

MEASUREMENT FUNDAMENTALS OF AC-DC SWITCHED-MODE POWER SUPPLIES

Dr. Gabriel Rojas
Application Engineer Power Electronics

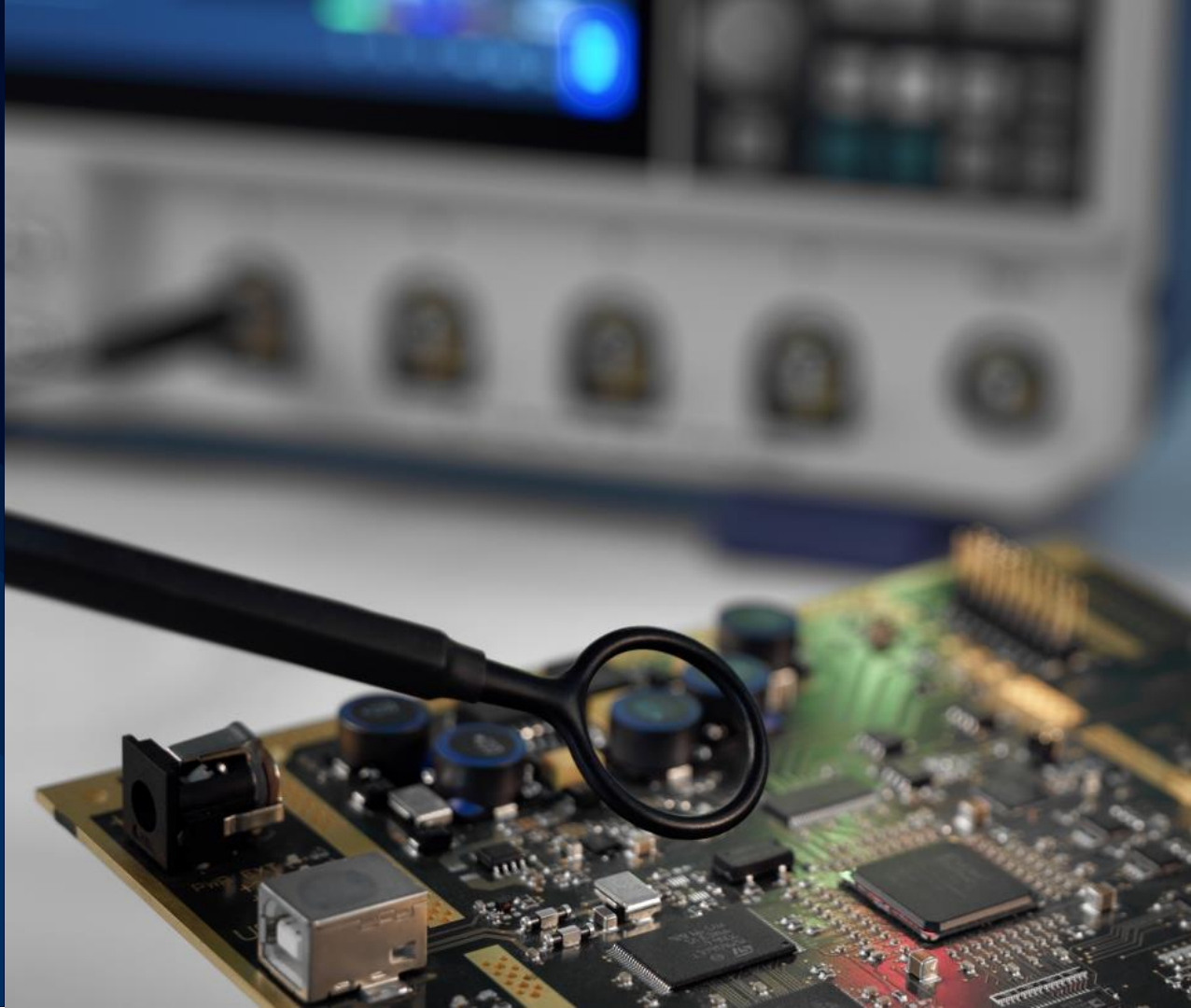
ROHDE & SCHWARZ

Make ideas real



AGENDA

- ▶ Motivation
- ▶ AC-DC SMPS Basics
- ▶ I/O Measurements
- ▶ Switching stage
- ▶ Final remarks



MOTIVATION

SMPS DESIGN STEPS



1 Define the architecture

2 Select the integrated circuits

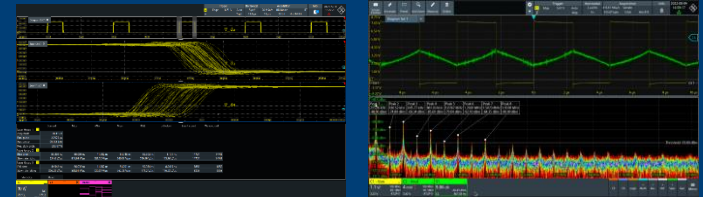
3 Circuit design

4 Simulation

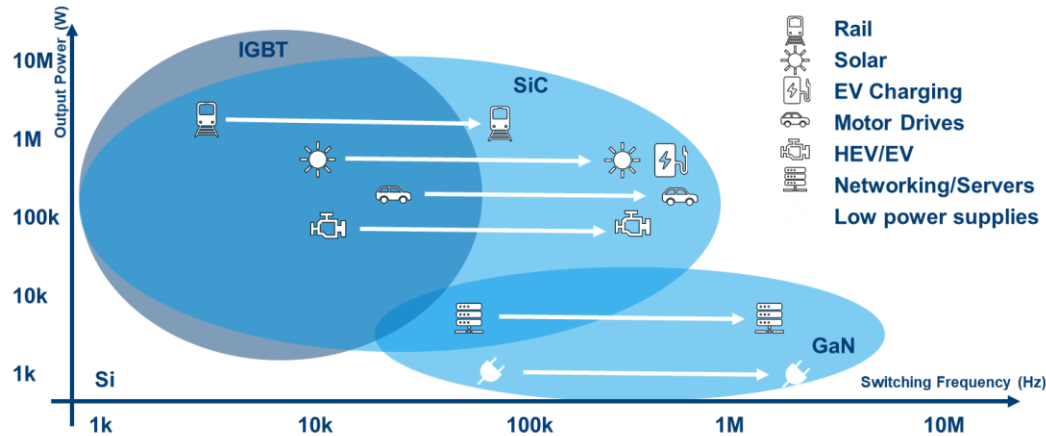
5 Testing

Testing the design

- Verify sub-circuits and switching times of the transistors
- Switching losses
- Characterization of passive components
- Stability
- Efficiency
- Transient response, start-up, shut down
- Voltage ripple
- Electromagnetic compatibility



WIDE BANDGAP MATERIALS

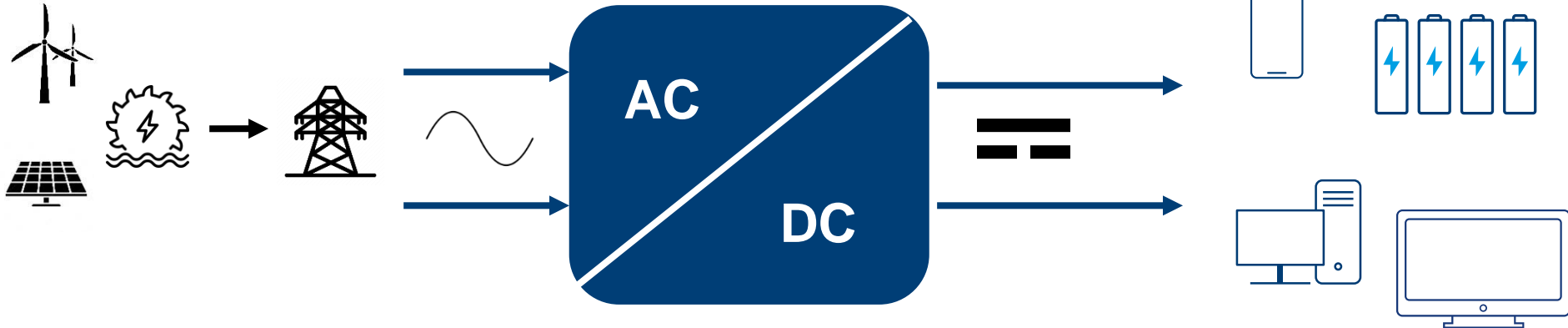


- ▶ New technologies with higher power density lead to a faster commutation of the transistors.
- ▶ SiC and GaN that operate with switching frequency > 1MHz is growing
- ▶ Parasitics appear at higher frequencies and must be considered
- ▶ Influence in conducted emissions

AC-DC SWITCHED MODE POWER SUPPLY

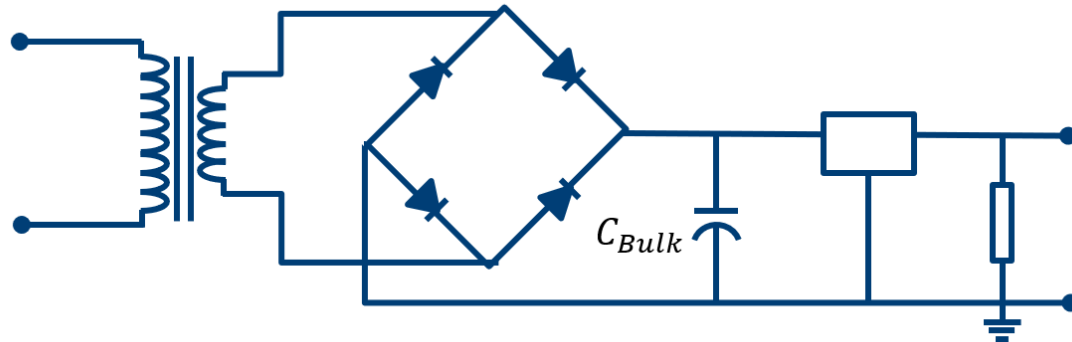
AC-DC CONVERSION

- ▶ Electronic equipment requires a low DC supply voltage for operation.
- ▶ Normally, this voltage is generated from the grid, which is an AC supply.
- ▶ The voltage supplied to the electronic equipment must fulfill international standards.
- ▶ Different existing solutions:
 - Linear power supplies
 - Switching-mode power supplies



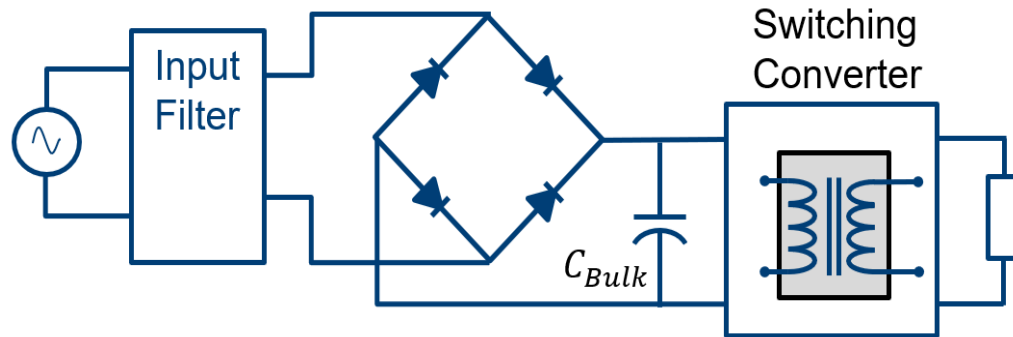
LINEAR POWER SUPPLY

- ▶ Transformer connected directly to the grid.
 - Steel or iron laminated
 - Isolation between higher and lower AC voltages
- ▶ After the rectifier, the lower DC voltage is regulated by a transistor operating in the linear region
 - + Low ripple and low noise
 - Low efficiency, Very bulky (line transformer + smoothing capacitor)



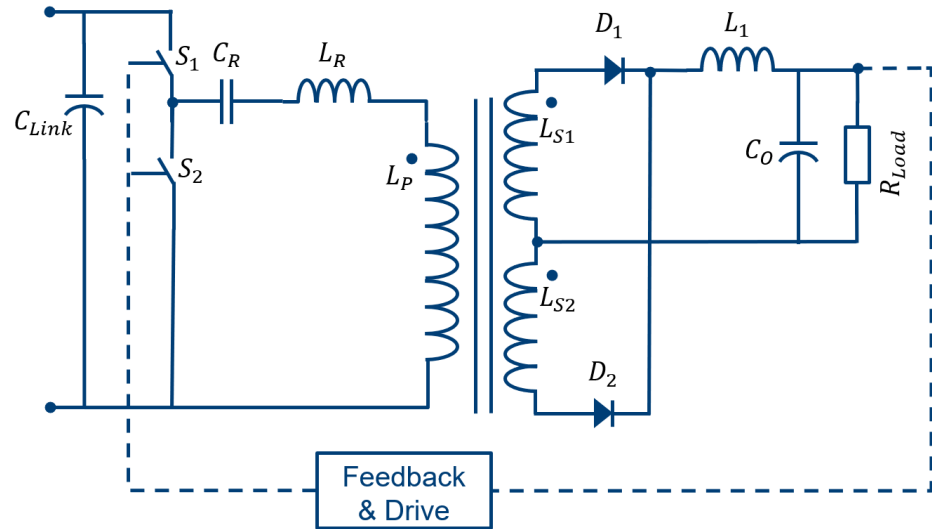
SWITCHING-MODE POWER SUPPLY

- ▶ Used in applications where efficiency and size are key
- ▶ The AC grid voltage is rectified and the resulting DC voltage is lowered by means of a switching converter
- ▶ A high frequency transformer is needed → 'Small'
- ▶ It requires an EMI input filter due to the noise generated by the high frequency switching.



DC-DC CONVERSION

- ▶ Most common topology used for the DC-DC converter is the resonant half bridge converter (LLC).
- ▶ Its three reactive elements (LLC tank) filter out the harmonics.
- ▶ High efficiency is achieved since all semiconductors switch at zero-voltage.
- ▶ Control loop that regulates the output voltage.

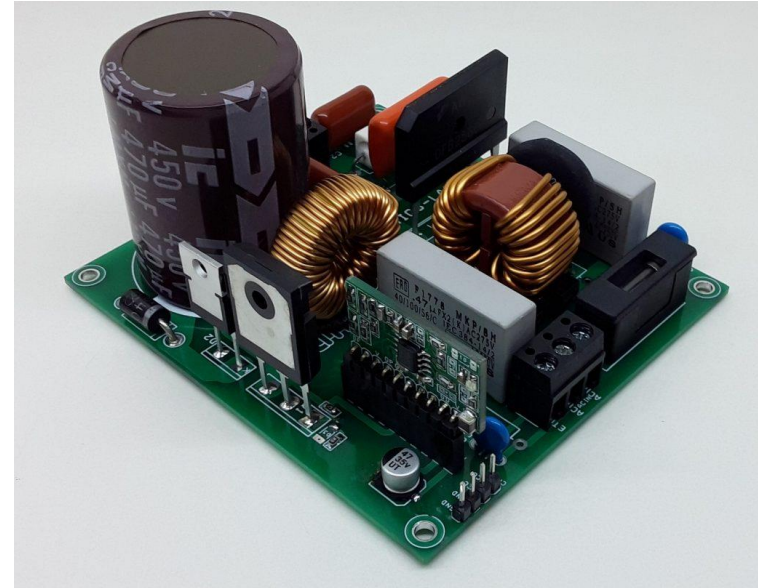


ACTIVE POWER FACTOR CORRECTION (PFC)

- ▶ An AC-DC converter does not need to comply with international standards if the power does not exceed 75 W. (EN61000-3-2)

The PFC arise a solution for converters with $P > 75 \text{ W}$

- ▶ It is a variant of the standard boost converter in order to obtain a power factor close to 1 and fulfill standards.
- ▶ Different variants: Simple with MOSFET, interleaved PFC, totem pole PFC and more.

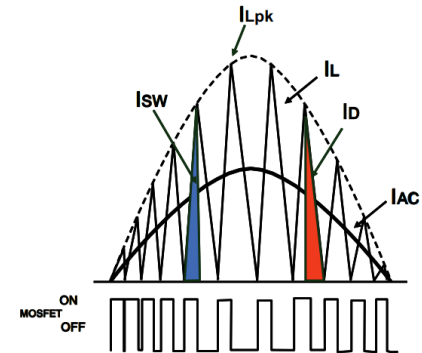


OPERATING MODES

There are different methods to control a PFC converter.

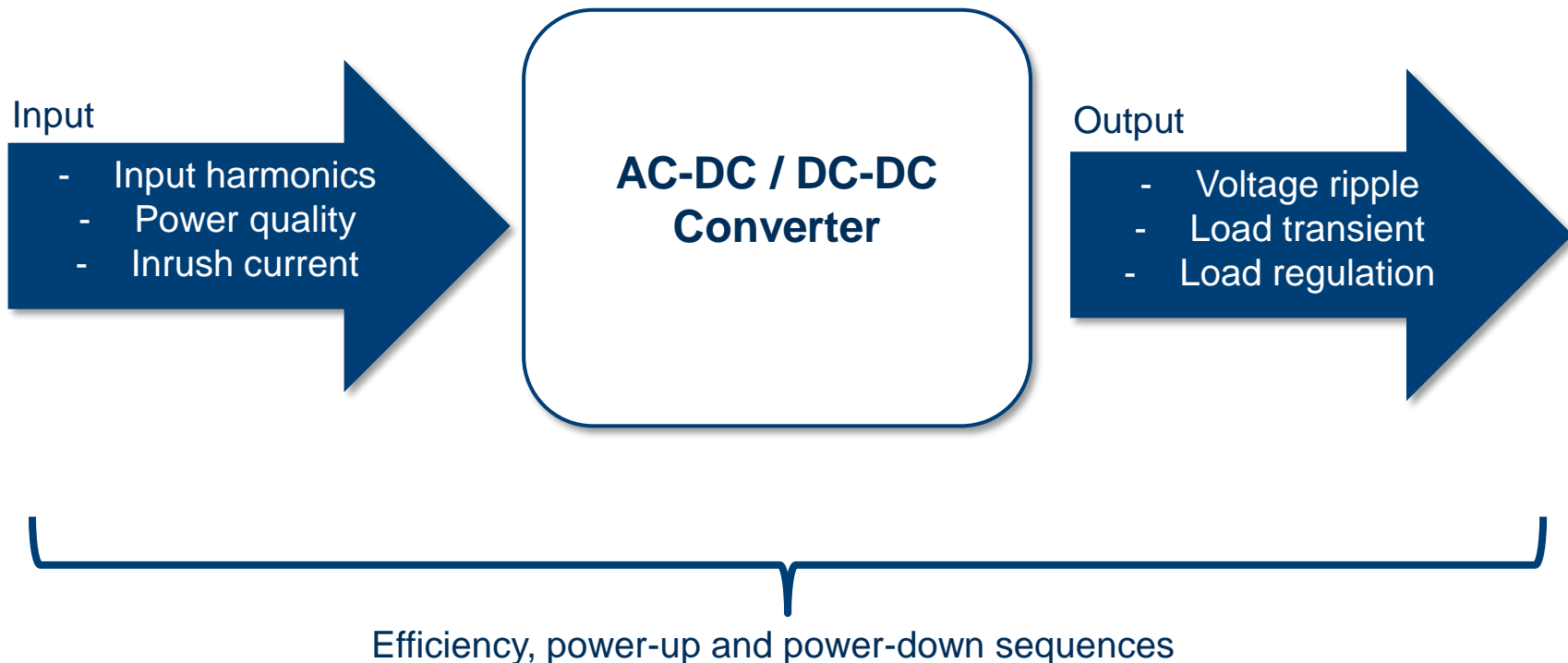
The most common are:

- ▶ Fixed frequency average current mode (FF PWM)
 - Complex control → Requires a sophisticated controller
 - Works in CCM
- ▶ Transition mode (TM)
 - Simpler and more economical control
 - Fixed on time, variable in frequency and duty cycle.
 - The inductor works in the boundary between CCM and DCM
 - Used in low power range applications



MEASUREMENTS

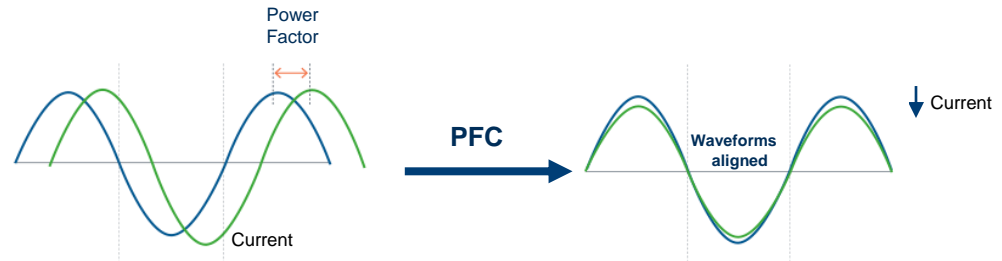
INPUT AND OUTPUT SIGNALS



POWER QUALITY

- ▶ Measuring power quality in an AC-DC SMPS is essential for:
 - Ensuring efficient operation
 - Proper component sizing
 - Preventing overloading,
 - Managing energy costs
 - Maintaining system reliability.

- ▶ The way a converter draws current from the grid can produce an input current which is leading or lagging in relation to the voltage of the AC source.
- ▶ A power factor correction (PFC) converter shapes the input current to be in phase with the input voltage.
- ▶ Minimizes the amount of power a load is not able to use



POWER QUALITY

REAL, APPARENT AND REACTIVE POWER

- Real power:

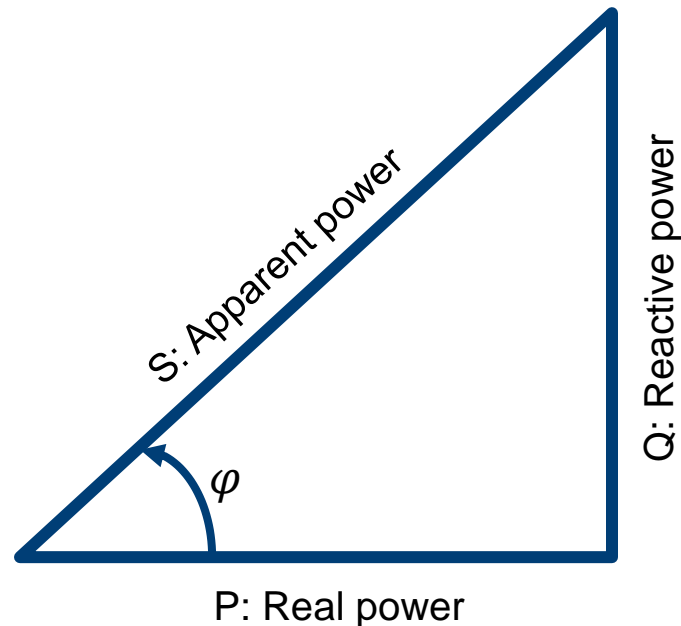
$$P = \frac{1}{T} \int_0^T u(t) * i(t) dt \text{ [W]}$$

- Apparent power:

$$S = U_{RMS} * I_{RMS} \text{ [VA]} \xrightarrow{\text{Power triangle}} S = \sqrt{P^2 + Q_{tot}^2}$$

- Reactive power:

$$Q_{tot} = \sqrt{Q_1^2 + Q_d^2} \text{ [var]} \xrightarrow{\text{Power triangle}} Q_{tot} = \sqrt{S^2 - P^2}$$



POWER QUALITY

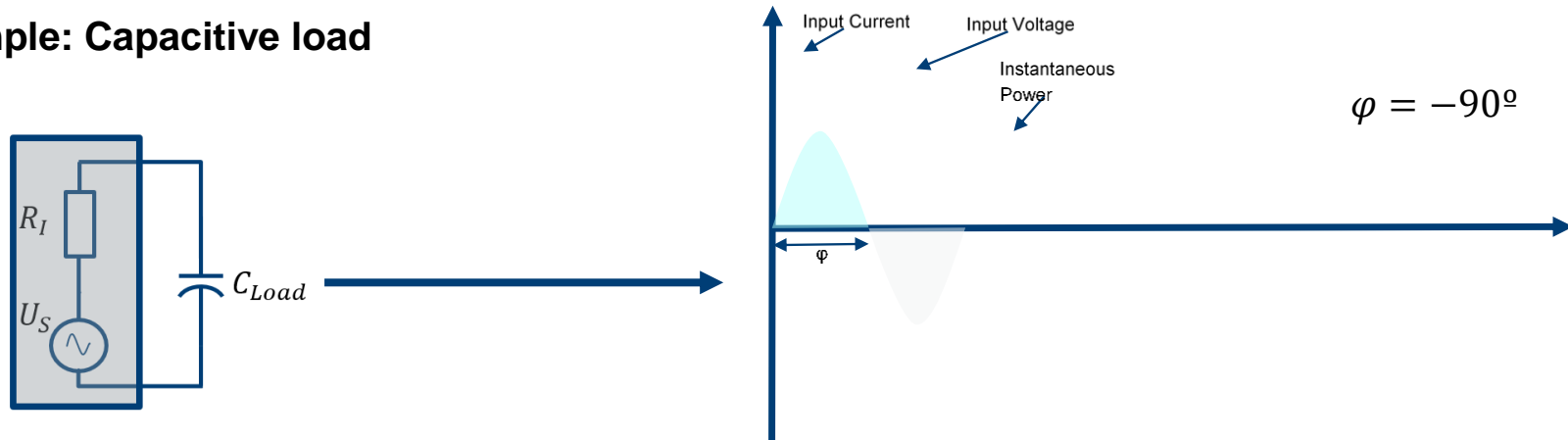
POWER FACTOR

- Refers to 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.

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

- The $\cos(\varphi)$ can only be used for pure sinusoidal waveforms

Example: Capacitive load



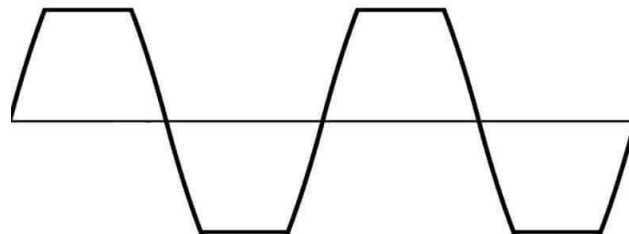
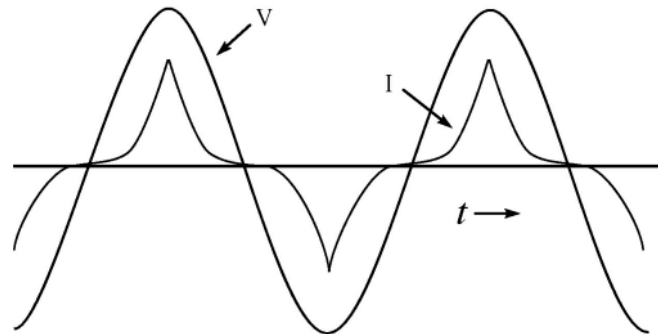
POWER QUALITY

CREST FACTOR

- ▶ Parameter to describe the quality of an AC waveform.
- ▶ Defines the ratio between peak value and RMS value:

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

- ▶ A pure sinusoidal waveform has a crest factor equal to $\sqrt{2} = 1,414$.
- ▶ Avoid the 'flat-topping' of the voltage waveform.

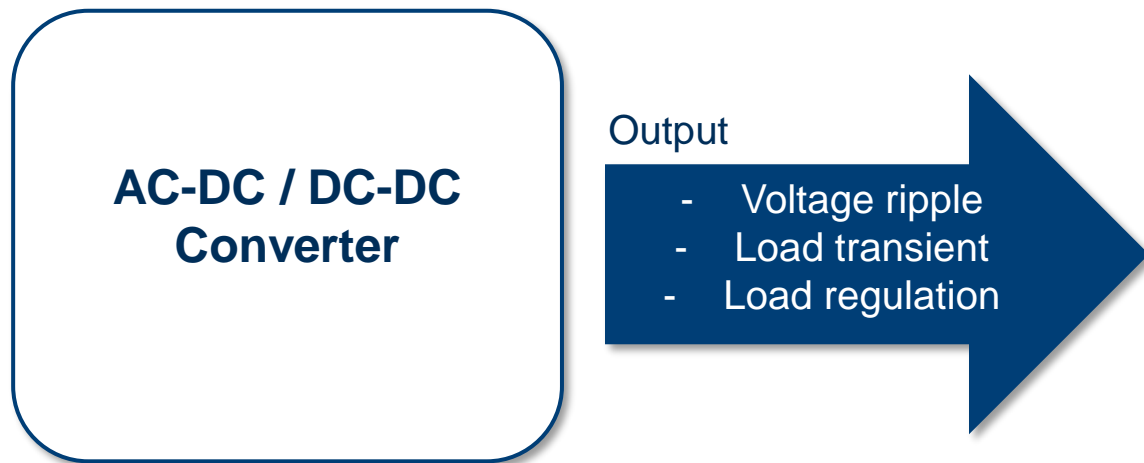


INPUT HARMONICS

- ▶ In a PFC converter, the input current drawn from the grid is not a pure sinusoidal wave. It consists of multiple harmonics at different frequencies.
- ▶ These harmonics can cause:
 - Increased power losses
 - Electromagnetic interference (EMI)
 - Overheating
- ▶ It is important to measure the input current harmonics in a PFC converter to identify any issues and ensure compliance with industry standards.

$$I_{RMS} = \sum_{N=2}^{\infty} I_n^2 \quad THD_i = \frac{I_{RMS}}{I_{1RMS}} * 100[\%]$$

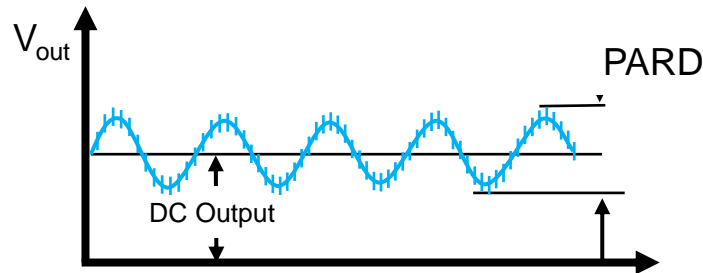
OUTPUT SIGNALS



VOLTAGE RIPPLE

WHAT IS RIPPLE?

- ▶ PARD = Periodic and Random Deviation
- ▶ Spurious AC components create ripple
 - Periodic: Ripple
 - Switching Noise
 - Load Step (Large)
 - LC Tank
 - Random: Noise
- ▶ Specified over a bandwidth
 - Typically 20 to 20 MHz
 - Careful, below 20 Hz is Output Drift



Examples

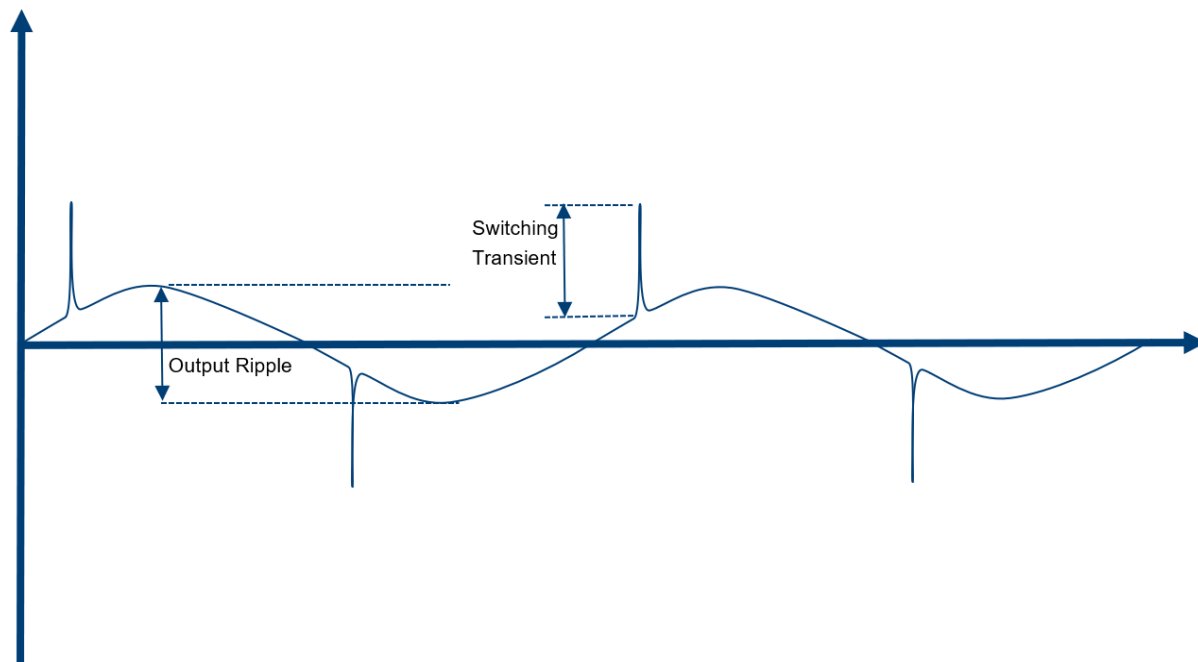


Rail Value	Tolerance	Need to measure
3.3 V	1%	33 mV _{pp}
1.8 V	2 %	36 mV _{pp}
1.2 V	2 %	24 mV _{pp}
1 V	1 %	10 mV _{pp}

VOLTAGE RIPPLE

SWITCHING TRANSIENTS

- ▶ High-frequency periodic deviation
- ▶ Superimposed on the output ripple peak to peak
- ▶ A proper test setup will determine the accuracy of this measurement.
 - External interference can affect peak to peak value.



OUTPUT VOLTAGE RIPPLE COMPARISONS



1:1 Passive



DC-Block



10:1 Passive

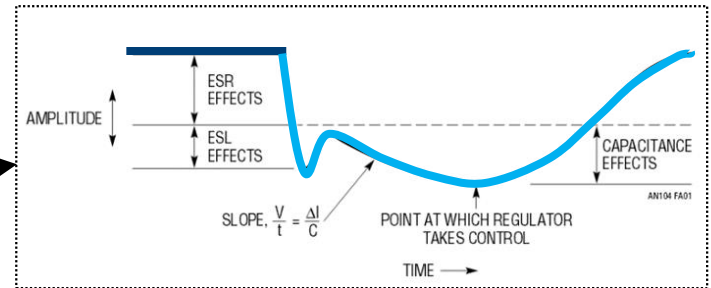
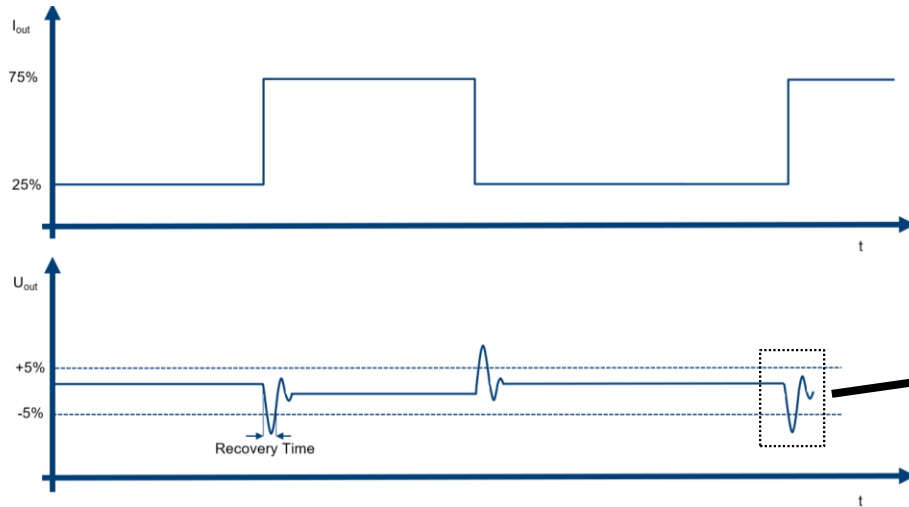


1:1 Active
Power Rail Probe



LOAD TRANSIENT

- ▶ Sudden change in the output load current caused by a change in the load resistance or a change in the output voltage demand.
- ▶ SMPS must respond quickly to load transients in order to maintain a stable output voltage. If the response is too slow, the output voltage may drop or overshoot, causing system instability or even damage to the load.



LOAD REGULATION

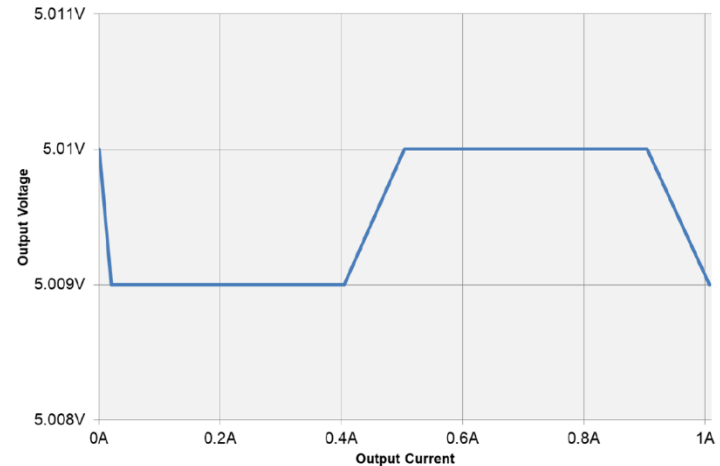
- ▶ Ability to stay within a specified limit, after a load change.
- ▶ Load regulation is important because changes in the load can cause changes in the output voltage, which can affect the performance of downstream circuits or devices.

$$\text{Load Regulation} = \frac{V_{NL} - V_{FL}}{V_{FL}} \times 100\%$$

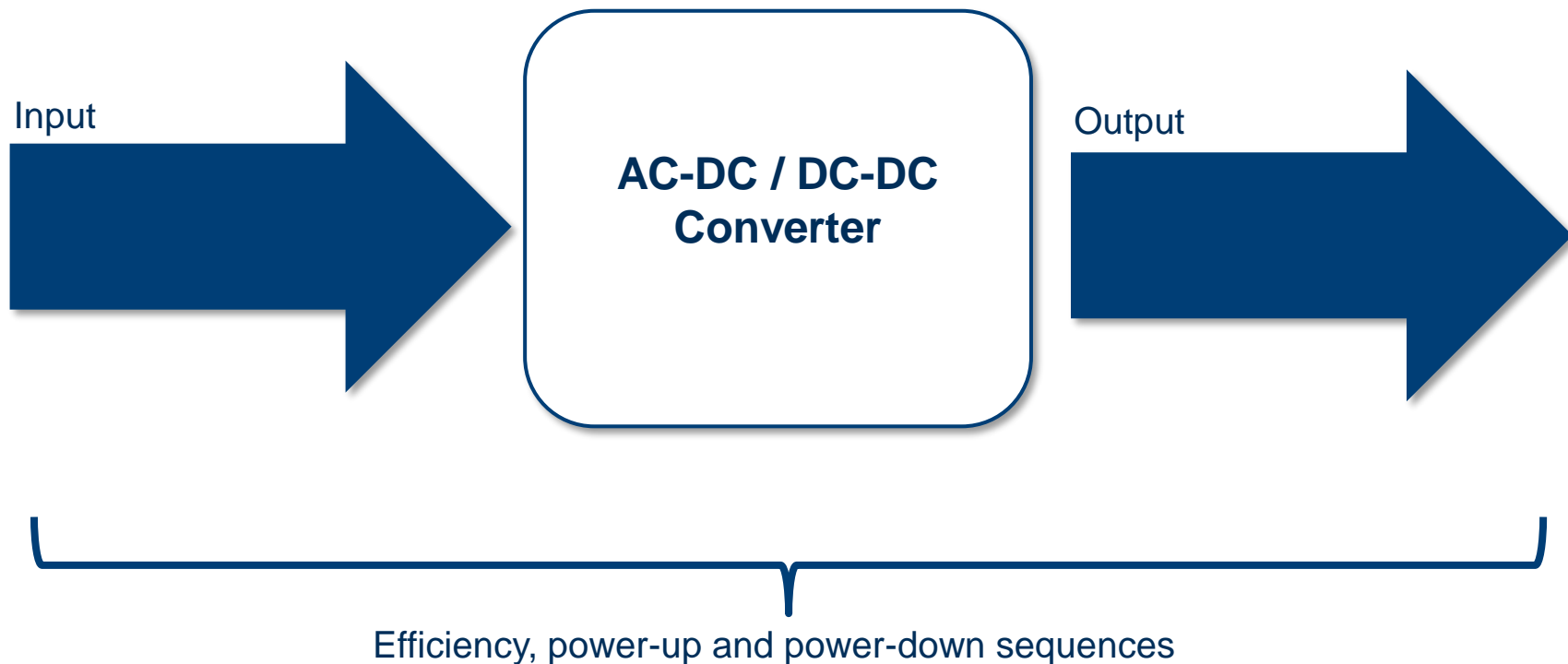
V_{NL} = No Load Voltage

V_{FL} = Full Load Voltage

- ▶ **Good value: 1–2 %**

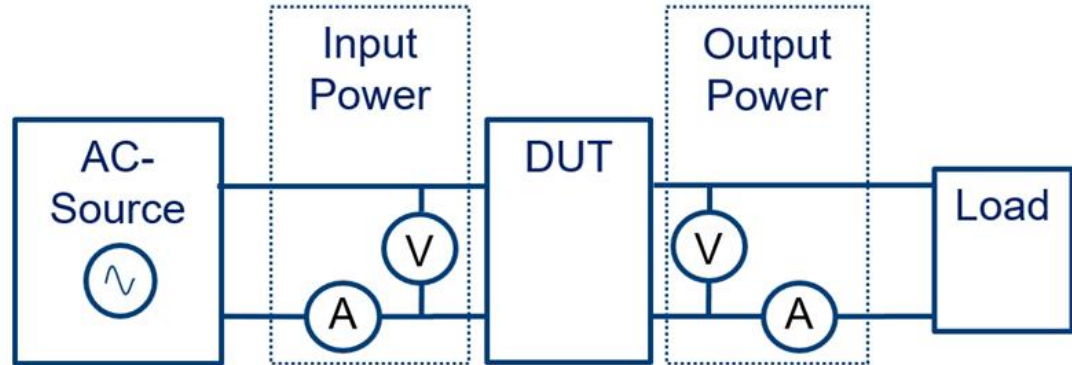


INPUT AND OUTPUT SIGNALS



EFFICIENCY

- ▶ Plays a crucial role in the design of AC-DC SMPS.
- ▶ It helps to:
 - Optimize component selection
 - Evaluate thermal performance
 - Ensure compliance with energy efficient regulations
 - Improve reliability
- ▶ **Typical setup:**

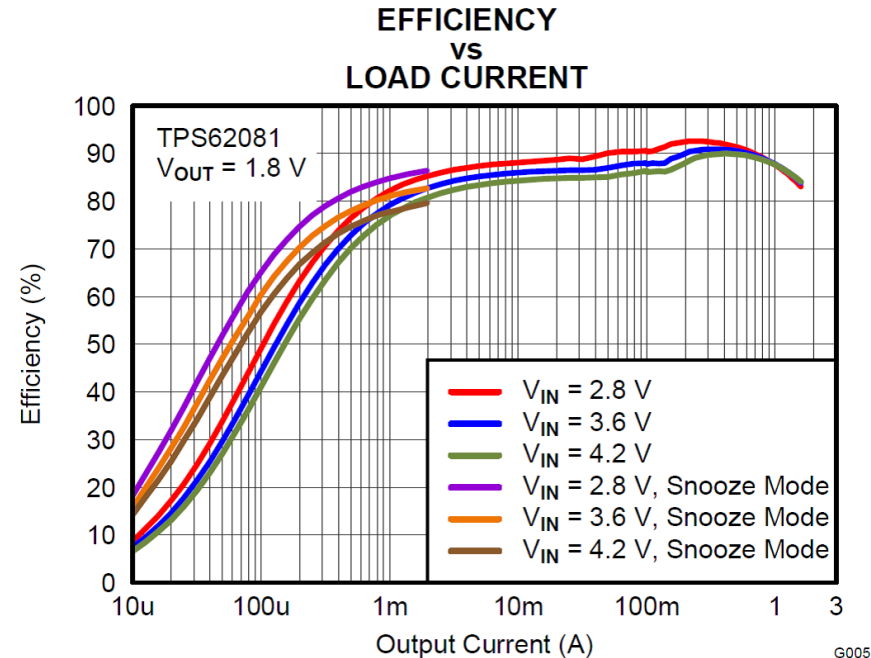


EFFICIENCY

- Is calculated as follows:

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

- The efficiency varies with different conditions, such as the output current and the input voltage of the converter.
- An efficiency chart is typically presented by manufacturers. It characterizes the SMPS under different load conditions.



TI TPS62080 Datasheet

EFFICIENCY DE-SKEW

- ▶ Voltage and current probes have different rise times and propagation delays
- ▶ For measurements that require both signals is essential to compensate the time delay.
- ▶ A deskew fixture can be used to align in time the signals.
 - It is limited to the rise time.
 - It can only work with a clamp-type probe that fits in the board.

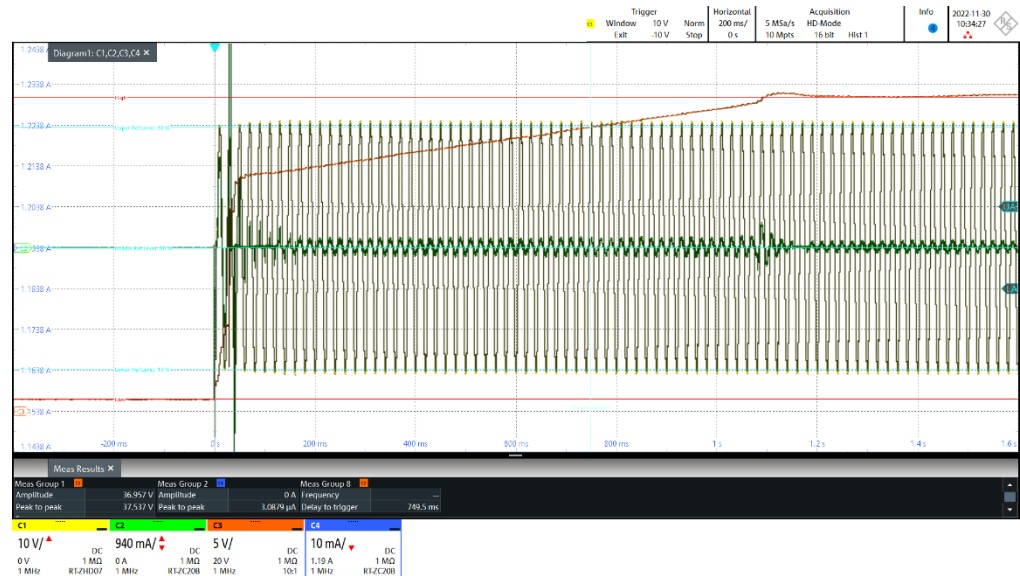


POWER-UP


- ▶ 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.

Why Measure Start-Up?

- ▶ Turn On Too Fast:
 - Too much in-rush current
 - Signal Overshoots
 - Reaching current limit
 - Hic-ups
- ▶ Turn On Too Slow:
 - Rail sequencing disrupted



START-UP SEQUENCE

- ▶ Most converters have a Soft-Start function meant to start-up in a smooth way and avoid large inrush currents or overshoots.
 - ▶ The main challenge is to acquire at the same time:
 - Input and output voltages
 - Switching characteristics
 - ▶ This requires significant memory depth.
- 

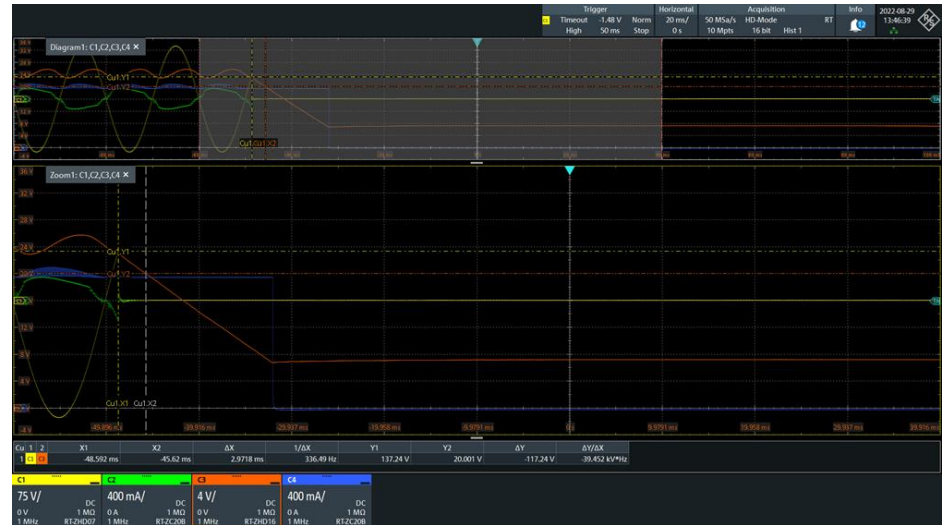


POWER-DOWN

- ▶ A controlled shutdown sequence ensures that the components are protected against abnormal conditions.
- ▶ Is important to measure the delay of the output voltage after the shut down occurs.

Why Measure Power-Down?

- ▶ Displacement currents may cause damage to the circuit.
- ▶ Measure how long the output rail provide sufficient energy after the AC power rail is switched-off.
- ▶ The shutdown of an electrical system needs to be in a predictive manner.



Switched Mode Power Supply Measurements

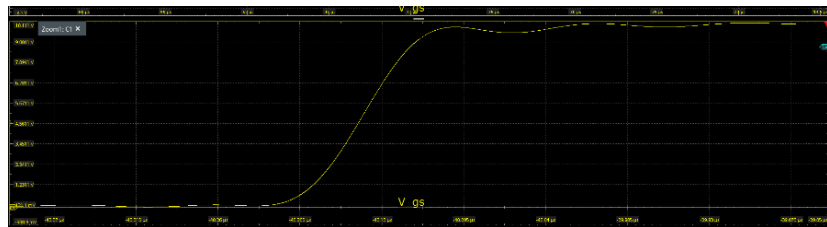
SWITCHING STAGE ANALYSIS

SWITCHING STAGE BANDWIDTH

- ▶ Among the greatest challenges in modern power electronics is testing systems with wide bandgap materials like SiC and GaN. Their faster switching times condition the bandwidth.
- ▶ Oscilloscope and probes must be chosen accordingly.

$$Bandwidth \sim \frac{0.35}{t_{sw, rise}}$$

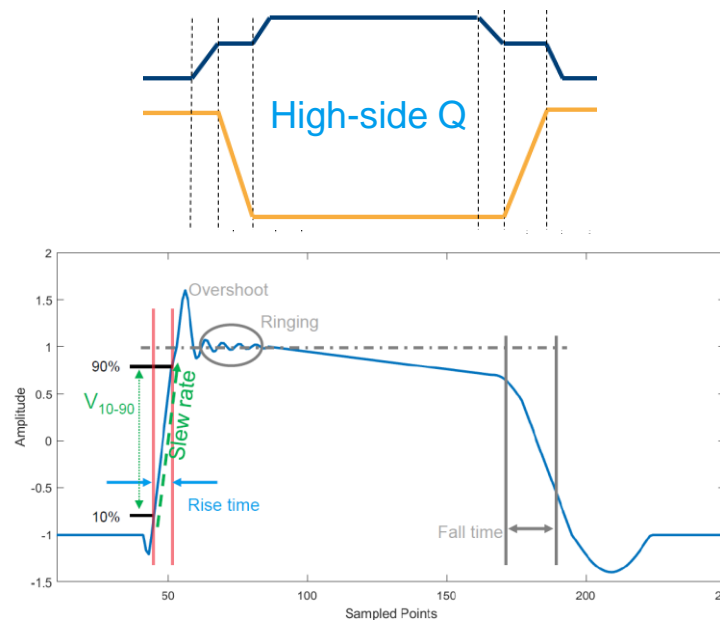
- ▶ Example: If a semiconductor has a rise time of 4 ns, a minimum bandwidth of 87.5 MHz is required.



SWITCHING STAGE

BEST PRACTICE MEASUREMENTS

- As a rule of thumb, it should be checked:
 - ✓ V_{GS} and V_{DS}
 - ✓ Rise times and fall times (10/90 or 20/80)
 - ✓ Overshoot, ringing
 - ✓ General timing of high- and low-side switch (synchronous converter)
 - ✓ Robustness test



SWITCHING STAGE TRANSISTOR

The characterization of a transistor requires three main measurements:

► **Drain to source voltage:**

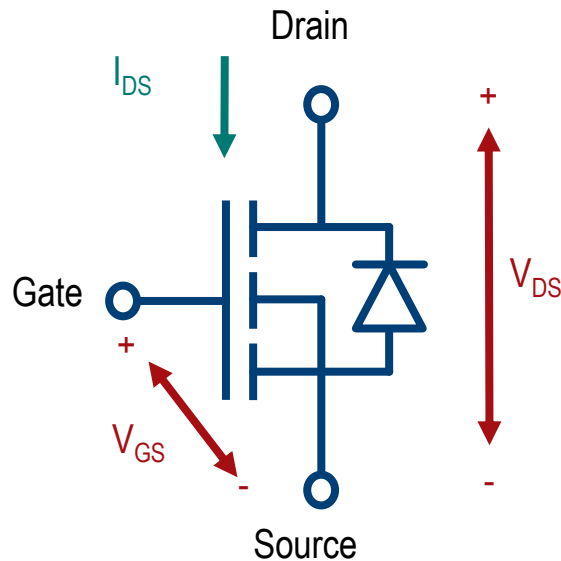
- Depending on the side it could be a floating or non-floating measurement
- Typically high voltages

► **Gate to source voltage:**

- Floating measurement
- Voltages in the range of -20 V to 20 V
- High common mode voltage in the high-side transistor

► **Drain to source current:**

- Capability of measuring AC currents



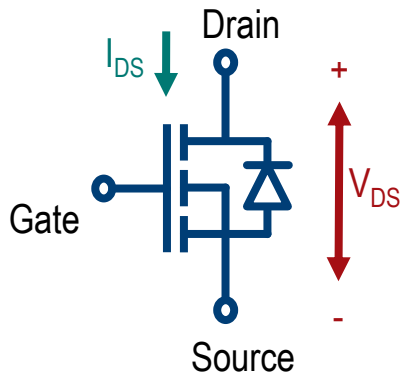
SWITCHING STAGE

QUANTIFY LOSSES

► Semiconductors operation generate losses

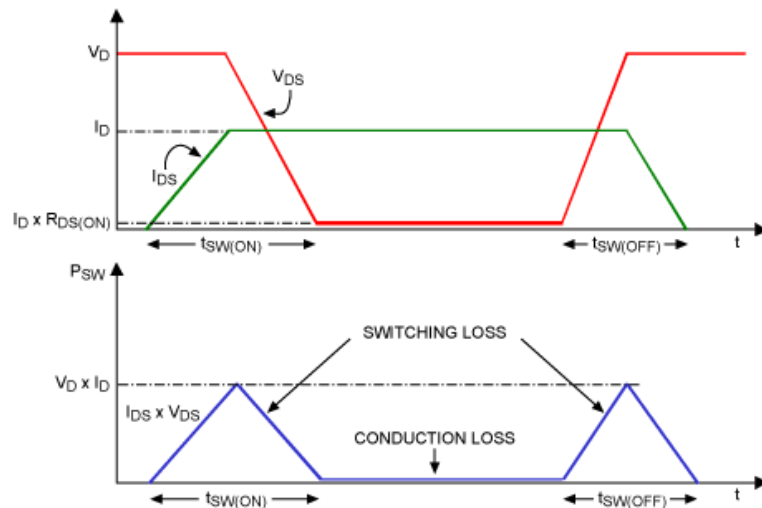
- Conduction losses
- Switching losses

► Losses are important for cooling system



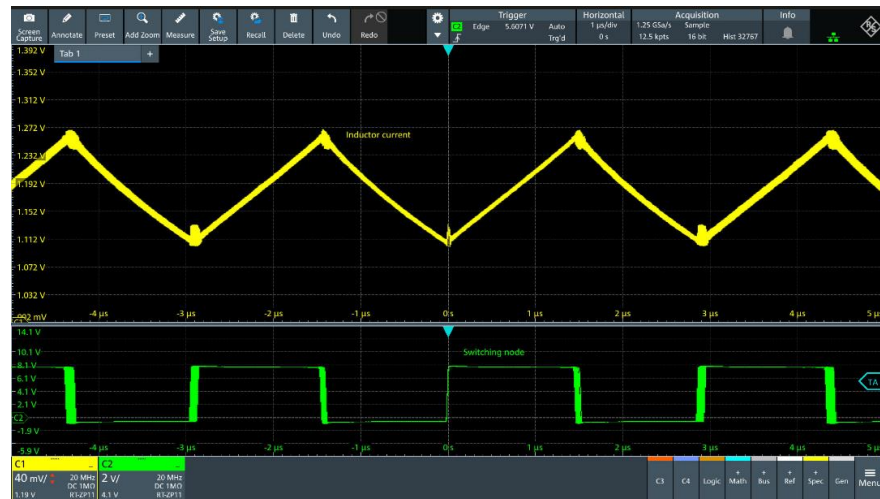
► Switching losses to be evaluated

- Turn on losses
- Turn off losses
- Reverse recovery losses



INDUCTOR CURRENT

- ▶ It is important to determine if the inductor is suitable for the converter or if saturation will occur during the operation.
- ▶ The inductor current I_L is a common measurement that is used to:
 - Determine conduction mode of the converter
 - Current zero cross detection
 - Evaluate the energy stored in the inductor
 - Characterize the inductor: Resistance and saturation



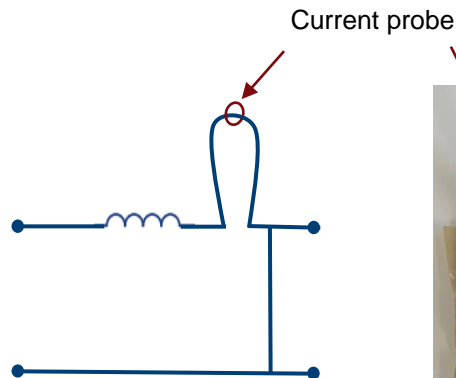
INDUCTOR CURRENT

HOW TO MEASURE IT?

There are two ways of measuring the inductor current:

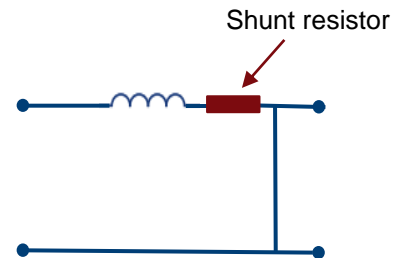
► **Use an auxiliary wire in series with the inductor.**

- Desolder with hot air to detach the one of the terminals of the inductor
- Use a small cable to connect in series the inductor.
- The cable should be long enough to attach a clamp-type current probe.



► **Use a shunt resistor**

- It is an alternative to the current probe but not recommendable.
- Switching noise can easily couple into the voltage measurement via the shunt resistor.



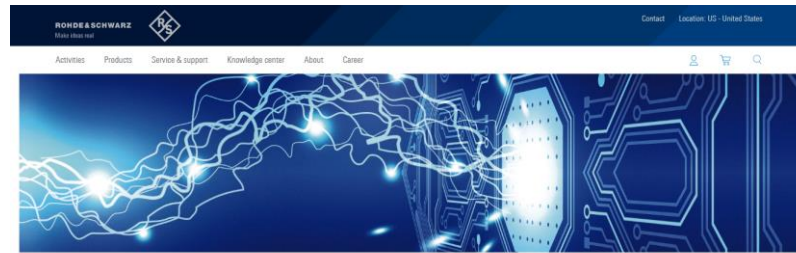
FINAL REMARKS

FINAL REMARKS

- ▶ Brief review of the most common measurements of AC-DC SMPSs.
- ▶ There are many more:
 - Double pulse test
 - Robustness
 - Inrush current
- ▶ Each application require its own measurement approach
- ▶ A proper probing is crucial:
 - Minimize parasitics
 - Enhance accuracy
- ▶ Oscilloscope is a powerful tool for design and it can be complemented with power analyzers, spectrum analyzers and EMI receivers for validation.

FIND OUT MORE:


- ▶ https://www.rohde-schwarz.com/us/applications/ac-dc-converter-testing-fundamentals-application-note_56280-1297283.html
- ▶ Application Note: AC-DC Converter Testing Fundamentals



AC-DC Converter Testing Fundamentals

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.

Name	Type	Version	Date	Size
 AC-DC Converter Testing Fundamentals 133387	Application note	2x	03-May-2023	3.1 MB

THANK YOU

ROHDE & SCHWARZ

Make ideas real

