 Power-Up and Power-Down Sequence

An essential test of an AC-DC power converter is to measure the time delay between the switch-on of the AC voltage and until the output voltage appears at the output in a valid range. This time measurement is essential because a fast startup of the system is important in many applications. A typical example is an electronic control gear used for lighting applications. In this application, it is very important that the user gets a fast response from the system after switch-on of the mains.

3.4.1 Fundamentals

Typically, the measurement consists of at least two measurements:

- Turn-on delay. It is defined as the delay between the first AC input cycle appears and when the output voltage enters the valid operating level or any digital status signal like "Power OK" is active.
- Turn-off delay. It is defined as the delay between the last AC input cycle and when the output power leaves the valid operating level or any digital status signal changes to "Power Not OK" or similar.

For a measurement of the delay between turn-on and operation, an oscilloscope with sufficient memory is essential as the sampling rate should be still high for time accuracy while the record length is significantly high (100ms -500ms).

In addition to the oscilloscope, the setup requires a laboratory AC source to supply the device under test. In this case, different phase angle of the voltage may be used to simulate the grid in all circumstances.

Of course, the DUT should be connected to the maximum load as this is typically the worst-case scenario.

3.4.2 Measurement

3.4.2.1 Turn-on Delay

The picture below illustrates the measurement of the delay of the PFC flyback stage with a load of 24W connected. The curser settings and the zoom capability support the user to obtain the delay measurement in an easy way.

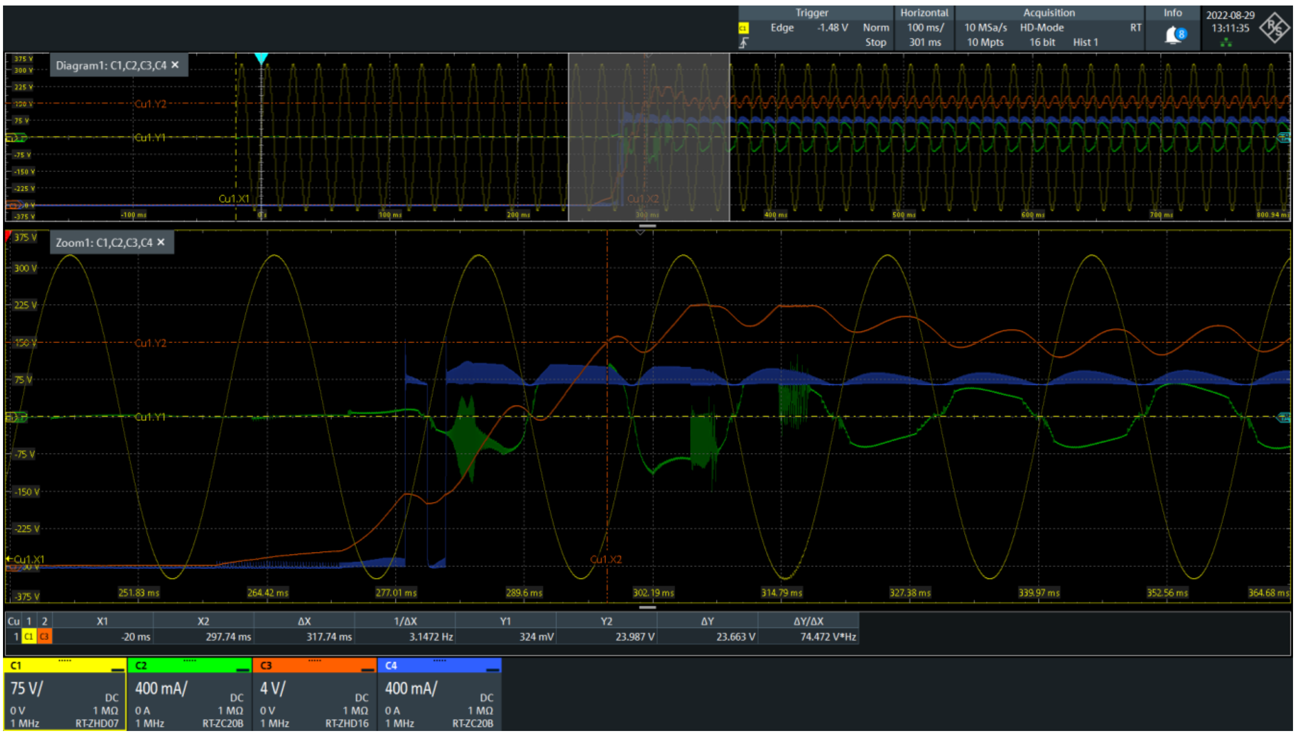


Figure 30 Turn-on Delay Measurement

C1 = Input Voltage

C2 = Input Current

C3 = Output Voltage

C4 = Output Current

The measured time delay of the converter between switch on of input voltage of channel 1 (curser position X1 @ -20ms) and valid output rail voltage of channel 3 (curser position X2 @ 297,74ms) is about Δx = 317ms. In addition, the input current and output current are measured to increase the understanding of the converter operation in more detail. Nevertheless, this measurement delay of 317ms is reasonable as it is caused by the internal soft start feature of the controller and the charge time of the bulk filter capacitor at the output.

3.4.2.1.1 Anomalous System Reaction

Even the measurement was correct presented in the previous chapter, several repetition of this delay measurements are required because the system may still show anomalous reactions. The measurement illustrated in the picture below was measured with the same DUT but is different from the previous measurement:

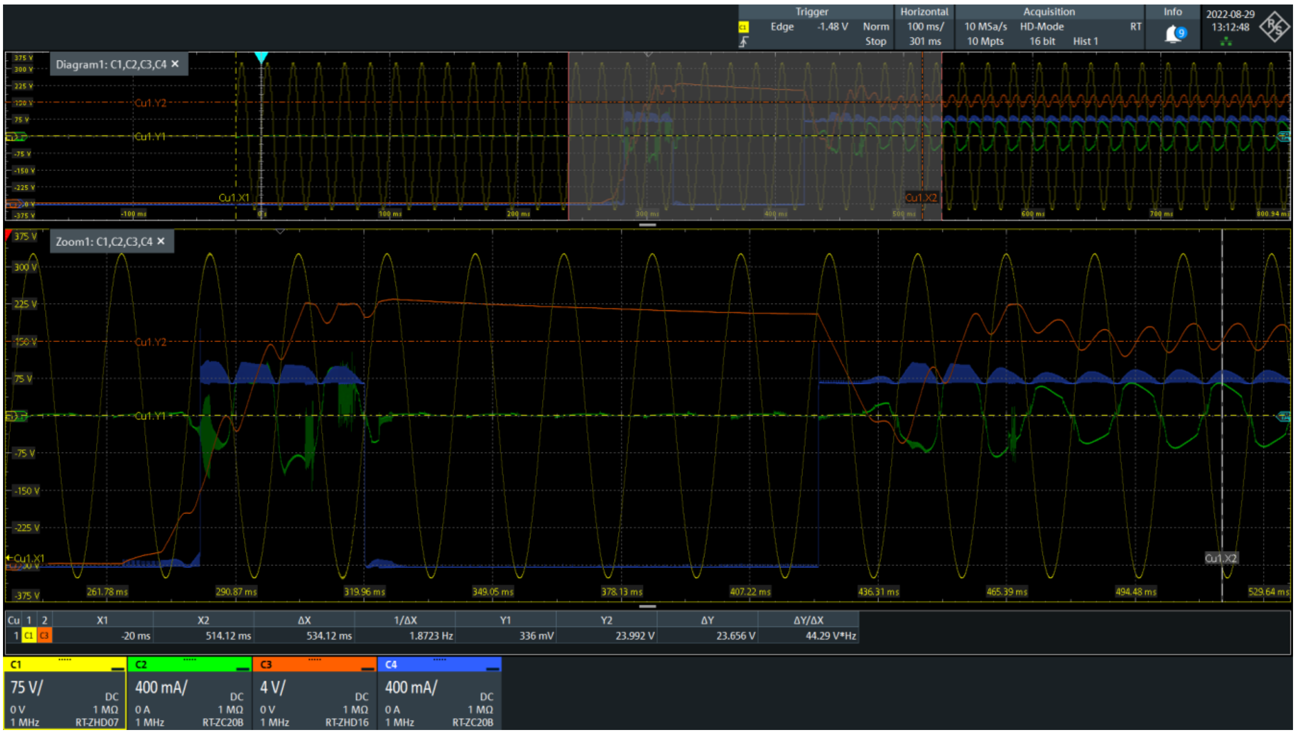


Figure 31 Turn-On Delay Measurement with Anomalous Reaction

In this measurement, the converter has started correct after approximately 320ms but it stopped operating immediately after few milliseconds in the valid output voltage range (Zoom1). After approximately 100ms the converter has restarted proper operation. The reason for this malfunction of the converter is probably caused by exceeding the overvoltage protection function of the controller. Further investigation of the root cause is required to validate this malfunction.

However, the oscilloscope and its rich set of features will provide the user to solve these kinds of critical issues.

3.4.2.2 Turn-Off Measurement

During the design process, the shutdown of an electronic system needs to be in a predictive manner. This controlled shutdown sequence ensures that e.g. components are protected against any abnormal conditions e.g. displacement currents. Furthermore, the time duration, how long the output rail provide sufficient energy after AC power rail is switched-off, is also important to validate. In some applications, it is required that the power supply provides enough energy for storing internal status information to the memory before the output rail exits the valid voltage range. Therefore, it is essential to measure the delay if the power supply is capable of providing this energy under all circumstances.

A turn-off measurement is illustrated in the picture below:

Figure 32 Turn-off Delays with AC Mains Input

C1 = Input Voltage

C2 = Input Current

C3 = Output Voltage

C4 = Output Current

After the AC rail is switched off by the laboratory power supply, the 24V output rail exits the valid voltage range (20V < U_{out} < 28V) after ΔX = 2,97ms. Of course, the time depends mainly on the energy stored within the output filter capacitors and the power consumption of the circuit design (microcontroller and memory) connected to this rail.

Nevertheless, the oscilloscope can provide detailed and accurate time measurements during power up and power down sequences.

4 Conclusion

The first part of this document presented the fundamentals of power conversion mainly with focus on the switching mode power supply. This part still applies even though new faster switching technologies like wide band gap enter the power supply market in various applications.

After the introduction part, most relevant test procedures including their fundamental theory for testing an AC-DC converter are highlighted. The test methods within this paper are related to backbox tests like measurements on input terminals, output terminals or both (efficiency). Of course, additional important measurements still do exist and are relevant as well to validate the DUT in more detail e.g. the validation of the switching stage. However, these specific test methods are highly dependent on the power supply structure. Therefore, these validation methods are not generic and are not covered within this document.

All measurements are performed with a single stage power supply with a smaller power level. However, the methods presented in this paper are also valid for multiple stage AC-DC converter where higher power levels can be achieved. Especially the PFC boost converter can be validated with the same test methods.

The oscilloscope is frequently used in the laboratory during product development for multiple time domain tasks. Therefore, it will be a good choice for executing the presented test methods. Nevertheless, some of the test methods can be also performed with other instruments like a suitable power analyzer. However, the oscilloscope is still the swiss knife in the lab and can be used in almost every measurement task. Of course, sufficient knowledge of the user is essential to make proper measurements. Especially, the selection of the voltage and current probes must be reasonable to obtain reliable measurement results.

If the user follows the recommended rules presented within this document, a suitable oscilloscope is a great tool to validate an AC-DC converter with the most relevant tests methods described within this paper and even more.

5 Literature

[1] "https://en.wikipedia.org/wiki/AC_power," [Online].

[2] Texas Instruments, "www.ti.com/product/UCC28780," 21 04 2021. [Online]. Available: https://www.ti.com/lit/ds/symlink/ucc28780.pdf?ts=1619674162057&ref_url. [Accessed 30 04 2021].

[3] "https://www.analog.com/en/design-center/evaluation-hardware-and-software/evaluation-boards-kits/dc1817b.html#eb-overview," [Online].

6 Ordering Information

Designation	Type	Order No.
Oscilloscope, 4 Channels	R&S®RTO6	1802.0001.04
Power Analysis Oscilloscope Software	R&S®RTx-K31	1801.6858.02
High Voltage Differential Probe	R&S®RT-ZHD07	1800.2307.02
Current Probe	R&S®RT-ZC20B	1409.8233.02
Power Rail Probe	R&S®RT-ZPR20	1800.5006.02

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