BEST PRACTICES ON HIGH VOLTAGE AND CURRENT PROBING

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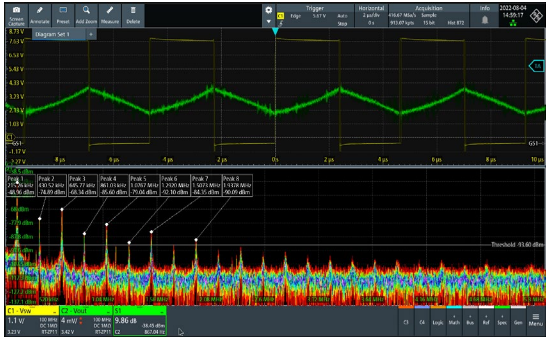
ROHDE&SCHWARZ
Make ideas real

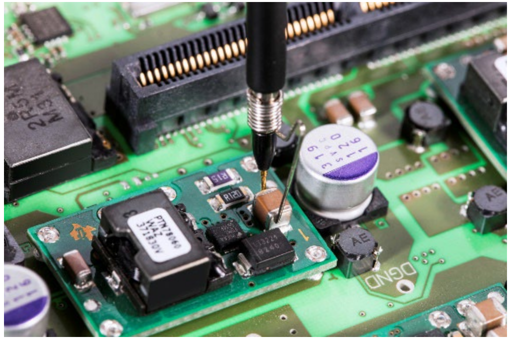
TESTING THE DESIGN

- 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



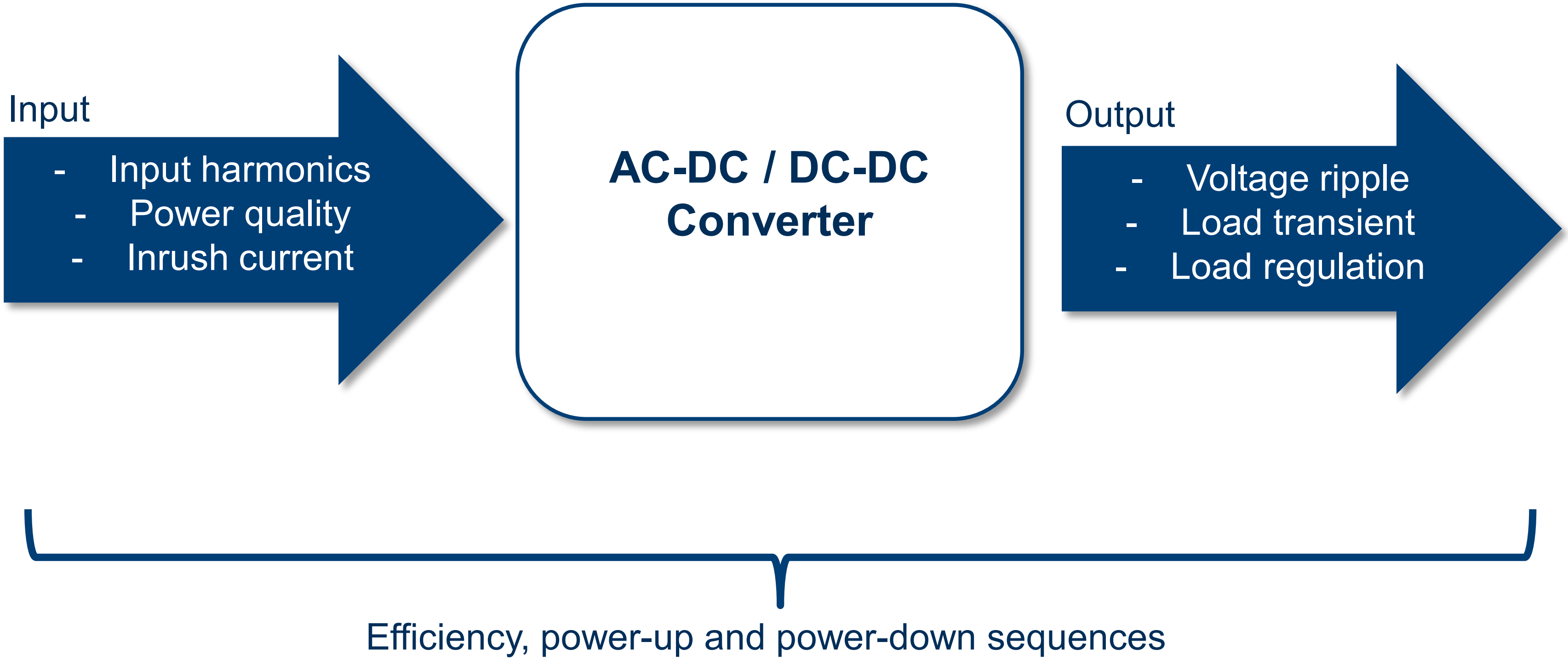
MAIN CHALLENGES

- High frequencies: Wide bandgap materials
- Dynamic range: Operation in wide ranges of current and voltages
- Alignment of current and voltage signals
- Noise: DC-DC converters can produce noise that can interfere with measurements
- Dynamic performance: Rapid changes in output voltage and current
- Accessibility to the DUT



TYPICAL MEASUREMENT SCENARIOS

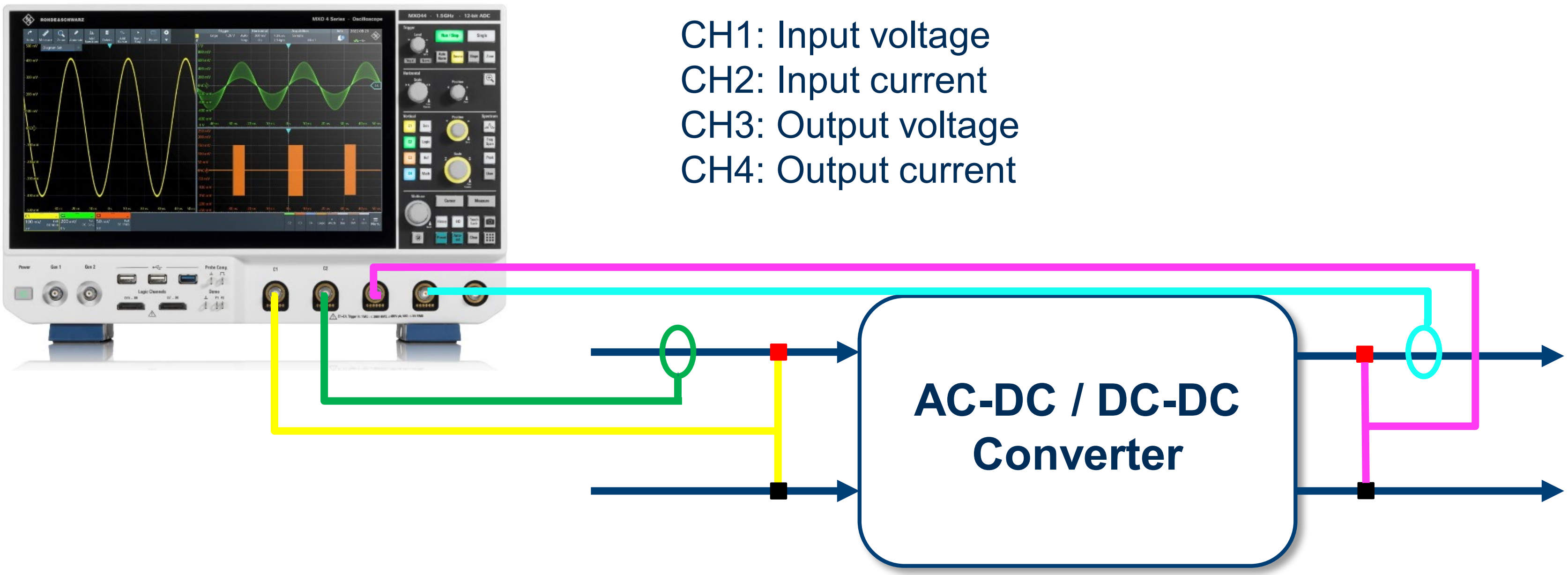
INPUT AND OUTPUT SIGNALS



INPUT AND OUTPUT SIGNALS

- It is necessary to measure the voltage and current and the input and the output
- A typical configuration would be:

CH1: Input voltage
CH2: Input current
CH3: Output voltage
CH4: Output current



INPUT AND OUTPUT SIGNALS
PROBES

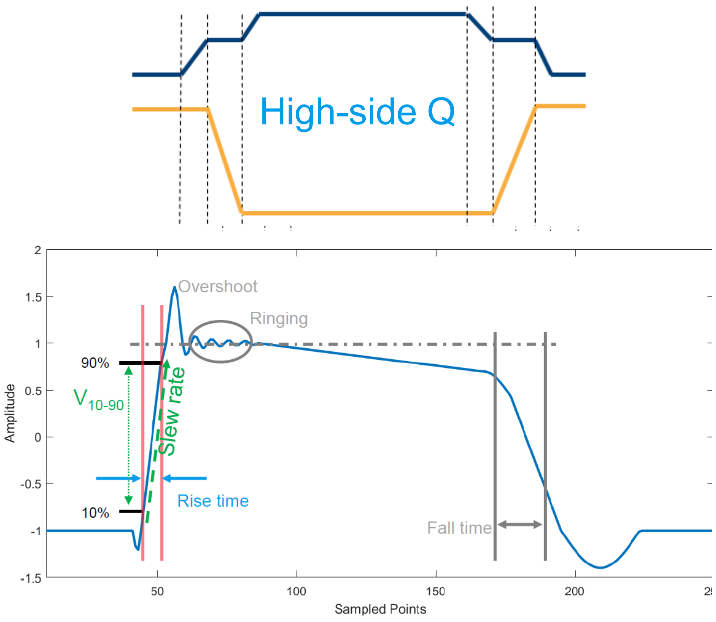
- The specifications of the probes depend on the voltage and current ratings, as well as the required bandwidth.

- **Voltage probes:**
  - The rated voltage of the probe should be greater than the voltage to be measured at the input and output terminals.
  - In general, a high voltage differential probe is recommended. Especially when measuring AC input signals.

- **Current probes:**
  - Clamp type probes are recommended when the input and output cables are accessible.

SWITCHING STAGE
BEST PRACTICE MEASUREMENTS

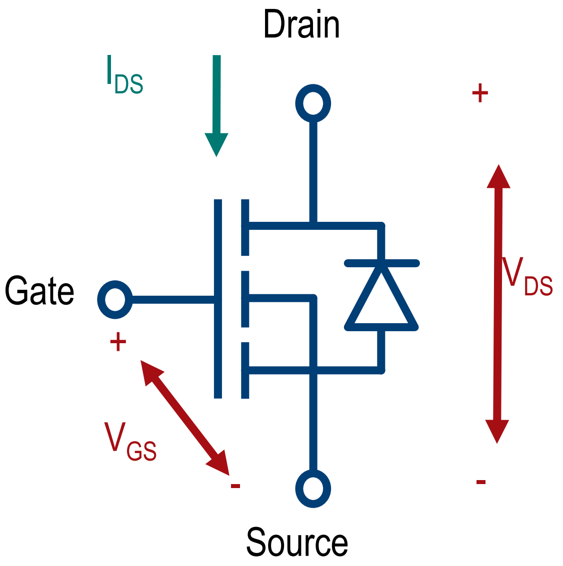
- As a rule of thumb, it should be checked:
  - ✓ V_{GS} and V_{DS}
  - ✓ Rise times and fall times (10/90 or 20/80)
  - ✓ Overshoot, ringing
  - ✓ General timing of high- and low-side switch (syncronous converter)
  - ✓ Robustness test



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

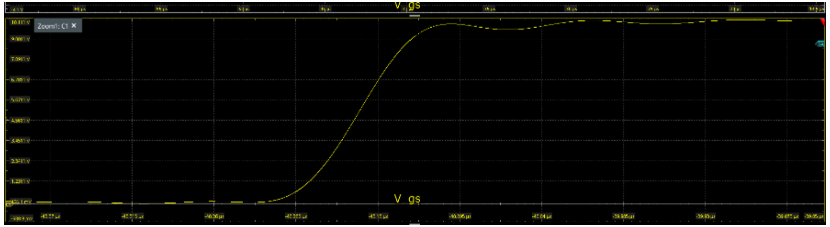


SWITCHING STAGE
BANDWIDTH

- Among the greatest challenges in testing the switching stage of the converters are the wide bandgap materials like SiC and GaN. Their faster switching times condition the bandwidth.
- Oscilloscope and probes must be chosen accordingly.

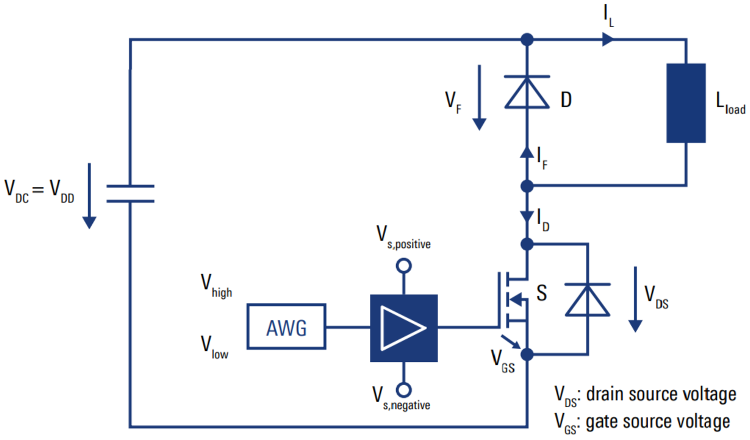
$$Bandwidth \sim \frac{0.35}{t_{sw,rise}}$$

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



SWITCHING STAGE
DOUBLE PULSE TEST

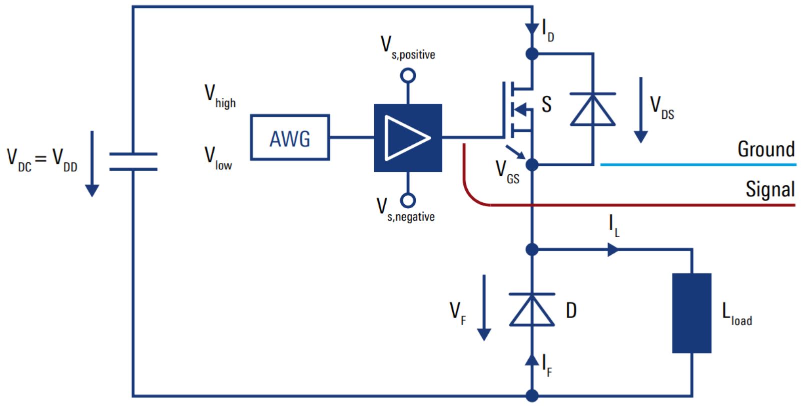
- Semiconductor switching losses play a key role in the design of power converters and it is important to quantify them.
- The double pulse test can deliver switching characteristics for all operating modes of a hard-switching power converter.
- Switching times and switching energies can be measured for high and low side devices.



SWITCHING STAGE
DOUBLE PULSE TEST

Voltage measurement

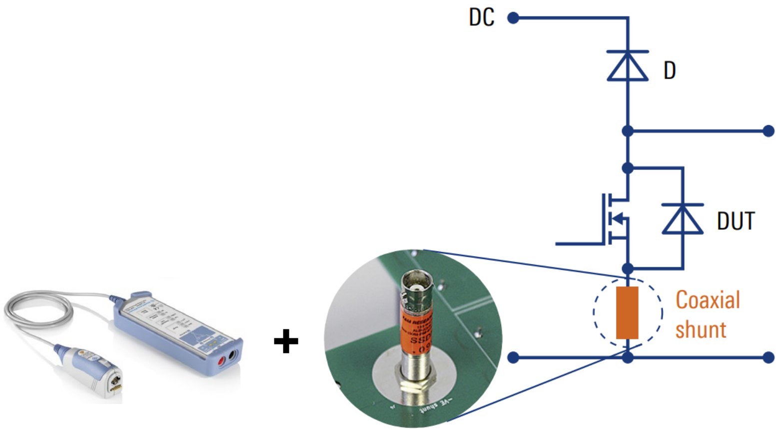
- Floating setups allow the usage of passive probes
- Grounded setups require the use of high voltage differential probes for the gate to source voltage measurement.
- Broadband differential probes can also be used depending on the voltage level to be measured.
- The rise time of the V_{DS} determines the required bandwidth

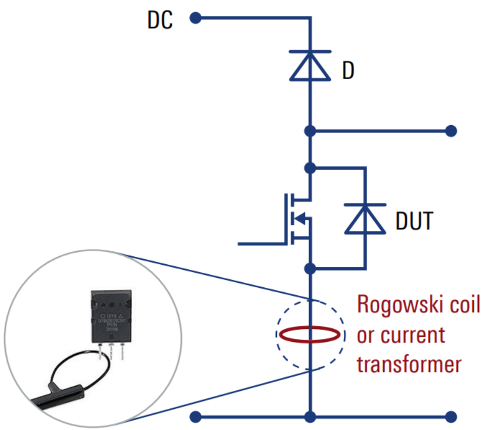


SWITCHING STAGE
DOUBLE PULSE TEST

Current measurement

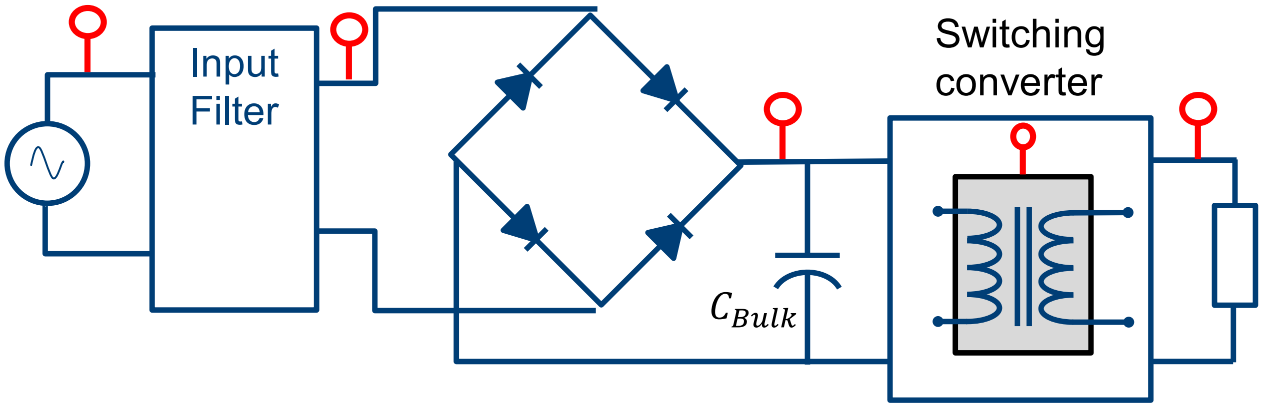
- Choosing the right current probe is a compromise between: current range, bandwidth, accessibility and the ability to measure DC currents.
- In general, magnetic core clamp-type probes are not used due to the impossibility of reaching the test point.
- Alternatives:





AC-DC AND MULTI-STAGE DC-DC CONVERTERS

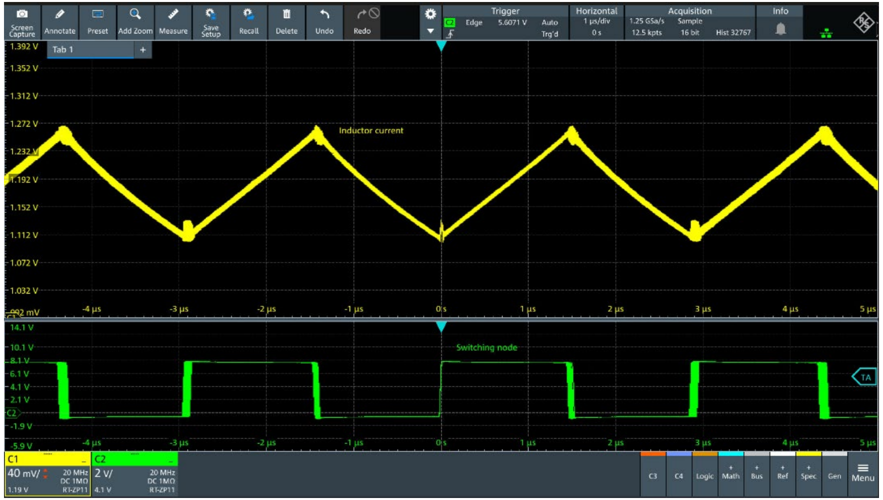
- In AC-DC (e.g. boost PFC) and multi-stage converters there are multiple test points that have to be measured simultaneously.
- This is done to verify the design of the different elements in the circuit, such as: filter, rectifier, switching converter, etc.
- In general, high voltage probes are used (passive or differential).



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

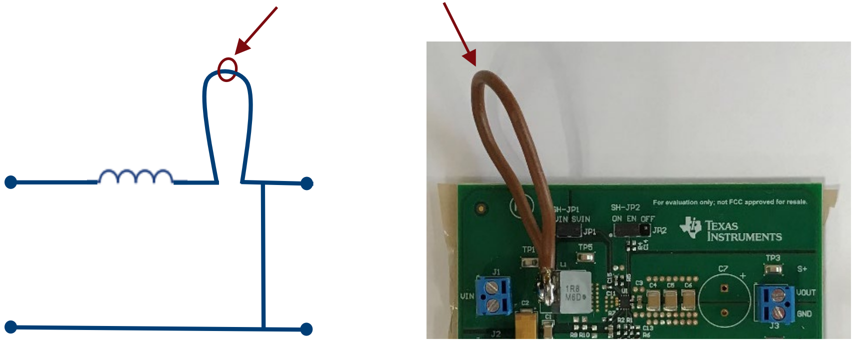


INDUCTOR CURRENT
HOW TO MEASURE IT?

There are two ways of measuring the inductor current:

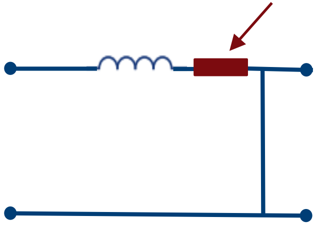
- **Use an auxiliary wire in series with the inductor.**
  - Desolder with hot air to detach the one of the terminals of the inductor
  - Use a small cable to connect in series the inductor.
  - The cable should be long enough to attach a clamp-type current probe.

Current probe

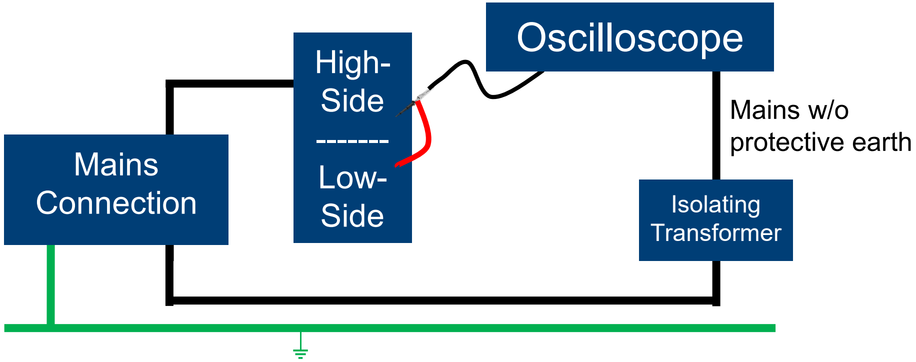


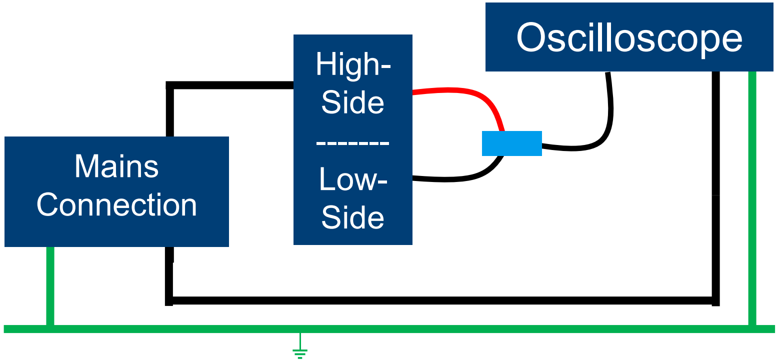
- **Use a shunt resistor**
  - It is an alternative to the current probe but not recommendable.
  - Switching noise can easily couple into the voltage measurement via the shunt resistor.

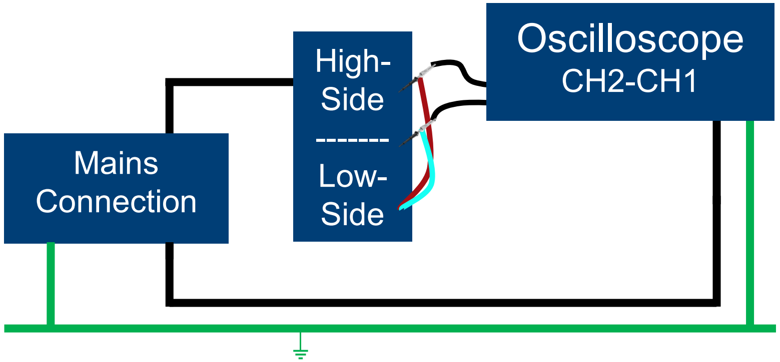
Shunt resistor

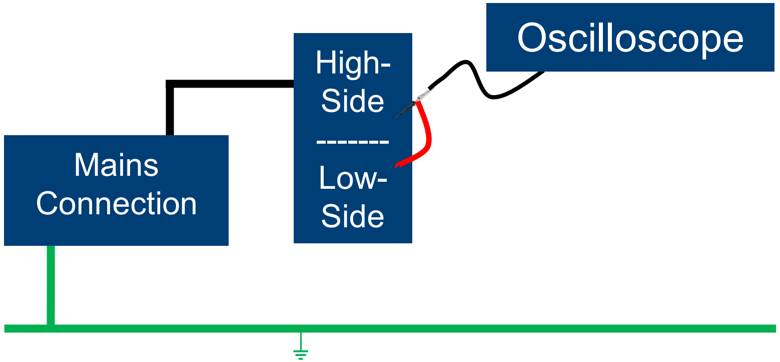


FLOATING MEASUREMENT TECHNIQUES









FLOATING MEASUREMENT TECHNIQUES

Floating Scope using isolating Transformer:

- Oscilloscope Ground provided by DUT and can differ from 0 V.
- All grounds are at the same level.
- Potential risk for electrical shock when touching the system.
- Stray capacitances and inductances of the setup can influence measurement results

High-Voltage Differential Probe:

- Can accurately measure small differential voltages in the presence of large common-mode voltages up to thousands of volt.
- High input impedance on both inputs to minimize loading and measurement errors.
- Bandwidth limited to typ. 200 MHz

2 Single-ended Probes + Math-function:

- Scope inputs can be overdriven easily.
- Vertical resolution is limited by offset range and divider ratio of the probe.
- Probes must be compensated against each other to achieve good results.
- In most cases: 2 probes of the same type have to be used, otherwise no compensation possible.

Isolated Channel oscilloscope:

- Isolated input has no direct electrical connection to earth ground.
- Great DC & low frequency CMRR.
- Bandwidth up to 500 MHz.
- Isolated probes are not true differential

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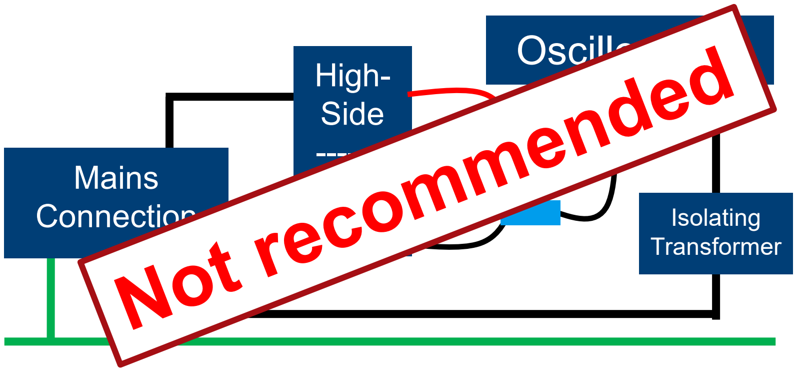
FLOATING MEASUREMENT TECHNIQUES
FLOATING SCOPE + HV DIFFERENTIAL PROBES

- A common practice is to use HV differential probes while the oscilloscope is floating by means of an isolating transformer.
- In this case, there is not a direct connection to the reference potential and the scope looks for its reference potential over the high impedance input of the HV differential probe.
- When using more than one HV differential probe, the floating reference voltage is a combination of the common mode voltage of the probes.
- The CMRR is affected and the overall performance of the probes may get worse



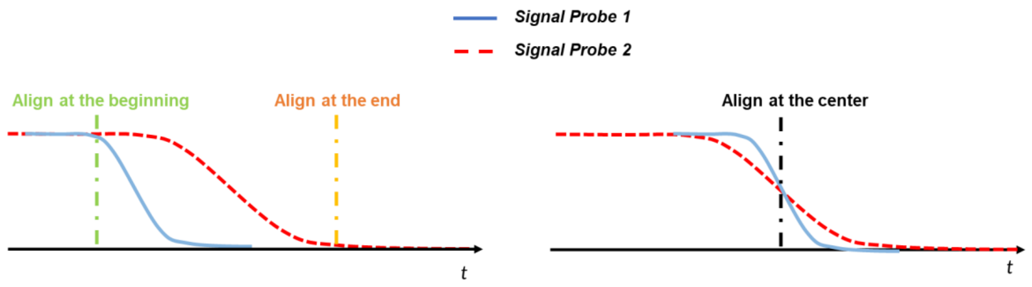
DE-SKEW

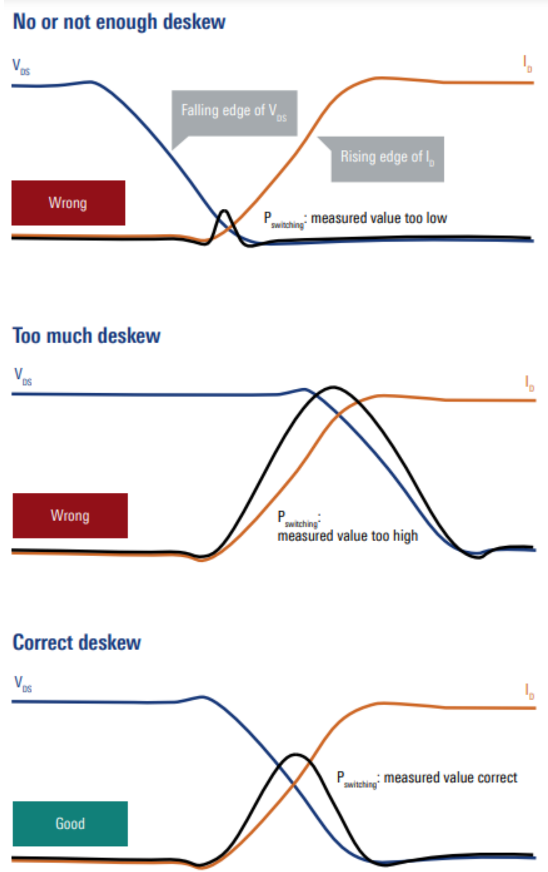
- ► Voltage and current probes have different rise times and propagation delays
- ► For measurements that require both signals (switching losses, efficiency, start-up) is essential to compensate the time delay.

- ► 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.

DE-SKEW

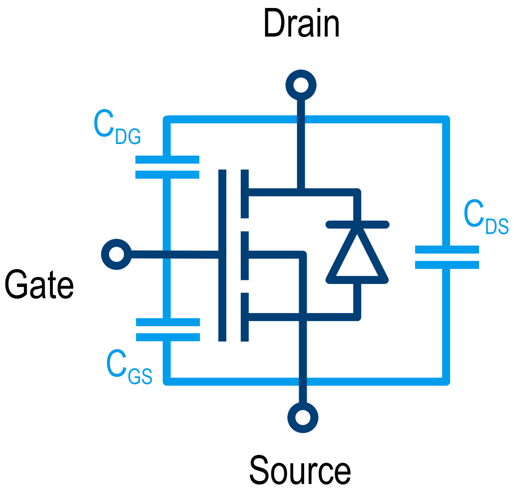
► For probes where the use of a deskew fixture is not possible, a manual deskew is required:
  - The point of alignment depends on the application
  - If the signals do not have similar shapes, the process is not straightforward.
  - This process is uncertain and requires repetitions

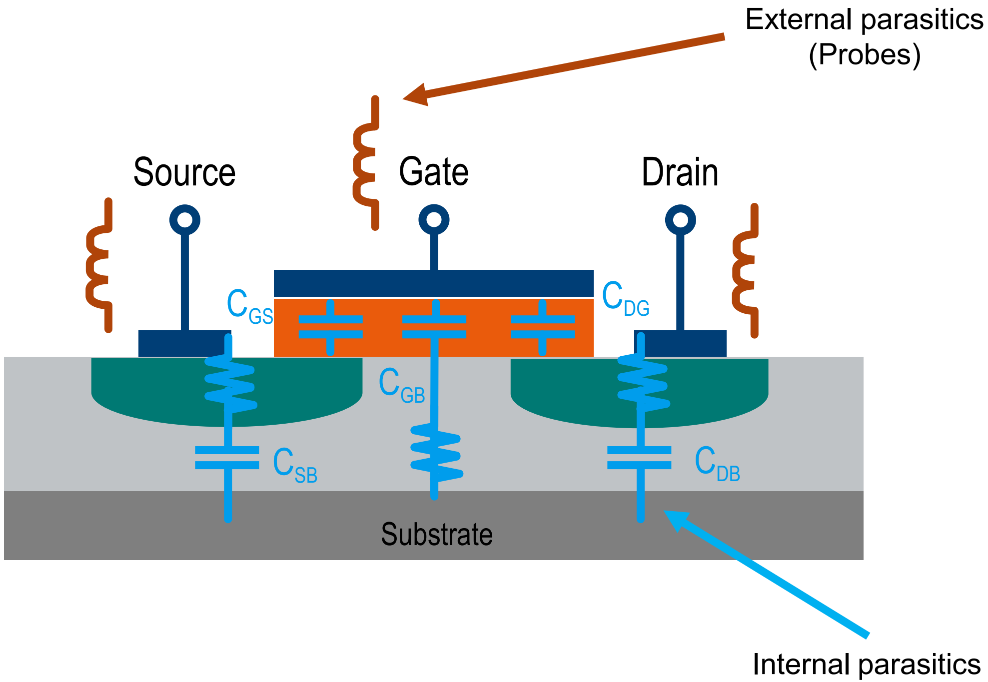




PROBING

PARASITICS



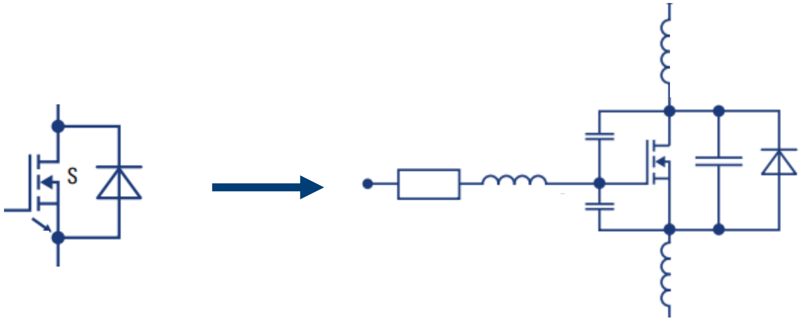


… internal parasitics are silicon based, normally capacitances of the substrate

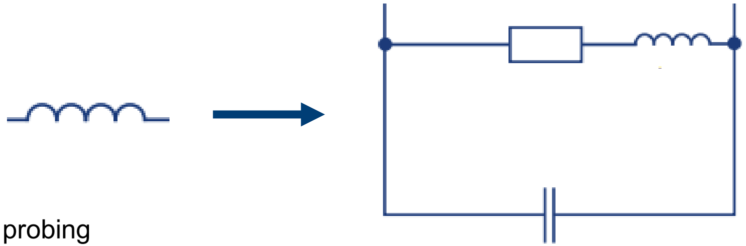
… external parasitics are formed due to bonding interconnections and probing

PARASITICS

- ► WBG transistors are very sensitive to parasitic inductance due to their switching speed.
- ► At such frequencies, it is difficult to measure the signals waveforms without adding spurious noise to the DUT.
- ► Thus, it is important to minimize the parasitics when measuring the different signals in the circuit.



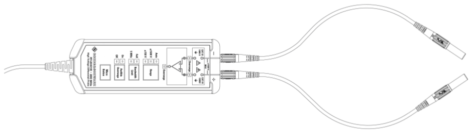
- ► Parasitics in passive components must be considered when testing a design based on WBG semiconductors.

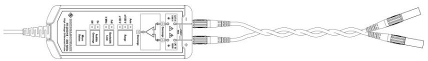


CONNECTIONS

► Leads and clips also have an influence in the measurement.

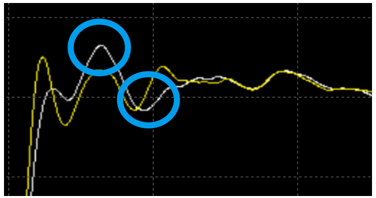
Untwisted or twisted?:

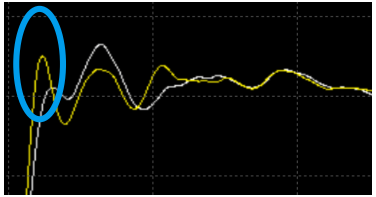




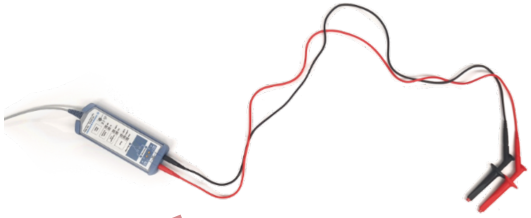
pro	minimizes the capacitive load on the measuring point
con	interferers are looped in

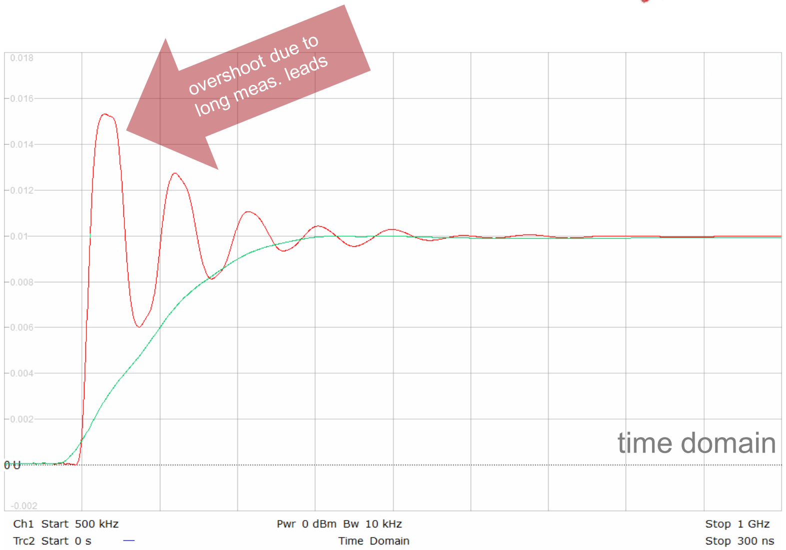
pro	interferers are minimized
con	greater load on the measuring point





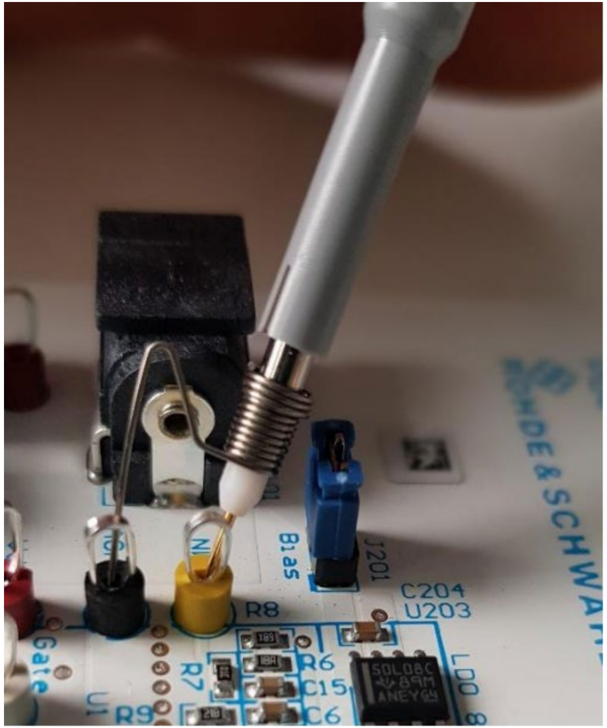
Length:





TEST POINTS

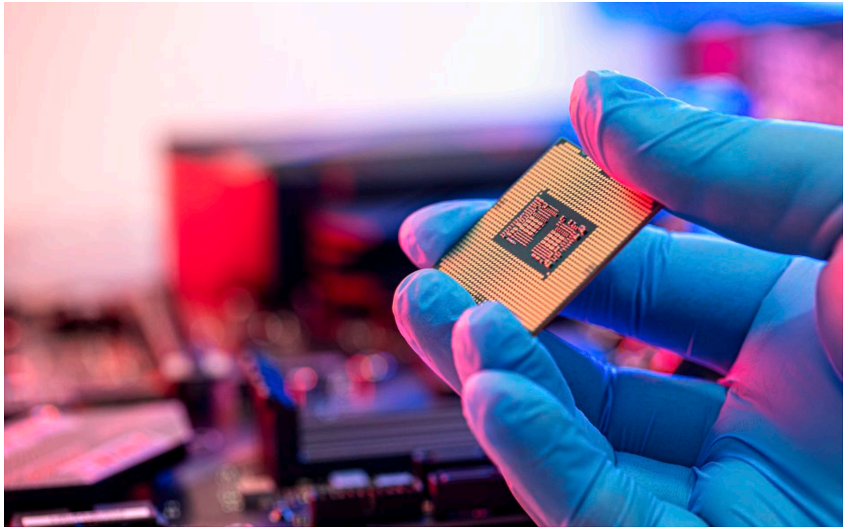
- Test points are used to validate the design.
- Is a small area of exposed copper where a probe can be connected.
- The most common signals that have test points are:
  - Power supply rails
  - Ground
  - Communication buses
- Too many test points:
  - Could accidentally short to another test point
  - Perforate power and ground planes
  - Degrade signal integrity
  - Contribute to EMC issues



ACCESIBILITY
PACKAGING

- Switching speed of WBG semiconductors limit the performance of the conventional packages due to parasitic capacitance and inductance.
- These parasitic components have a direct influence in overvoltage, EMI and in the measurements.

- State-of-the-art integrated circuits (ICs) that use SiC and GaN are capable of integrating half-bridge, full-bridge, push-pull and other architectures into a single package.
- This packaging limit the number of test points in the switching stage. It is not possible to measure the internal signals (Vgs, Id) in such packages.



DERATING

Higher frequencies

↓

Probe input impedance decreases

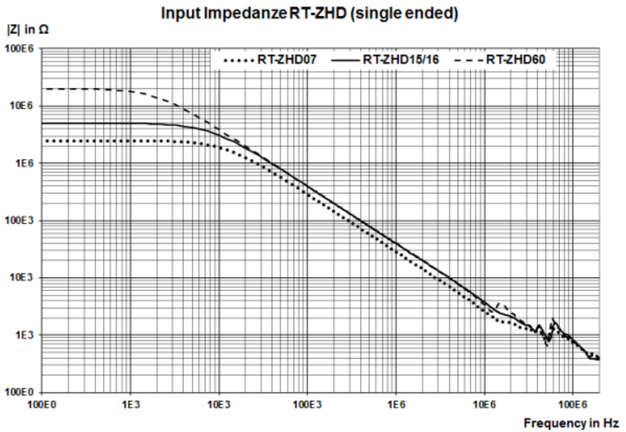
↓

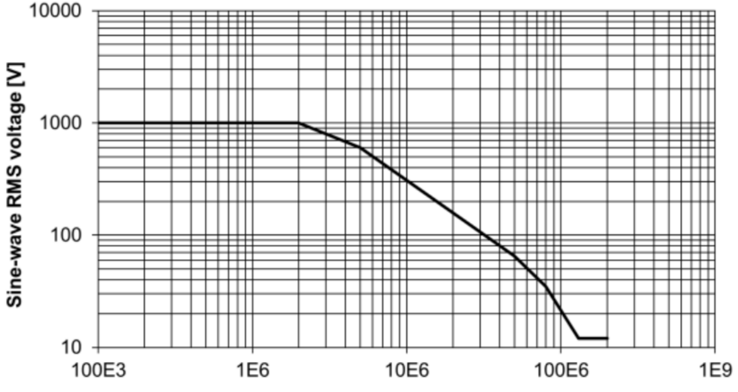
Increase in the current flowing through the probe

↓

RMS input voltage rating decreases

Maximum power rating of the probe must not be exceeded





HOW TO MEASURE CURRENTS?

CURRENT MEASUREMENTS

- The selection of a current measurement technique is a challenging task and several aspects must be taken into account:
  - Bandwidth
  - Sensitivity
  - Maximum current
  - Accessibility to the test point
  - Saturation
  - Insertion impedance
  - Positioning

- This selection is a compromise and highly depends on the application

INSERTION IMPEDANCE

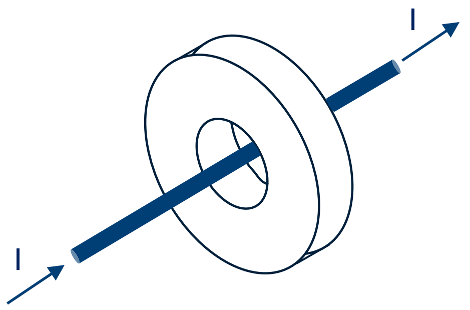
- It refers to the equivalent impedance that appears in series to the circuit (conductor under test) when it is being probed.
- The insertion impedance can be calculated as:

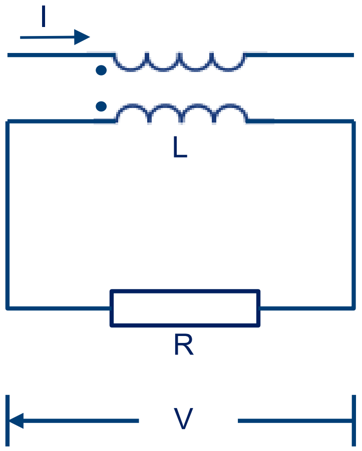
$$Z_{ins} = Z_{refl} + Z_{intr}$$

- Where Z_{refl} is the secondary impedance reflected into the primary by transformer action and Z_{intr} is the intrusion impedance originated by the core material of the current probe.

$$Z_{refl} = \frac{(\omega M)^2}{R+j\omega L}, \quad Z_{intr} = j\omega \frac{L}{N^2} - j\omega \frac{L_0}{N^2}$$

- At lower frequencies, the core losses are negligible.

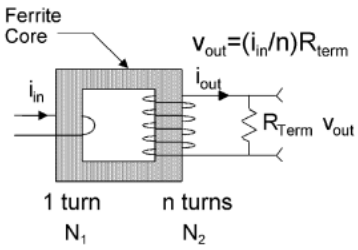




POSITIONING

Orientation of current

- The orientation of the probe matters.
- The current probe is designed to work as a coupled transformer where the primary is the wire and the secondary the probe. Thus, it expects the current to be flowing in a specific direction.

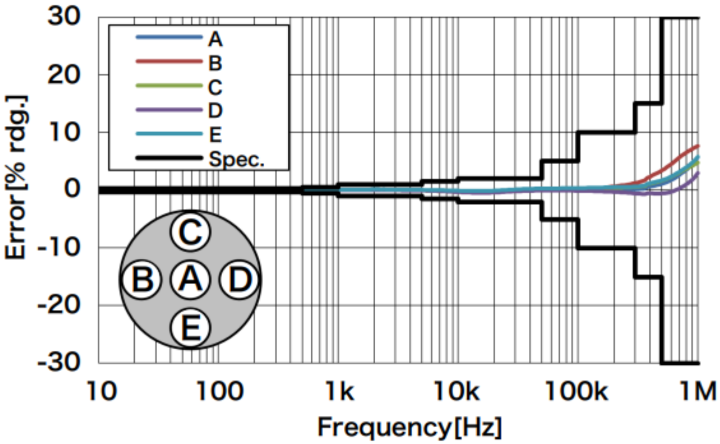


- An incorrect orientation translates into an inverse output voltage of the current probe.
- Probes are calibrated considering a single current direction.

Cable position

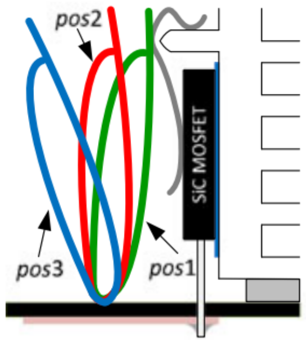
- The clamp-type current probes exhibit dependency on the positioning of the conductor.
- It should be placed in the center of the aperture since the characterization of the probe is done in this position.

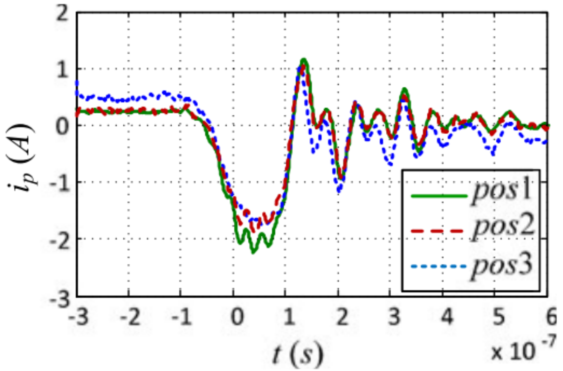
→ achieve best possible accuracy, and reproducibility.

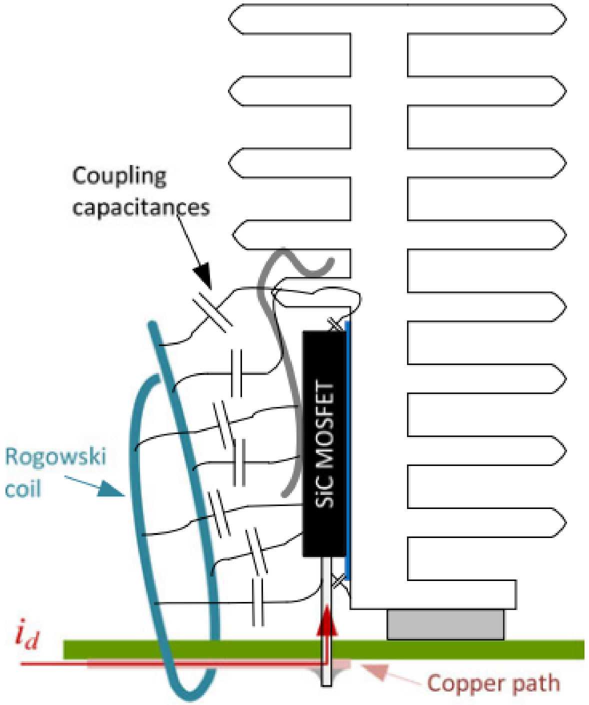


POSITIONING
COUPLING CAPACITANCES

- ► Besides the conductor position, the relative position of the current probe is also important.
- ► When the probe is close to a component, it will suffer from electromagnetic interference due to capacitive coupling.
- ► The distance to nearby components should be kept to a minimum.



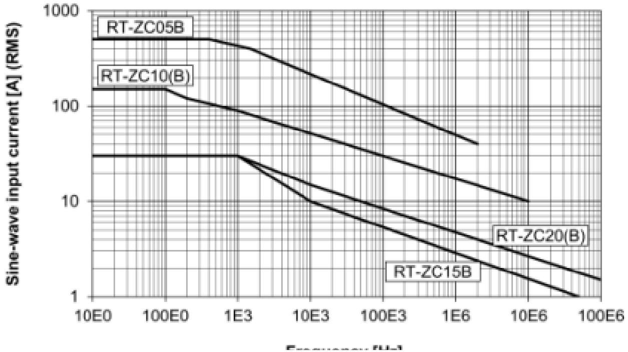


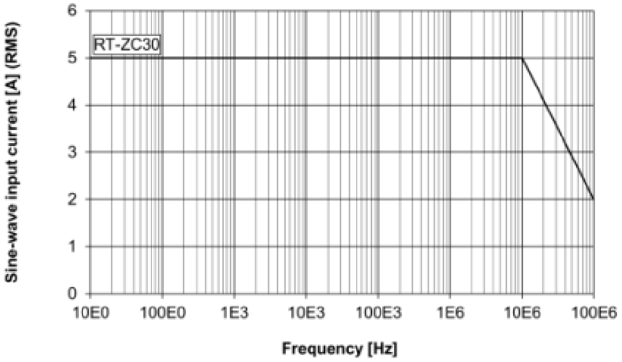


Oyarbide (2017). New Current Measurement Procedure Using a Conventional Rogowski Transducer for the Analysis of Switching Transients in Transistors.

NONLINEARITY OF CURRENT MEASUREMENTS
HIGH CURRENTS AT HIGH FREQUENCIES

- The linear operation of a probe is given by the amp-second product, which is defined as the average current multiplied by the pulse width.
- When the maximum value is reached, the probe goes into saturation and the core is unable to handle the induced flux B.
- The $Z_T I = U$ equation is no longer valid and the peaks of the waveform are not displayed in the oscilloscope.
- The amp-second product evidences the dependence of the core saturation on the frequency. Thus it is important to observe the derating curve in the manufacturers datasheet.





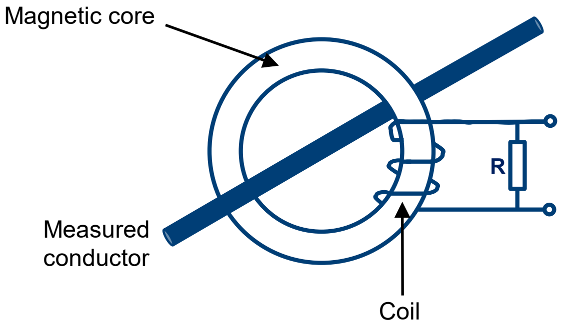
TEMPERATURE

- One of the potential problems when using the clamp-type probes is the damage from self-heating.
- The maximum rated current assumes sine-wave input under standard conditions.
- For frequencies higher than 1 kHz the temperature in the sensor head rises because of the excitation loss that cannot be prevented.
- The temperature also increases when the measured current waveform contains other frequency components

COMMONLY USED PROBES

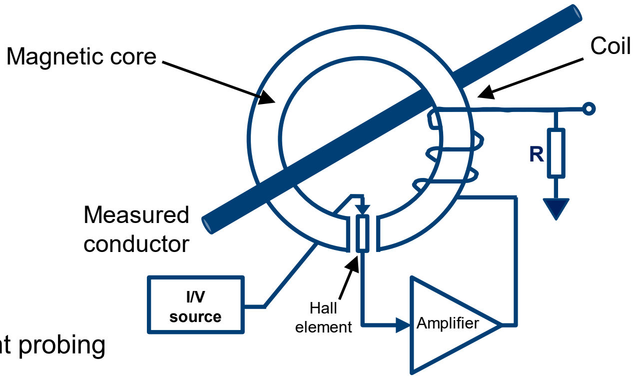
Current transformer

- It produces AC current in the secondary, which is proportional to the current in the primary.
- The number of turns is designed based on the current levels expected to be measured.
- It can only measure AC current.
- CTs reduce currents in a high voltage environment in a way that is safe for measuring equipment.
- Saturation at low frequencies



AC/DC zero flux + Hall element

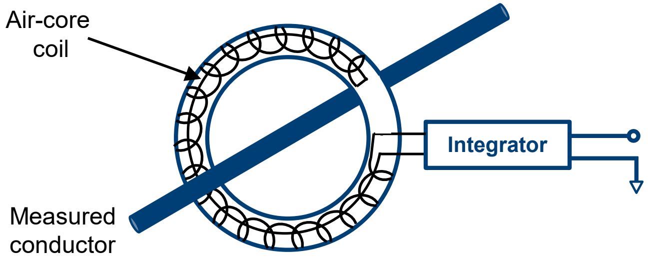
- It combines the CT and hall effect sensors in order to measure AC and DC currents.
- It is characterized by the high sensitivity and low noise.
- Especially designed for oscilloscopes, where small current waveforms must be observed.
- There is an offset drift when the temperature changes.
- High bandwidth: can be greater than 100 MHz.



COMMONLY USED PROBES

Rogowski coil

- This type of sensors do not include a magnetic core, which allows:
  - Low insertion impedance
  - No saturation
  - Lack of heat generation
- Thus, it is suitable for high currents
- It can only measure AC currents
- Bandwidth limited to 50 MHz. The integrator and the length of the cable influence this limit.

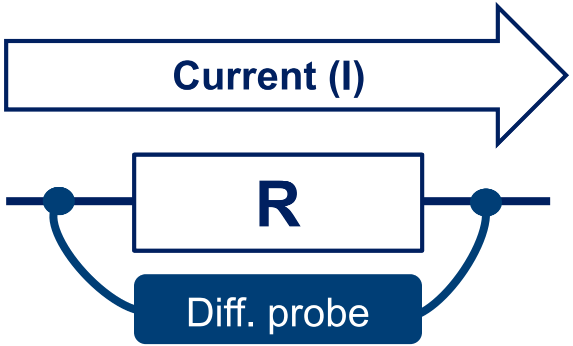


Shunt resistor

- It applies Ohm's law to measure the current.

$$R = \frac{V}{I}$$

- The shunt is a (low-value) resistor that it is connected in series in order to carry the current of interest.
- It can measure AC and DC currents.
- Ideal for SUTs with no clamp accessibility. – but it requires a differential probe



COMMONLY USED PROBES

Sensor	Type	DC?	Bandwidth	Saturation	Position	Intrusive	Current level	Thermal drift?	Precision	Physical principle
Current transformer	Fixed / Clamp	No	< 100 kHz	Yes	Important	Yes	**~ kAmps**	**No**	Average	Faraday's law
Zero flux + Hall	Clamp	Yes	< 120 MHz	Yes	Very important	Yes	< 100 A	Yes	Good	Magnetic field
CT + Fluxgate	Clamp	Yes	< 3 MHz	Yes	Important	Yes	< 1 kA (@ 200 kHz)	**No**	**Excellent**	Magnetic field
Rogowski coil	Clamp	No	< 50 MHz	**No**	Very important	**No**	**< 4 kA**	**No**	Average	Faraday's law
Shunt resistor	Fixed	Yes	**< 1 GHz**	**No**	Does not matter	Yes	< 200 A	Yes	Good	Ohm's law

THANK YOU FOR YOUR ATTENTION

ROHDE & SCHWARZ

Make ideas real