On The Benefits of Floating Electrical Measurement

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Concept and Experimental Evaluation of a Novel DC – 100 MHz Wireless Oscilloscope

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Outline

► Typical Testing of Power Electronics
► State of the Art Isolated Measurement Principles
► New Concept: Wireless Oscilloscope
► Experimental Verification
► Summary
Typical Situation at Testing of Power Electronic Systems

► Measurements during bringing into service of converters

MV grid e.g. 10kV

Converter Cell

AC/DC

AC/DC

AC/DC

AC/DC

DC/DC

DC/DC

DC/AC

Converter Cell

50Hz + Ripple

High dV/dT

Floating potential

Several kHz

► Floating Potential(s)!
  – Up to tens of Kilovolts
  – Up to tens of Kilovolts/Microsecond

► Voltages / Currents
  – Millivolts to Kilovolts
  – Ampères to Kiloampères
  – DC to Tens of Megahertz
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- Typical Testing of Power Electronics
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State of the Art Isolated Voltage Measurement

► Basic Types
  – Differential Probes

  – Optically Isolated Systems
    (analog link / digital link)

► Drawback: Probe Combines Isolation and Measurement
  – Differential probe: strong attenuation of input voltage
  – Optical systems: high bandwidth / data rate real time signal transmission
State of the Art Isolated Voltage Measurement

- Trade-Off: Voltage Isolation vs. Measurement Bandwidth of Commercially Available Measurement Systems
State of the Art Isolated Current Measurement

► **Basic Types**
- Current Transformers
- Current Compensated Transformers (clamp-on current probes)
- Rogowski Coils

► **Drawback: Combination of Isolation and Measurement**
- Parasitics scale with geometrical dimensions
- Large size – high isolation – low bandwidth
State of the Art Isolated Current Measurement

► Trade-Off: Voltage Isolation vs. Measurement Bandwidth of Commercially Available Measurement Systems
State of the Art Isolated Voltage / Current Measurement

**Goal: New Measurement Concept!?!**

- Reaching **no intrinsic isolation voltage**
- Reaching at least **100 MHz bandwidth**
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Wireless Oscilloscope – Basic Idea

► Provide the Isolation at a Different Position in the Measurement Chain
  – Separate data acquisition (channels) and user interface!
  – No need for isolated probes / sensors
  – No need for an additional oscilloscope

► System Overview

**Wireless Oscilloscope**

- Signal processing
- A/D-conversion
- Data storage
- Battery powered

**Graphical User Interface**

- Waveform display
- Configuration by user
- Data export
- Math. functions
Wireless Oscilloscope – Overview

► Isolated Channel(s) and GUI

► Specifications of Prototype

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analog Bandwidth</td>
<td>DC–100 MHz</td>
</tr>
<tr>
<td>Sampling Rate</td>
<td>400 MS/s</td>
</tr>
<tr>
<td>Memory Depth.</td>
<td>200’000 S</td>
</tr>
<tr>
<td>Resolution</td>
<td>8 Bit</td>
</tr>
<tr>
<td>Input Voltage</td>
<td>± 80 mV ... ± 20 V ≥ 800 mV ... ± 200 V (1:10 passive probe) ...</td>
</tr>
<tr>
<td>Input Impedance</td>
<td>1 MΩ</td>
</tr>
<tr>
<td>Input Capacitance, Differential</td>
<td>15 pF</td>
</tr>
<tr>
<td>Input Capacitance, Common Mode</td>
<td>26 pF</td>
</tr>
<tr>
<td>Battery</td>
<td>Li-Ion, Rechargeable</td>
</tr>
<tr>
<td>Battery Runtime (typ.)</td>
<td>&gt; 8 h</td>
</tr>
<tr>
<td>Communication</td>
<td>Bluetooth, Class 1</td>
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<tr>
<td>Trigger</td>
<td>Wireless &amp; Optical</td>
</tr>
<tr>
<td>Physical Dimensions</td>
<td>141 mm x 81 mm x 32 mm</td>
</tr>
<tr>
<td>Weight</td>
<td>350 g</td>
</tr>
</tbody>
</table>
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Analog Bandwidth

► Isolated Channel – Schematic Overview

► Analog Frontend: $f_{-3dB} = 200$ MHz

► Limitation by Sampling Rate
  – 400 MS/s sampling rate
  – Reconstruction of periodic signals with $f_{\text{max}} = 200$ MHz (Nyquist-Shannon)
  – Rule of thumb: $f_{-3dB} \cdot t_{\text{rise}} \approx 0.35$
    Sampling rate limits bandwidth to $f_{-3dB,max} \approx 140$ MHz
Common Mode Rejection @ $f = 200$ kHz

**Measurement Setup**

- **Wireless Scope**
  - $v_M \rightarrow$ PC

- **Differential Probe**
  - $v_{CM}$
  - $i_{CM}$

**Measurement: Differential vs. Wireless**

**Differential Probes (State of the Art)**
- Diff. Probe 1 (25 MHz) $\approx 42$dB
- Diff. Probe 2 (100 MHz) $\approx 54$dB
- Diff. Probe 3 (100 MHz) $\approx 61$dB

**Wireless Oscilloscope**
- Direct Connection $\approx 100$ dB
- 1:1 Passive Probe $\approx 100$ dB
- 1:10 Passive Probe $\approx 80$ dB
Common Mode Rejection @ $f = 200$ kHz

Measurement Setup

Wireless Oscilloscope: Influence of Passive Probe (1:10)

- Passive Probe 1: ≈ 79 dB
- Passive Probe 2: ≈ 80 dB
- Passive Probe 3: ≈ 85 dB
- Passive Probe 4: ≈ 90 dB

Wireless with Different Passive Probes
Isolated Voltage Measurement 1/2

Measurement Setup

- High-Side Gate-Emitter Voltage
  - Small amplitude of ca. ±15 V with respect to the floating load voltage $v_L$ of ca. 0/600 V

Differential Probe 1
- Strong CM error of the measurement during the high $dv/dt$ of the load voltage $v_L$

Wireless Scope
- No visible CM error of the measurement (Miller plateau is flat as expected)
Isolated Voltage Measurement 2/2

**Measurement Setup**

- Shorted Probe Leads on Floating Load Voltage
  - Differential input signal \( = 0 \text{ V} \)
  - Floating load voltage \( v_L \) of ca. \( 0/600 \text{ V} \)

- Error decays only with a time constant of ca. \( 7 \mu\text{s} \)

**Differential Probe 1**
- Strong CM error during \( \text{d}v/\text{d}t \) transients of ca. \( 4 \text{ V} \)
- Error decays only with a time constant of ca. \( 7 \mu\text{s} \)

**Wireless Scope**
- Only very small CM error
- Low noise level
Isolated Current Measurement 1

**Measurement Setup**

- **Shunt & Wireless Scope**
- **Shunt & Differential Probe**

**Load Current on Floating Voltage**

- **0.1 Ohm Coaxial Shunt + Diff. Probe 3**
  - Strong CM error
  - High noise level

- **0.1 Ohm Coaxial Shunt + Wireless Scope**
  - Identical to clamp-on current probe, no errors
Isolated Current Measurement 2 – Overview

► MOSFET Drain Current
  – Floating Reference Voltage
  – High Bandwidth Current Transients (turn-on / turn-off)

► Measurement Setup
  – 0.1 Ohm Shunt & Wireless Scope
  – Current Transformer
  – Rogowski Coil

Shunt & Wireless Scope  Current Transformer  Rogowski Coil
Isolated Current Measurement 2 – Results

► Rogowski Coil
- Delay
- Limited bandwidth
- Ringing due to CM transients
- Limited isolation voltage

► Current Transformer
- High bandwidth
- No apparent CM error
- High-pass characteristic (no DC)
- Limited isolation voltage

► Shunt & Wireless Scope
- High bandwidth
- No apparent CM error
- DC – 100 MHz
- No intrinsic limitation on isolation voltage
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Wireless Oscilloscope – Isolated Measurement

- High Bandwidth (DC – 100 MHz)
- No Intrinsic Limitation on Isolation Voltage

![Diagram of Wireless Oscilloscope with Enertronics WP-A100 model highlighting no intrinsic isolation limitation at 100 MHz bandwidth.](image)
Summary

- **Wireless Oscilloscope**
  - **Isolation**
    - No intrinsic limitation
    - Use non-isolated probes / sensors
  - **Accuracy**
    - High CMRR
    - Low Noise
  - **Handling**
    - Highly secure
    - No cabling needed
  - **Analog Bandwidth**
    - DC – 100 MHz
    - Variable attenuation
    - Variable offset
Summary

► Wireless Oscilloscope

► Isolation
  – No intrinsic limitation
  – Use non-isolated probes / sensors

► Accuracy
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  – Low Noise

► Analog Bandwidth
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References


Questions?