MEASUREMENT FUNDAMENTALS OF AC-DC SWITCHED-MODE POWER SUPPLIES

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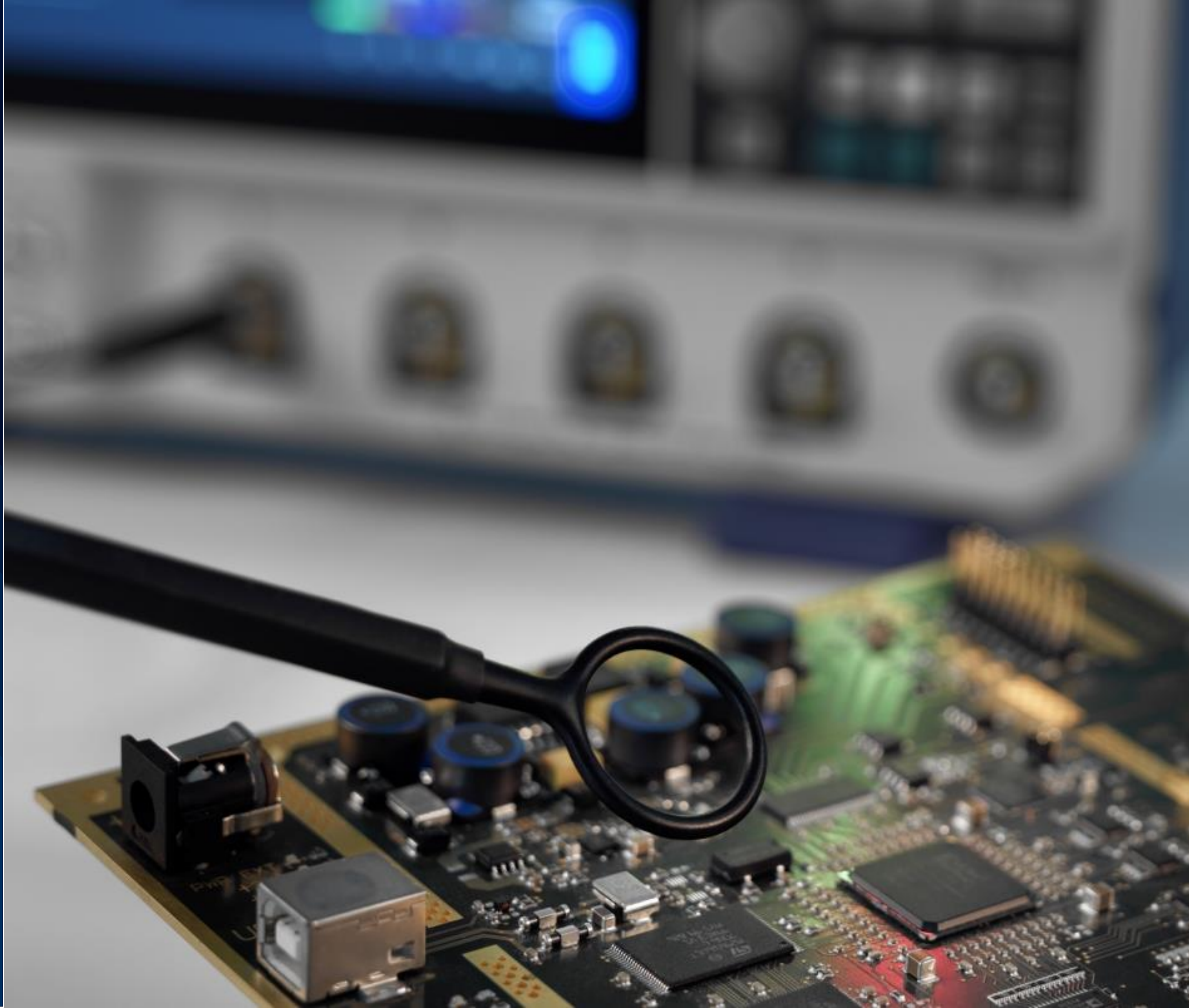
AGENDA

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



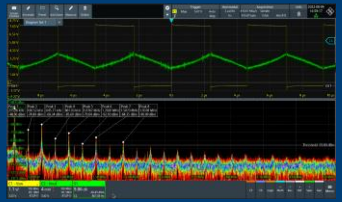
MOTIVATION

SMPS DESIGN STEPS

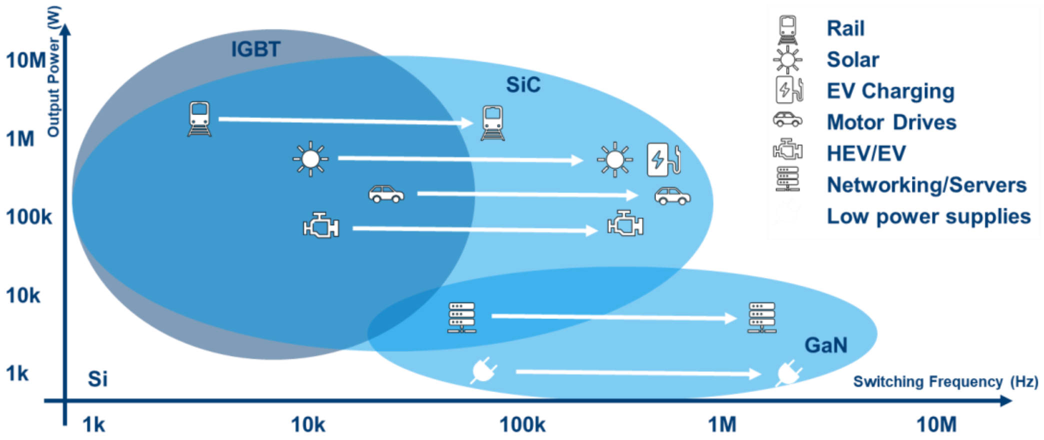
1. Define the architecture
2. Select the integrated circuits
3. Circuit design
4. Simulation
5. Testing

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



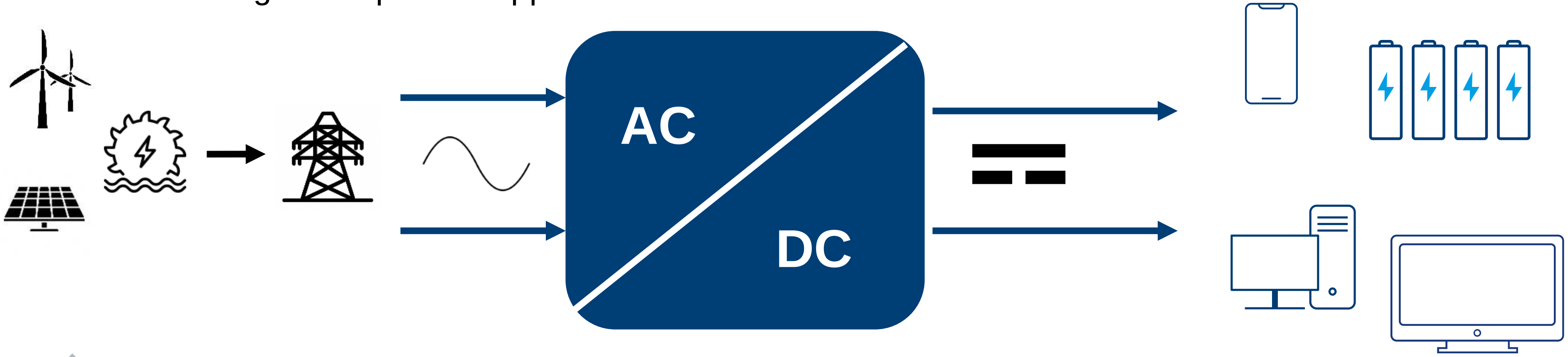
- New technologies with higher power density lead to a faster commutation of the transistors.
- SiC and GaN that operate with switching frequency > 1MHz is growing

- 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

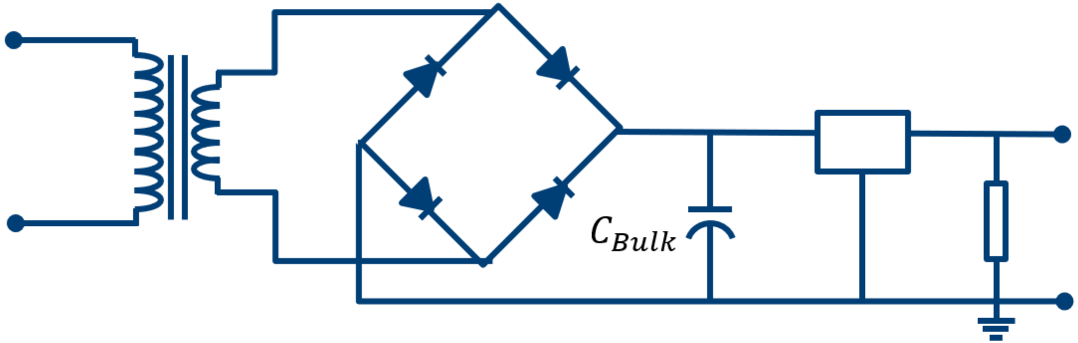


LINEAR POWER SUPPLY

- ► 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

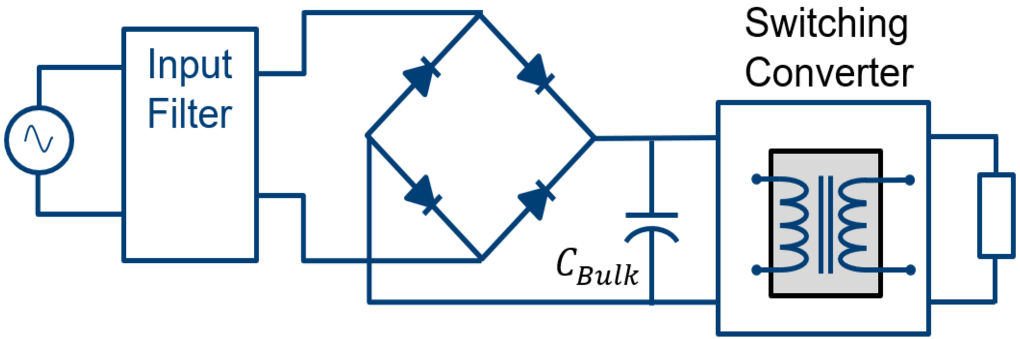
  \+ Low ripple and low noise

  \- Low efficiency, Very bulky (line transformer + smoothing capacitor)



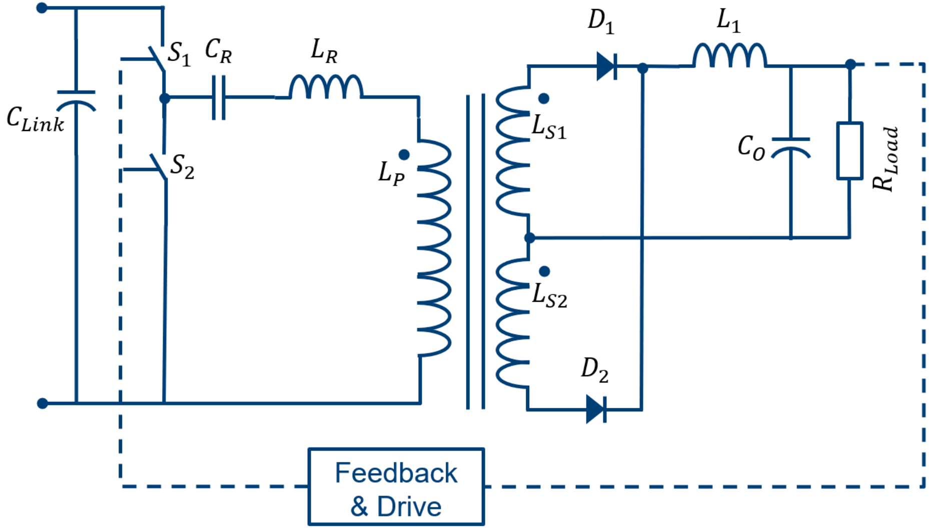
SWITCHING-MODE POWER SUPPLY

- 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.



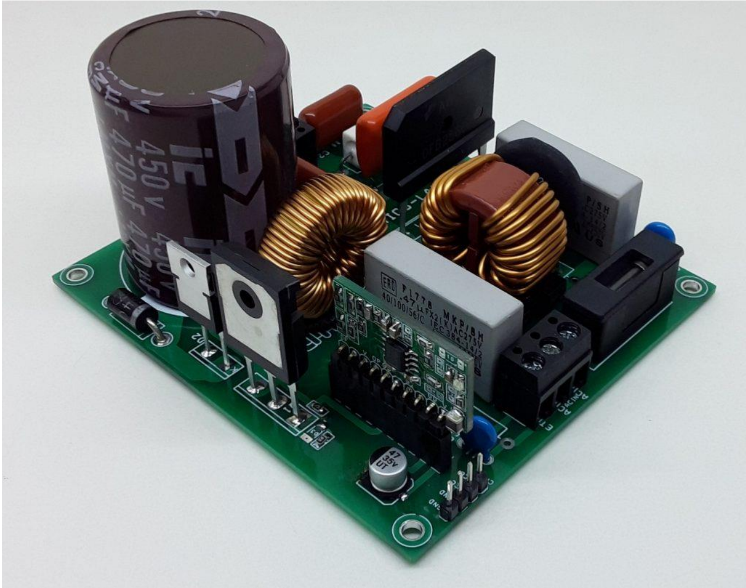
ACTIVE POWER FACTOR CORRECTION (PFC)

► 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 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.

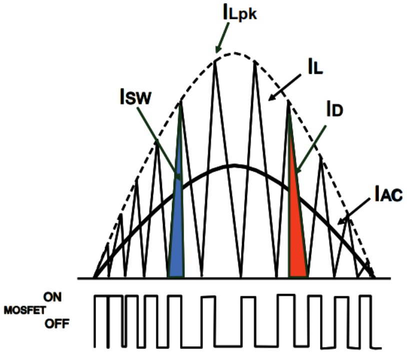


OPERATING MODES

There are different methods to control a PFC converter.

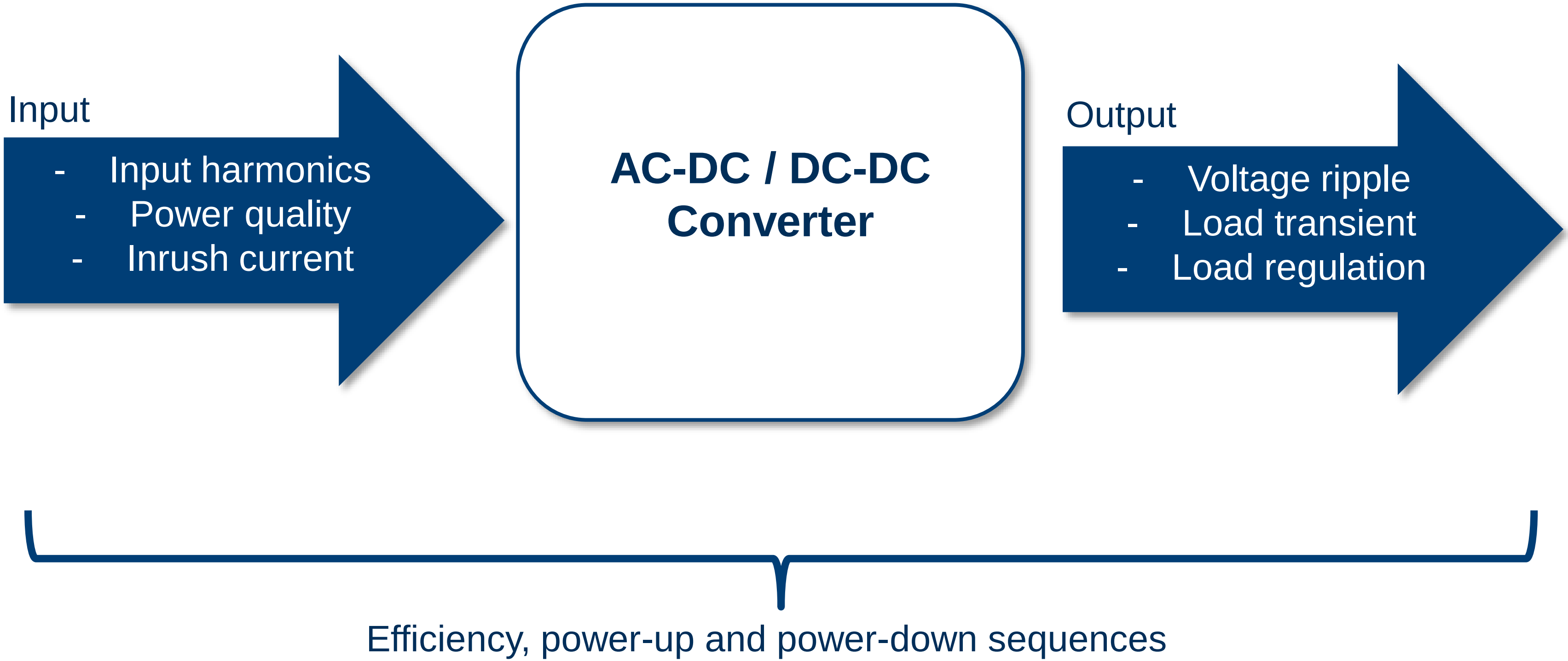
The most common are:

- ► 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

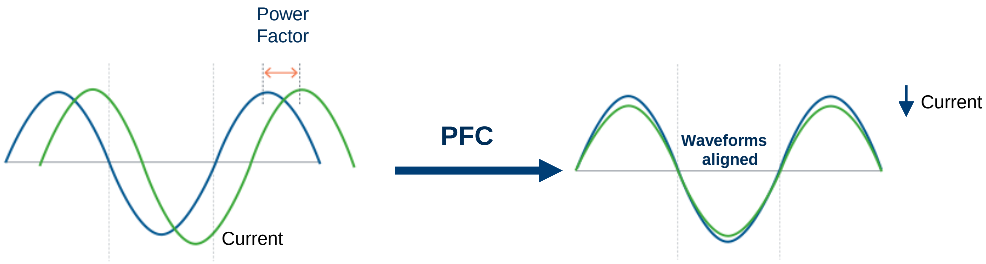
INPUT AND OUTPUT SIGNALS



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 and 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:

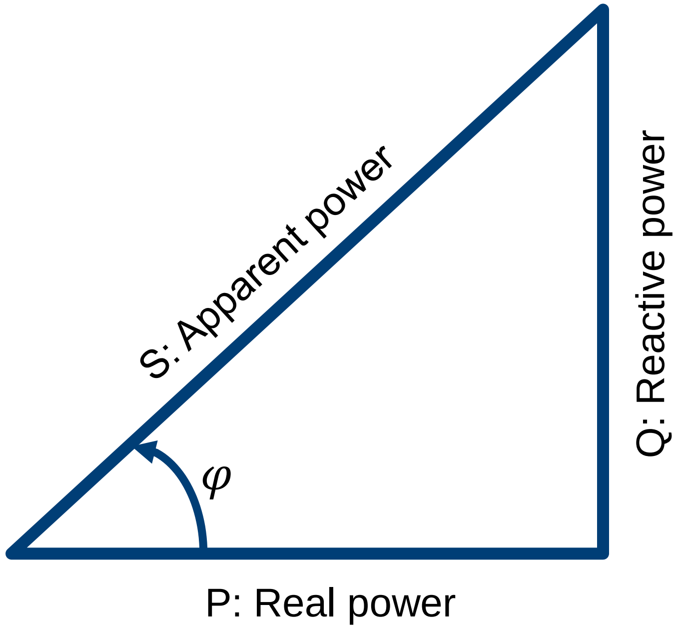
$$P = \frac{1}{T}\int_0^T u(t) * i(t)dt \ \ [W]$$

► Apparent power:

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

► Reactive power:

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



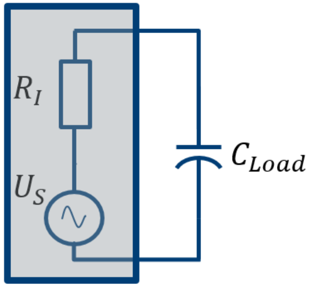
POWER QUALITY
POWER FACTOR

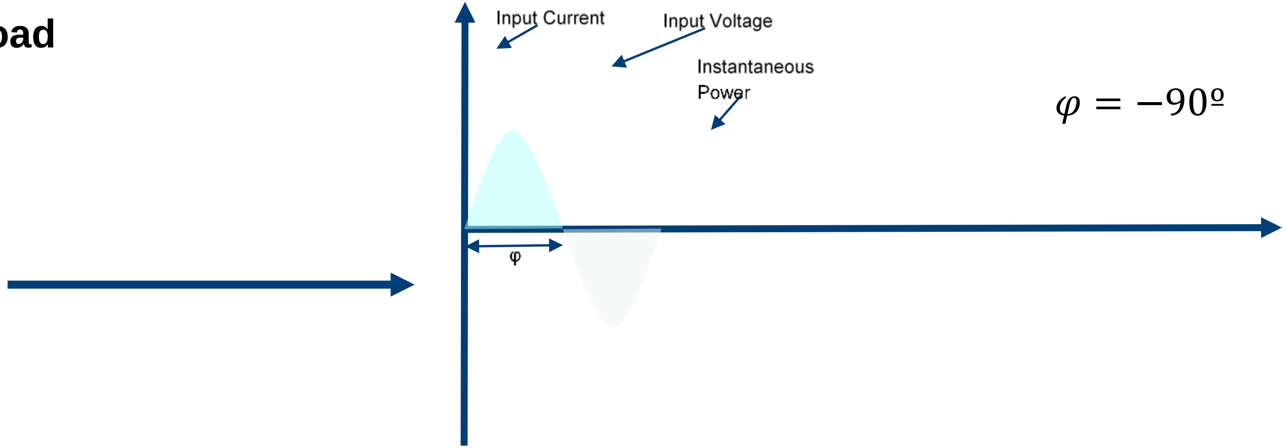
- Refers to the ratio of power utilized by the load to the power delivered to the load and is expressed as a number between 0 and 1.

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

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

Example: Capacitive load





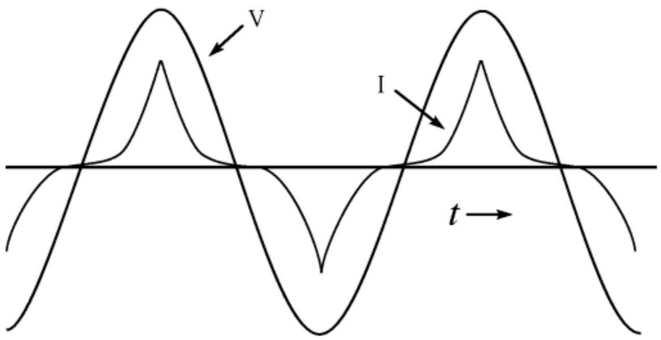
$$\varphi = -90º$$

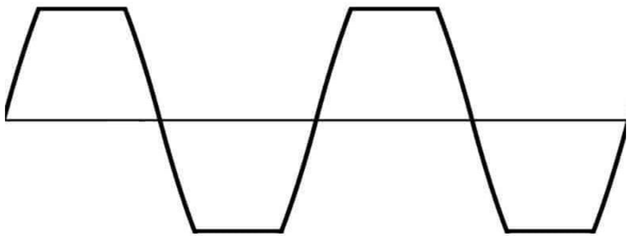
POWER QUALITY
CREST FACTOR

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

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

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





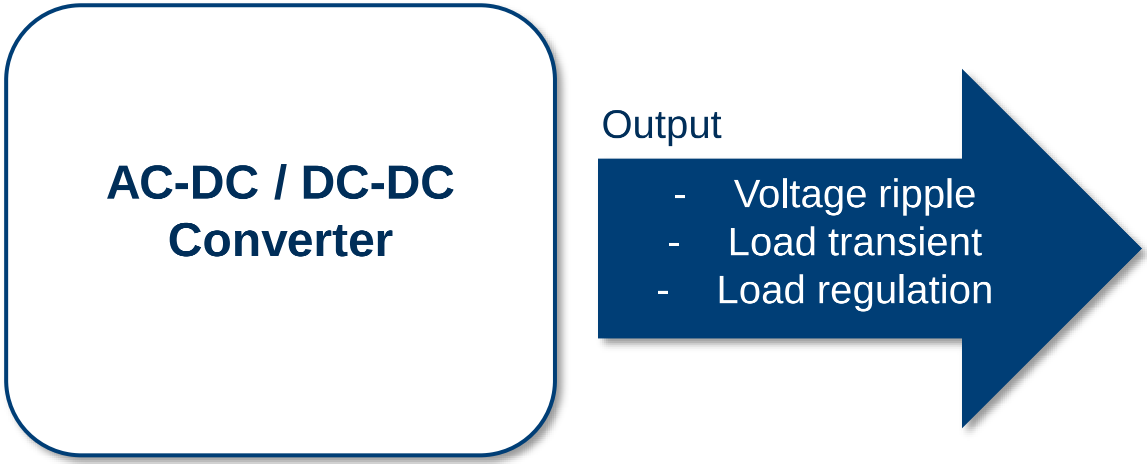
INPUT HARMONICS

- 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.

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

OUTPUT SIGNALS

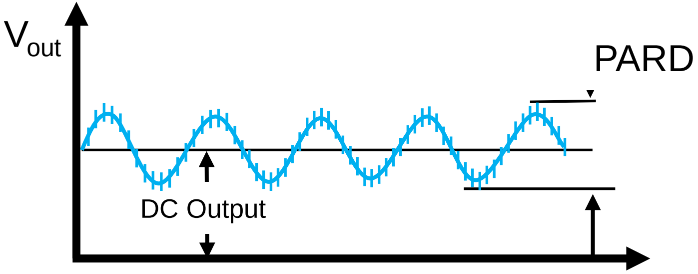


VOLTAGE RIPPLE
WHAT IS RIPPLE?

- 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



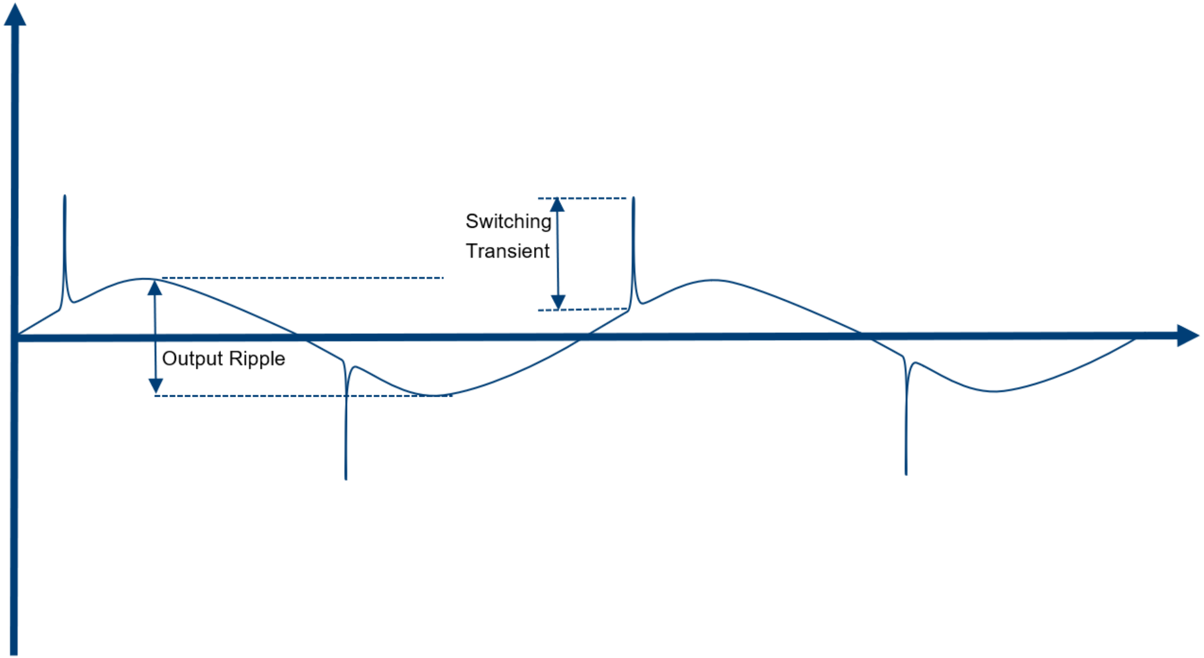
Examples

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

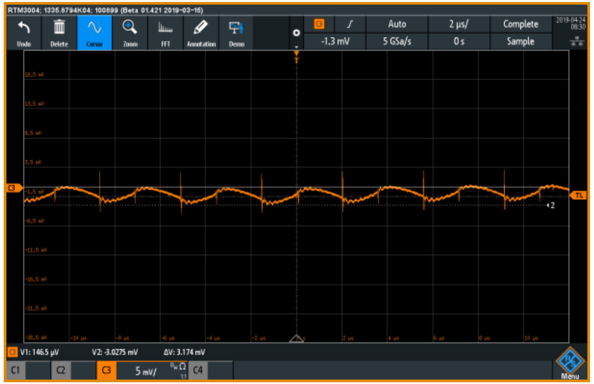
- High-frequency periodic deviation
- Superimposed on the output ripple peak to peak

- A proper test setup will determine the accuracy of this measurement.
  - External interference can affect peak to peak value.



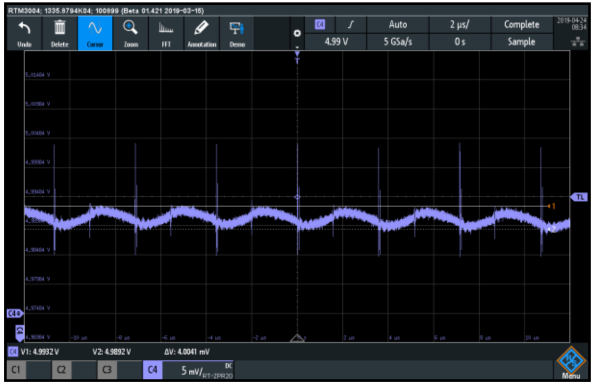
OUTPUT VOLTAGE RIPPLE COMPARISONS

1:1 Passive



DC-Block

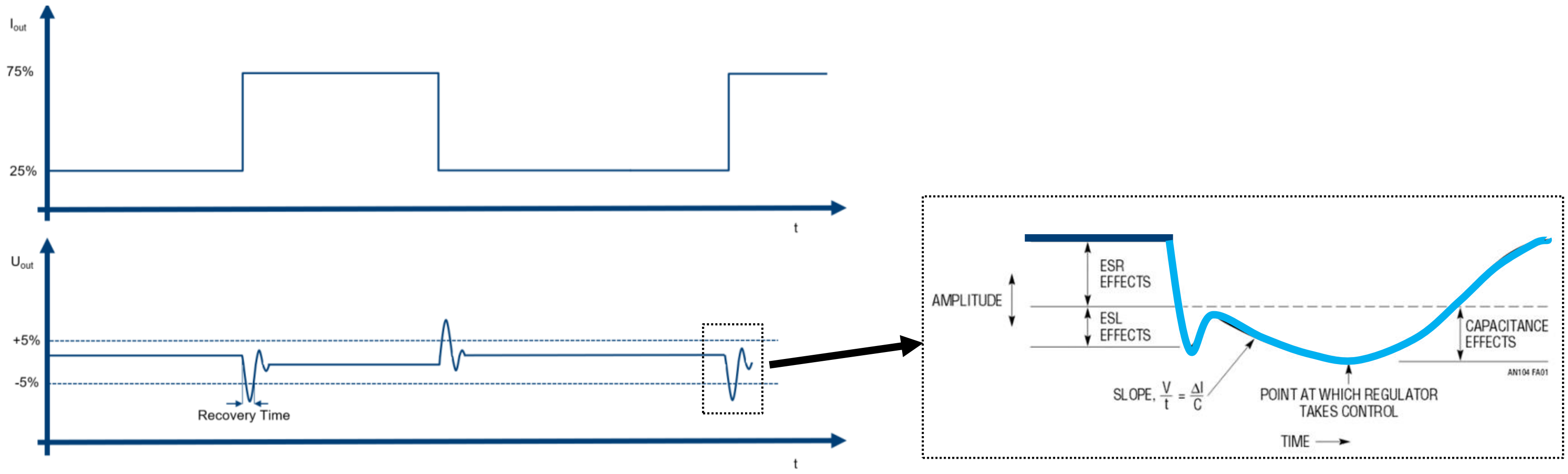
10:1 Passive



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.

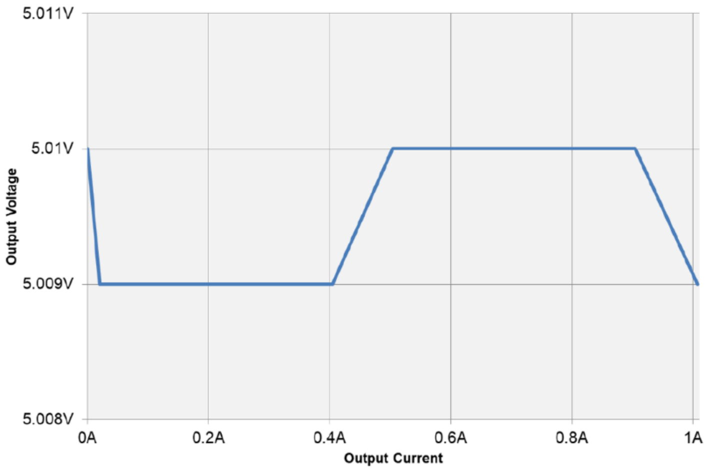


LOAD REGULATION

- 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.

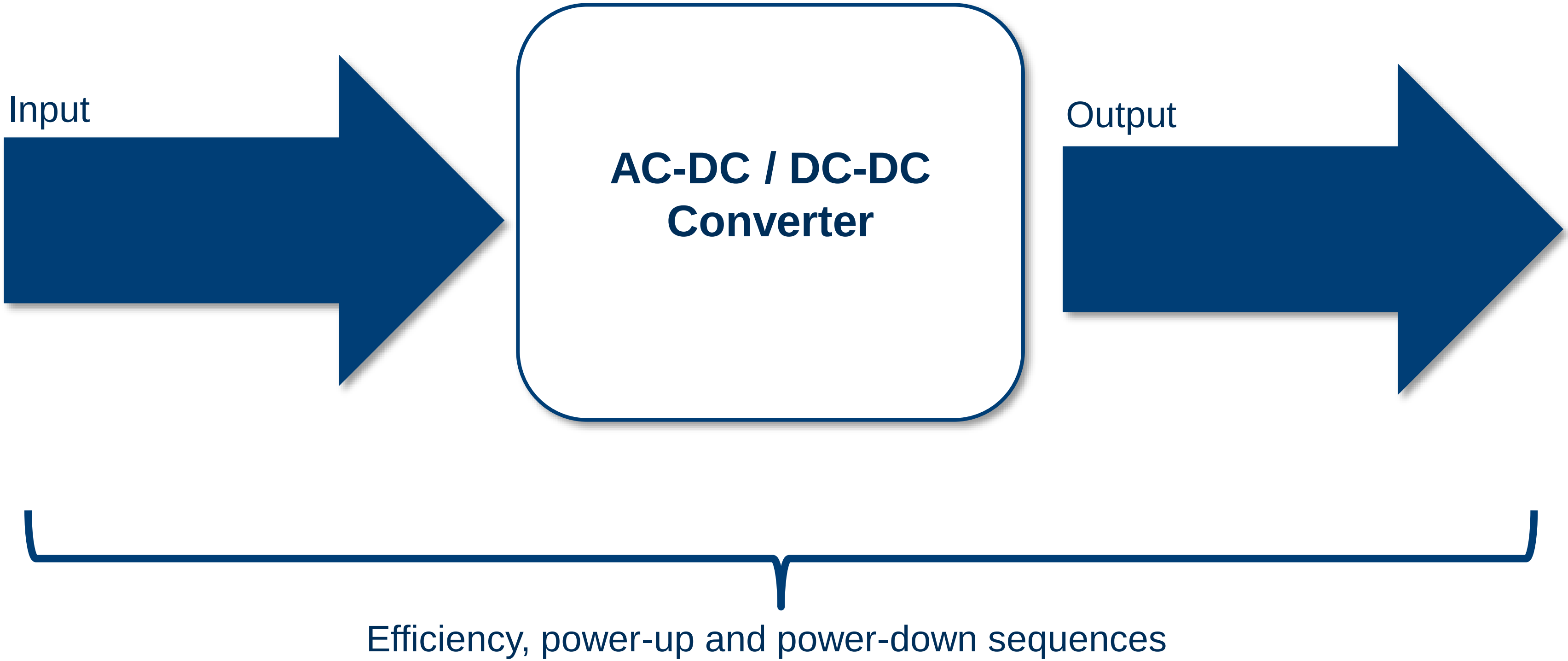
$$Load\ Regulation = \frac{V_{NL} - V_{FL}}{V_{FL}} \times 100\%$$

V_{NL} = No Load Voltage
V_{FL} = Full Load Voltage



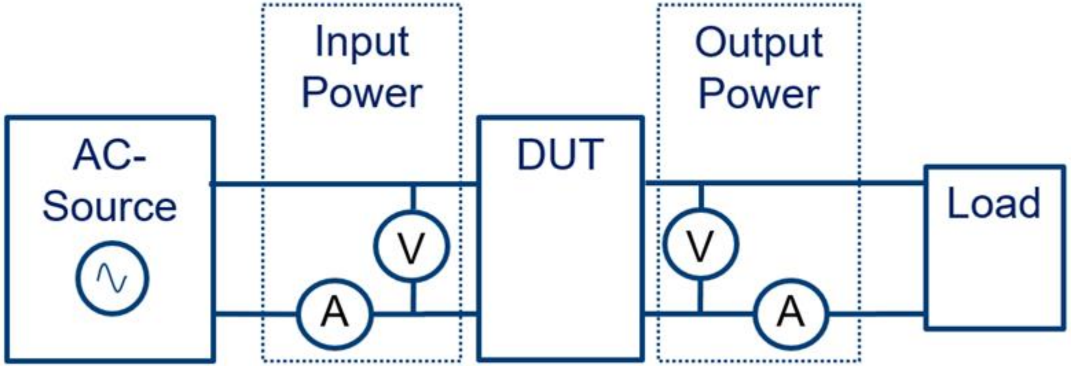
- **Good value: 1–2 %**

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:**

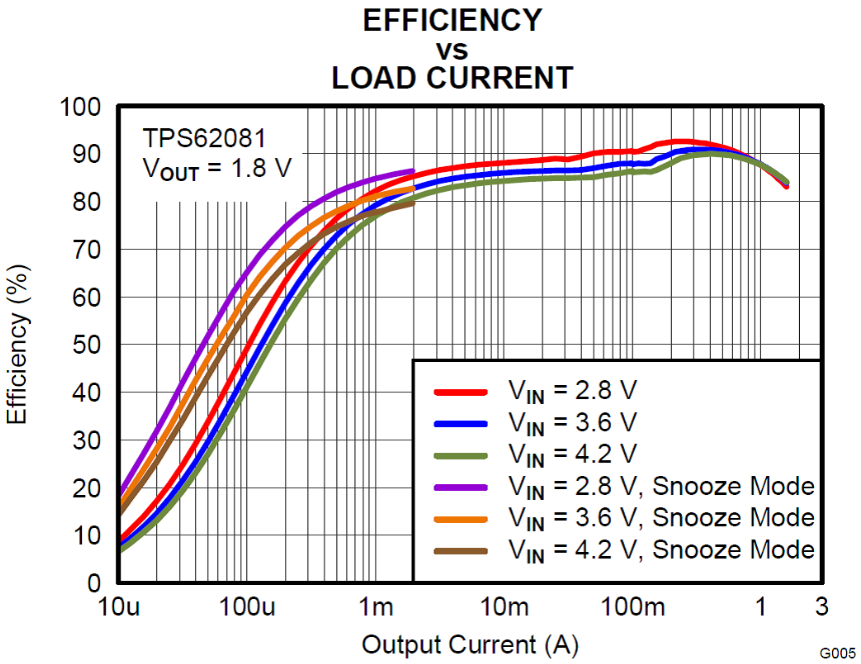


EFFICIENCY

- 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 characterize 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

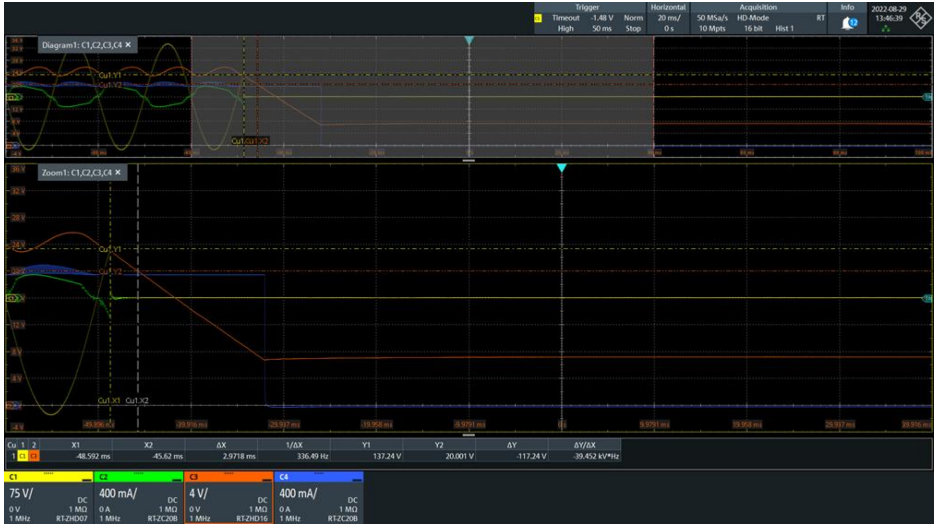
- Most converters have a Soft-Start function meant to start-up in a smooth way and avoid large inrush currents or overshoots.
- The main challenge is to acquire at the same time:
  - Input and output voltages
  - Switching characteristics
- This requires significant memory depth.

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

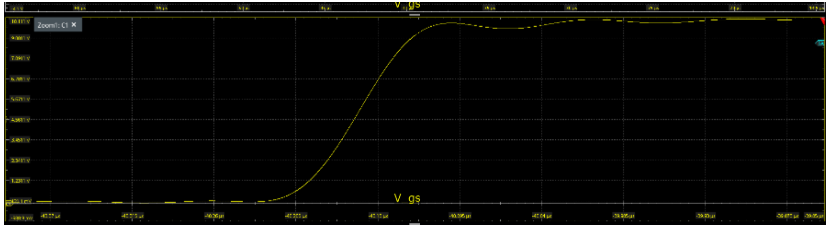
SWITCHING STAGE ANALYSIS

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.



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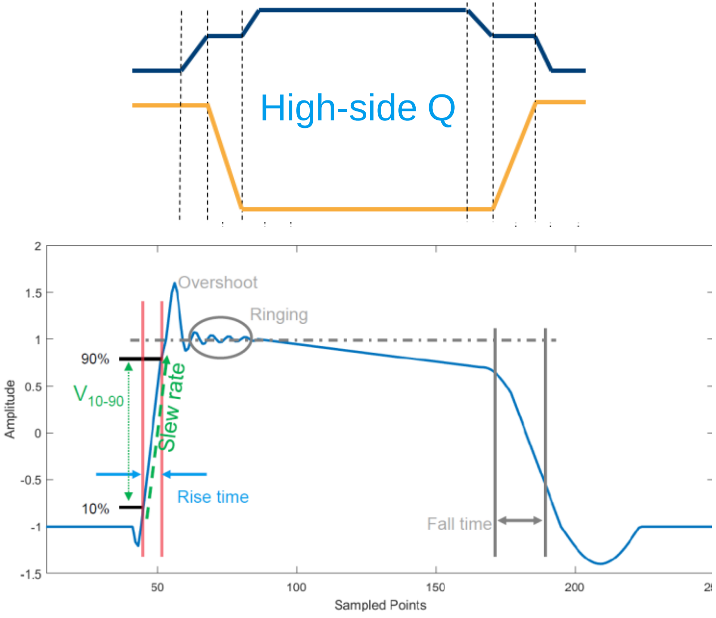
SWITCHING STAGE
BEST PRACTICE MEASUREMENTS

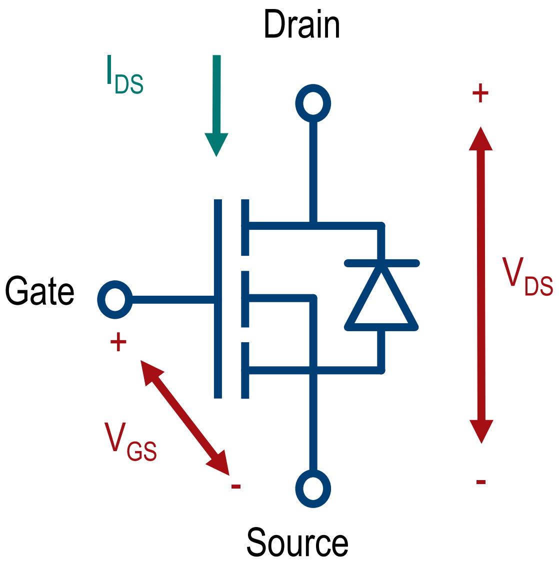
- As a rule of thumb, it should be checked:
  - ✓ V_{GS} and V_{DS}
  - ✓ Rise times and fall times (10/90 or 20/80)
  - ✓ Overshoot, ringing
  - ✓ General timing of high- and low-side switch (syncronous converter)
  - ✓ Robustness test



SWITCHING STAGE
TRANSISTOR

The characterization of a transistor requires three main measurements:

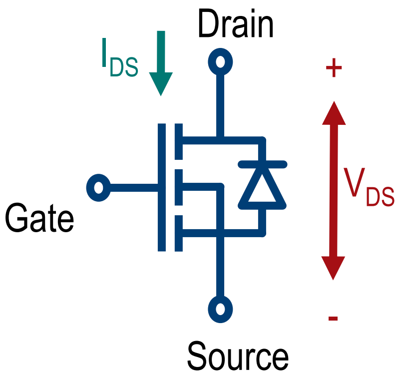
- **Drain to source voltage:**
  - Depending on the side it could be a floating or non-floating measurement
  - Typically high voltages
- **Gate to source voltage:**
  - Floating measurement
  - Voltages in the range of -20 V to 20 V
  - High common mode voltage in the high-side transistor
- **Drain to source current:**
  - Capability of measuring AC currents



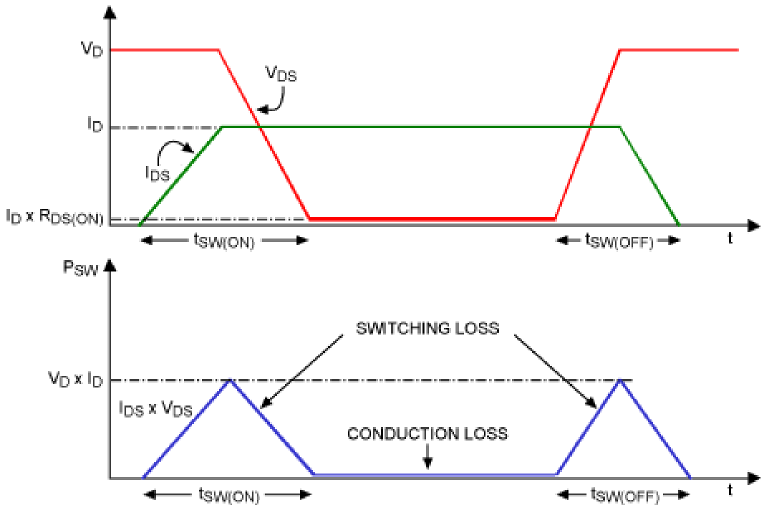
SWITCHING STAGE
QUANTIFY LOSSES

- **Semiconductors operation generate losses**
  - Conduction losses
  - Switching losses

- **Losses are important for cooling system**



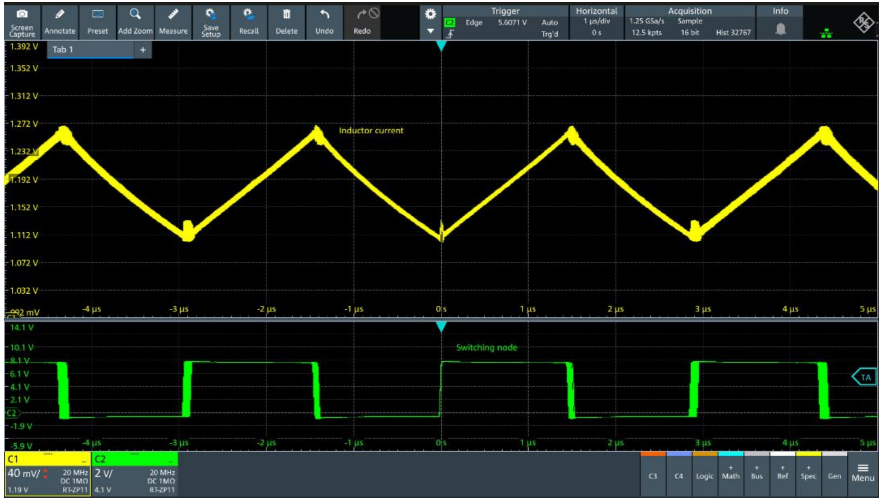
- **Switching losses to be evaluated**
  - Turn on losses
  - Turn off losses
  - Reverse recovery losses



INDUCTOR CURRENT

- It is important to determine if the inductor is suitable for the converter or if saturation will occur during the operation.

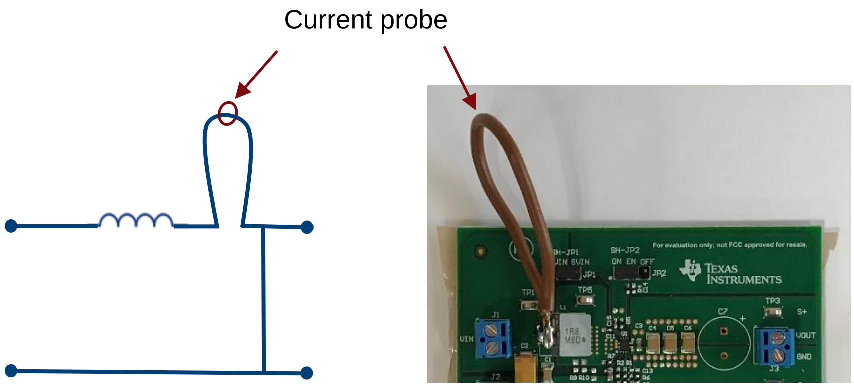
- The inductor current I_L is a common measurement that is used to:
  - Determine conduction mode of the converter
  - Current zero cross detection
  - Evaluate the energy stored in the inductor
  - Characterize the inductor: Resistance and saturation



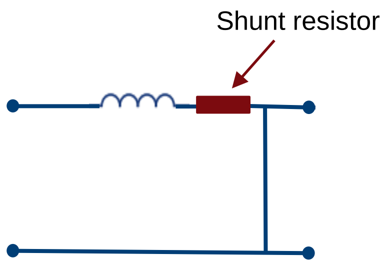
INDUCTOR CURRENT
HOW TO MEASURE IT?

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

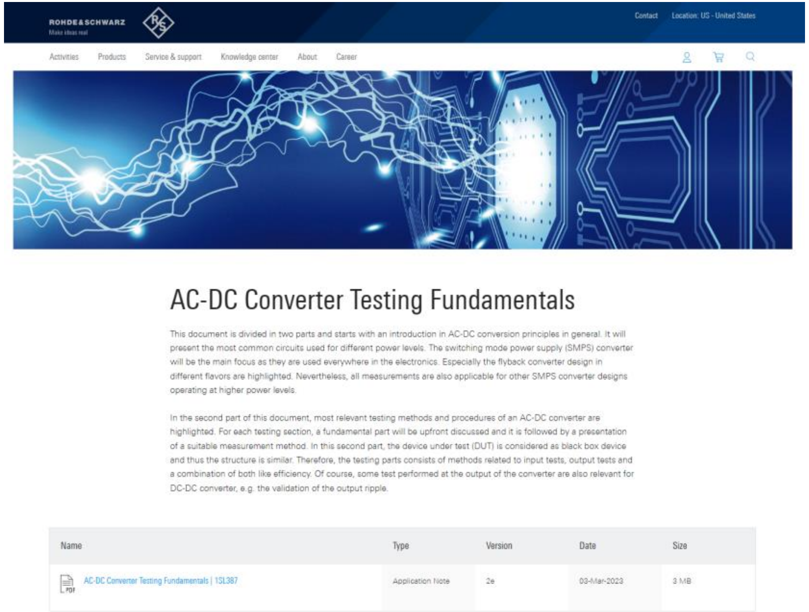
FINAL REMARKS

- 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



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