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Alexander Stock

▲ Alexander earned his Masters in Electrical Engineering at the Technical University of Applied Sciences Aschaffenburg and his Doctorate in Engineering focused on Dynamic power measurements in electric motor drive applications.

▲ He recently joined HBK as a Technologist focused on Electric Power Testing.

▲ When he isn't in the lab, he enjoys traveling, endurance sports such as biking and jogging and cooking.

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Understanding Measurement Uncertainty for Electric Drives
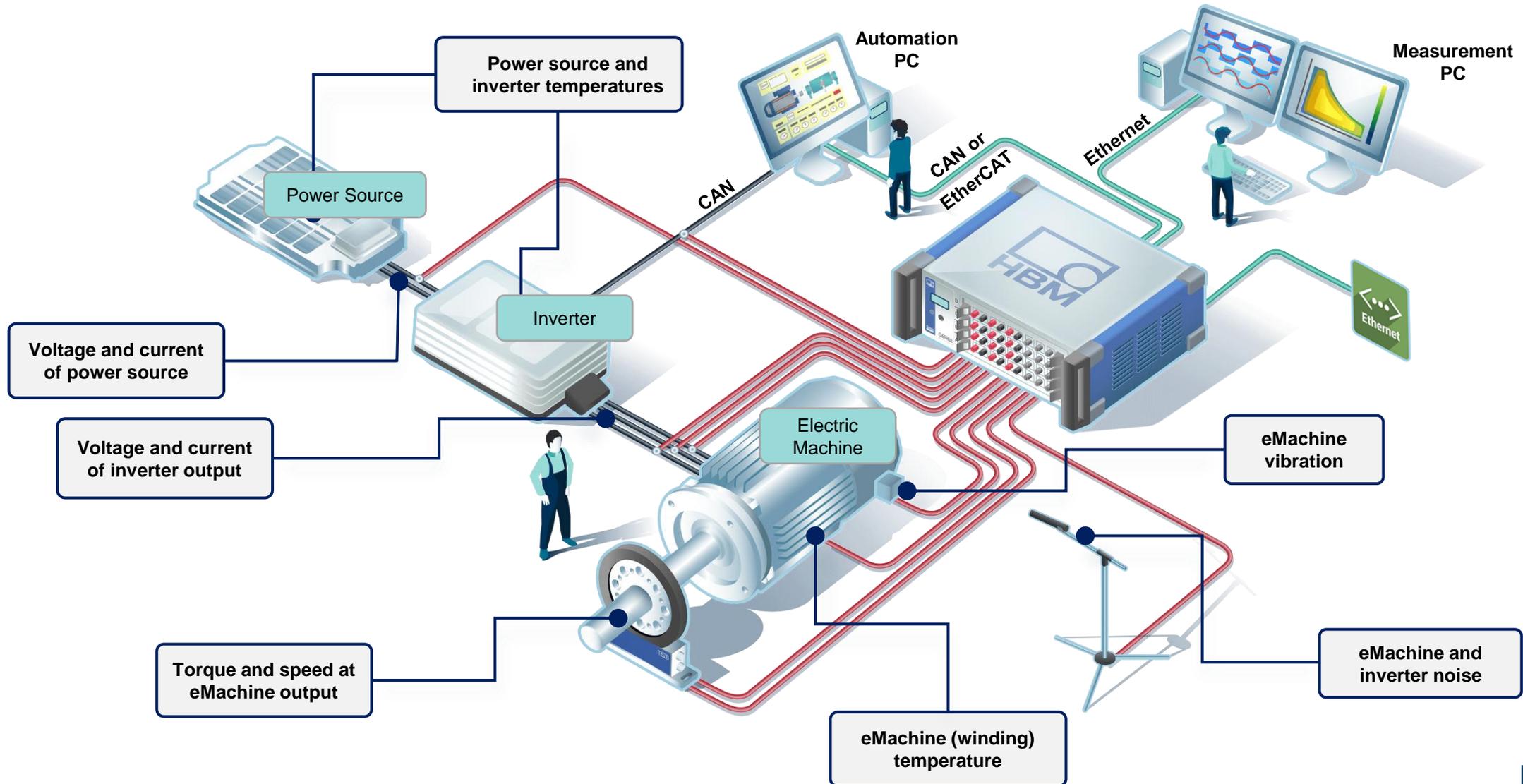
HBK WEBINAR

Dr.-Ing. Alexander Stock

08.03.2022

Contents

1. Measurement on the electric drive train

2. Measurement uncertainty (MU)

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4. MU in dynamic measurement of electric power

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6. Summary & Outlook

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Measurement on electric drive train

Automation PC

Measurement PC

Power source and inverter temperatures

Power Source

CAN

CAN or EtherCAT

Ethernet

Ethernet

HBM

Inverter

Voltage and current of power source

Voltage and current of inverter output

Electric Machine

eMachine vibration

Torque and speed at eMachine output

eMachine (winding) temperature

eMachine and inverter noise

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Technical challenges measuring eDrive systems

Quasi-stationary drives (e.g., industrial drives, such as pumps or fans)

Highly dynamic drives (automotive, robotics)

Start-up process

Fig. reference [4]

Fig. reference [4]

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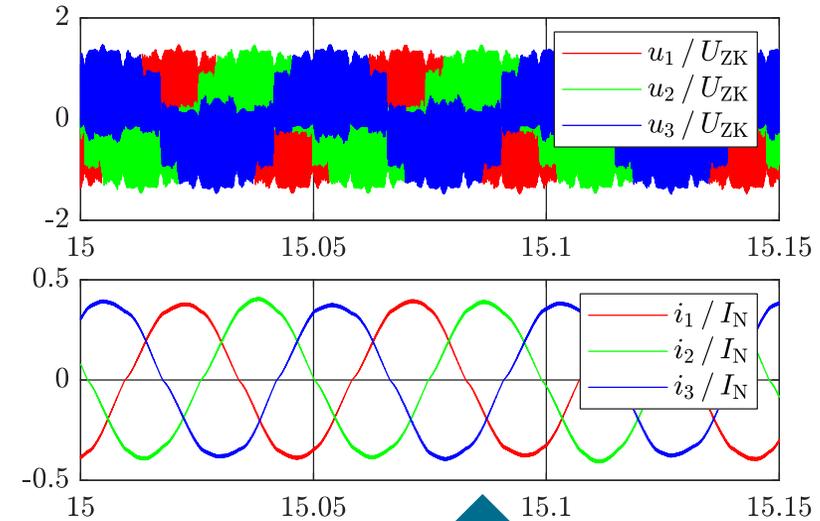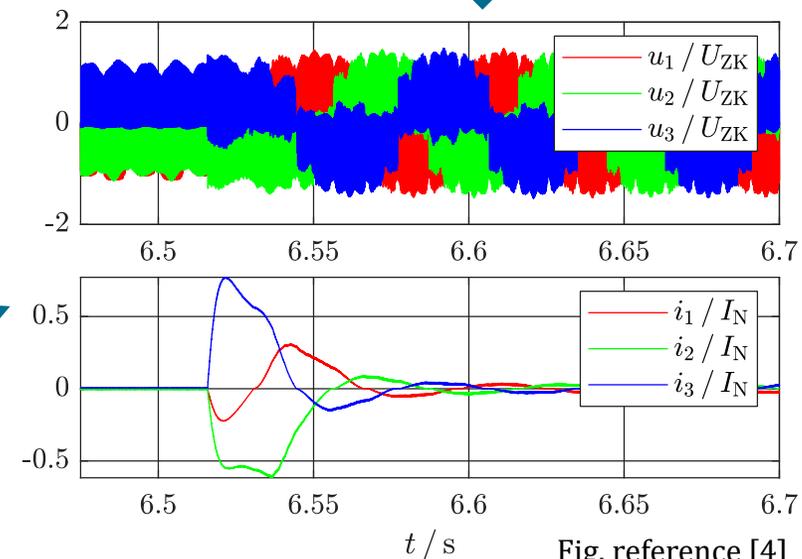
Statements on Measurement Uncertainty

GUM, section 3.1.2 (Basic Concepts):

„In general, the result of a measurement is only an approximation or estimate of the value of the measurand and thus is complete only when accompanied by a statement of the uncertainty of that estimate."

Prof. Werner Richter (University of Leipzig):

Specifying a measurement result without indicating the measurement uncertainty is so uncertain that it is better not to specify at all.

Dave Packard:

"Measurements are always wrong - it's just a matter of how wrong."

Influence and effects of measurement uncertainty (MU)

MU in voltage and current

- All measurands are related to MU

MU in energy/power → efficiency

- MU propagates to calculated quantities

MU in vehicle range

- Lower MU in voltage and current → higher range specification
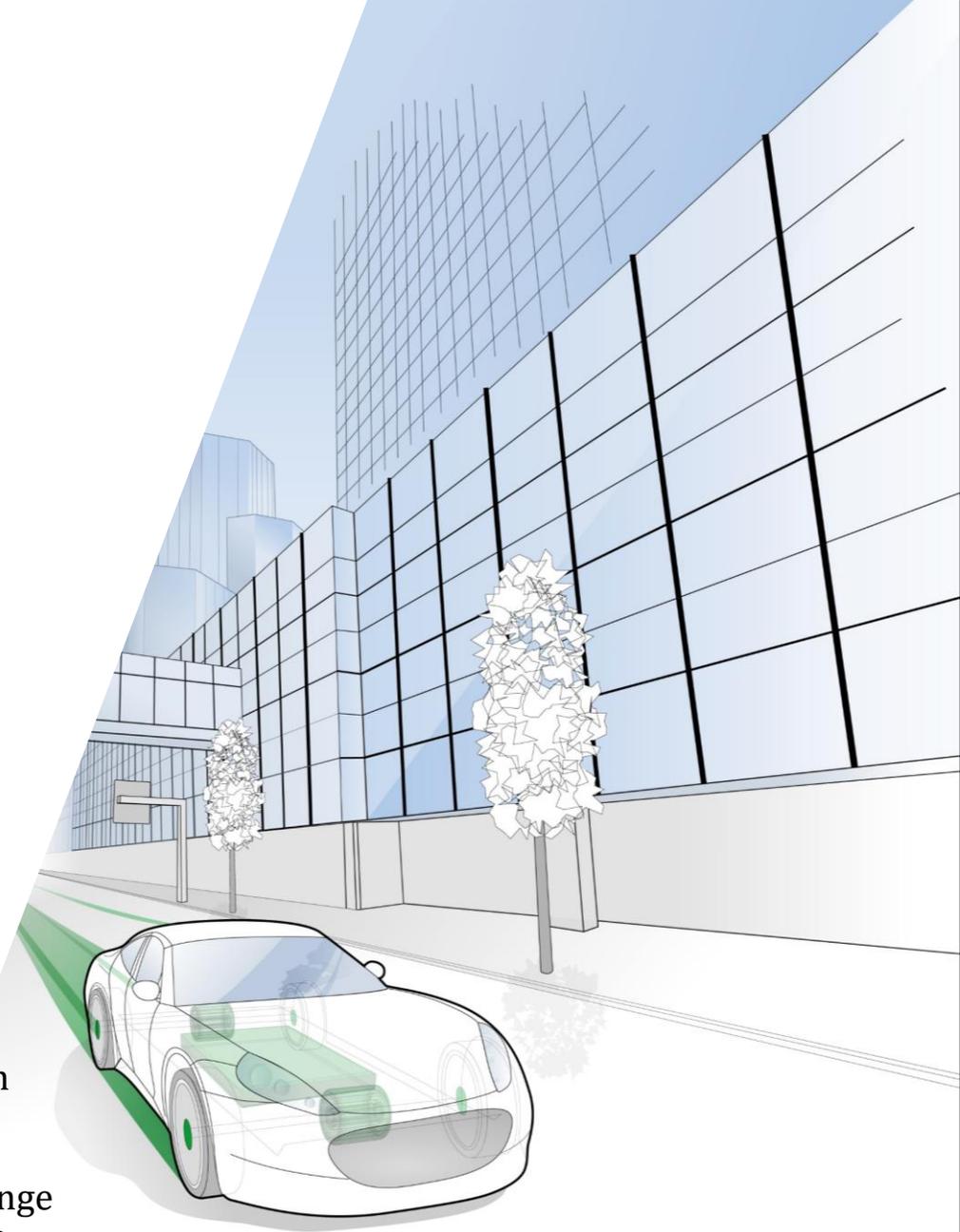
# Systematic and random error effects (influences)

Systematic error effects [3,4]

- Reproducible under equal environmental conditions

- Generally avoidable by compensation
  (calibration)

- Examples:
  incorrectly adjusted measuring device,
  environmental conditions (temperature),
  manufacturing tolerances leading to wrong
 scaling/offset
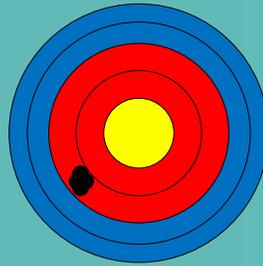
Random error effects [3,4]

- Measured values scatter around the true value
  (even under the same ambient conditions and
  compensated systematic errors)

- Not reproducible → not compensable

- ("Real") randomness of quantum
  mechanical processes, e.g., thermal noise/resistive
  noise

- Apparently random but actually deterministic
  /deterministically chaotic processes whose source is
  only partially known or even completely unknown
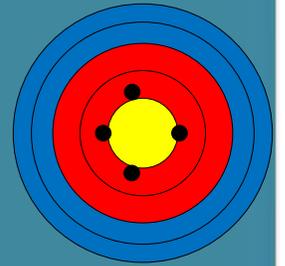
→ Apparently random effects may be transferred to systematic effects through system
knowledge improvement (more detailed model) [3,4].

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Measurement Uncertainty (basic terms)

- Example: standard normal distribution

- Measurement uncertainty instead of measurement error (error is unknown because true value is unknown)

- Compensation of systematic effects

- Random effects result in MU represented by probability distribution

- After compensation of systematic influences, a measured value is in the interval of the specified MU of ±σ with a probability of 68.27%.

- References [1-3]

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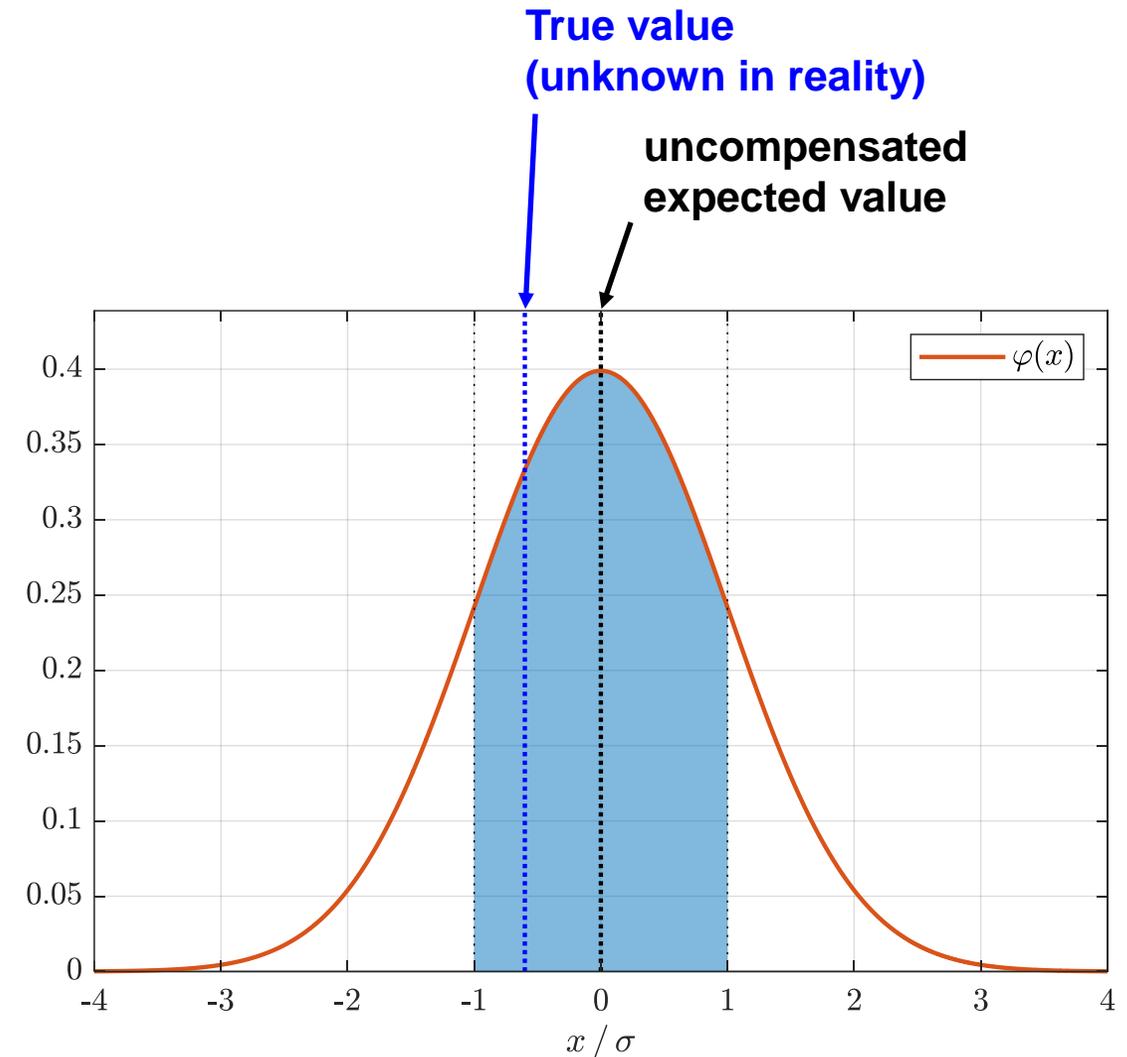
Error propagation

- Maximum measurement error of a variable y as a function of the variables $x_1 \dots x_n$ and their measurement errors $\Delta x_1 \dots \Delta x_n$ [2,3]:

$$\Delta y = \left| \frac{\partial y}{\partial x_1} \cdot \Delta x_1 \right| + \left| \frac{\partial y}{\partial x_2} \cdot \Delta x_2 \right| + \cdots + \left| \frac{\partial y}{\partial x_n} \cdot \Delta x_n \right| = \sum_{k=1}^{n} \left| \frac{\partial y}{\partial x_k} \cdot \Delta x_k \right|$$

- Measurement uncertainty of a variable y as a function of the uncorrelated variables $x_1 \dots x_n$ and their uncertainties $\delta x_1 \dots \delta x_n$ (Gaussian error propagation) [2,3]:

$$\delta y = \sqrt{\left(\frac{\partial y}{\partial x_1} \cdot \delta x_1 \right)^2 + \left(\frac{\partial y}{\partial x_2} \cdot \delta x_2 \right)^2 + \cdots + \left(\frac{\partial y}{\partial x_n} \cdot \delta x_n \right)^2} = \sqrt{\sum_{k=1}^{n} \left(\frac{\partial y}{\partial x_k} \cdot \delta x_k \right)^2}$$

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Measurement uncertainty of DC power measurement (ideal)

- Measurement of the DC current I and the DC voltage U

- Calculation of the DC power (instantaneous power and active power are equivalent and constant)

$$P = U \cdot I$$

- Propagation of the measurement uncertainties of voltage and current to the measurement uncertainty of power

$$\delta P = \sqrt{\left(\frac{\partial P}{\partial U} \cdot \delta U\right)^2 + \left(\frac{\partial P}{\partial I} \cdot \delta I\right)^2} = \sqrt{(I \cdot \delta U)^2 + (U \cdot \delta I)^2} \quad \text{(Absolute MU)}$$

$$\frac{\delta P}{P} = \sqrt{\left(\frac{\delta U}{U}\right)^2 + \left(\frac{\delta I}{I}\right)^2} \quad \text{(Relative MU)}$$

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Measurement uncertainty of power measurement (sinusoidal, ideal)

- Measurement of the sinusoidal AC current $i(t)$ and the sinusoidal AC voltage $u(t)$

- Calculation of the instantaneous power and the active power [5]

$$p(t) = u(t) \cdot i(t) \qquad\qquad P = \overline{p(t)}\Big|_T = \frac{1}{T} \cdot \int_T p(t) \, \mathrm{d}t = U \cdot I \cdot \cos(\varphi)$$

U, I: RMS values of voltage & current

φ: phase shift angle between voltage & current

- Measurement uncertainty of active power

$$\delta P = \delta P = \sqrt{\left(\frac{\partial P}{\partial U} \cdot \delta U\right)^2 + \left(\frac{\partial P}{\partial I} \cdot \delta I\right)^2 + \left(\frac{\partial P}{\partial \varphi} \cdot \delta \varphi\right)^2} = \sqrt{(I \cdot \cos(\varphi) \cdot \delta U)^2 + (U \cdot \cos(\varphi) \cdot \delta I)^2 + (U \cdot I \cdot \sin(\varphi) \cdot \delta \varphi)^2}$$

$$\frac{\delta P}{P} = \sqrt{\left(\frac{\delta U}{U}\right)^2 + \left(\frac{\delta I}{I}\right)^2 + (\tan(\varphi) \cdot \delta \varphi)^2} \qquad \text{(Relative MU)}$$

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Measurement uncertainty of power measurement (arbitrary waveforms)

◢ Applying the Gaussian error propagation to $P = \frac{1}{T} \cdot \int_T p(t)\,\mathrm{d}t$ is an analytical challenge

◢ Practical implementation of active power calculation on measuring devices is discrete anyway

$$P = \frac{1}{N} \cdot \sum_{k=1}^{N} u_k \cdot i_k$$

◢ Max. Measurement error [4,6]: $\quad \Delta P = \frac{1}{N} \cdot \sum_{k=1}^{N} |i_k \cdot \Delta u_k| + \frac{1}{N} \cdot \sum_{k=1}^{N} |u_k \cdot \Delta i_k|$

◢ MU [4,6]: $\quad \delta P = \sqrt{\frac{1}{N^2} \cdot \left(\sum_{k=1}^{N} \left(i_k \cdot \delta_{u_k}\right)^2 + \sum_{k=1}^{N} \left(u_k \cdot \delta_{i_k}\right)^2 \right)}$

◢ Suitable method for dynamic processes/transients

◢ Bandwidth must be considered in addition to the error propagation when estimating the MU

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Challenges in error propagation

◣ Each individual **active power value is calculated from N samples** of voltage & current $P = \frac{1}{N} \cdot \sum_{k=1}^{N} u_k \cdot i_k$

◣ **Each sample contains a certain MU**, which is then propagated to calculated quantities, such as active power

◣ **Systematic errors** (uncalibrated sensor) have the **same effect on every sample value** (e.g., manufacturing tolerances of circuit components of the input amplifier)

   → **Error is not reduced** by extending the averaging interval by means of **increasing the number of samples** N used for averaging

◣ **Random errors** (e.g., thermal noise) **can cancel out/neutralize** each other by averaging

   → Measurement errors are reduced by an increased number N of values used for averaging (ideal DC case: factor $^1/_{\sqrt{N}}$)

◣ **Interpretation and categorization of data sheet** information

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Evaluation of data sheet information

- **MU of a quantity** (e.g., current) depends on the **MU of individual sensors** in the respective measuring chain (current transformer, burden resistor, measuring amplifier, etc.)

- **MU of each sensor** may depend on different, separately specified **influencing effects** (such as temperature, aging, etc.)

- **Individual influencing effects** are either specified in **absolute values, or relatively** with respect to the measured value or the full-scale value/measuring range

- The total measurement uncertainty of a measurand results from the squared superposition of the individual specifications:

$$\delta I = \sqrt{\sum_j (\delta I_{\mathrm{m},j} \cdot I)^2 + \sum_k (\delta I_{\mathrm{r},k} \cdot I_r)^2 + \sum_l \delta I_{\mathrm{off},l}^2}$$ (for sinusoidal quantities or DC quantities)

depending on the measured value | depending on the measuring range | absolute offset

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Measurement Uncertainty Tool

Metrological analysis of the dynamic measurement uncertainty

◣ Design of two galvanically isolated full bridge circuits in SiC technology
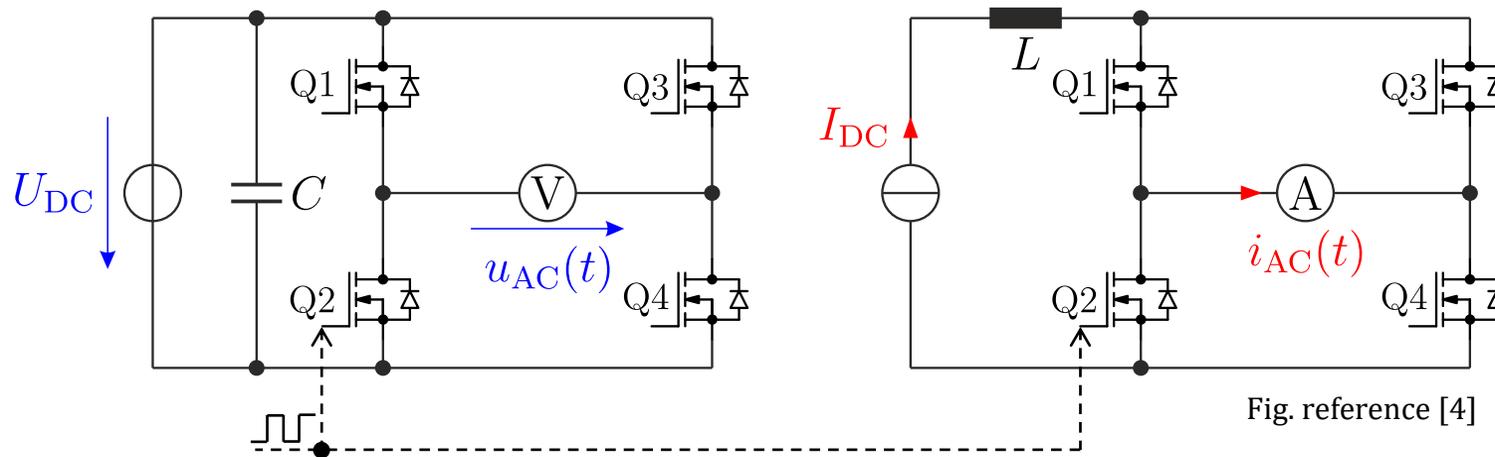
cooperation with THAB
Prof. Dr.-Ing. Johannes Teigelkötter

Fig. reference [4]

◣ Synchronized control (PWM), maximum offset time of 25ns

◣ Generation of nearly ideal rectangular voltages and currents

◣ Calculation and comparison of "virtual" DC power and AC power ("virtual", since voltage and current are generated separately → the power does not physically occur)

◣ Without phase shift, DC and AC power are expected to be equal (ideal case)

Measurement of signals with oscilloscope

▲ Switching time approx. 50 ns

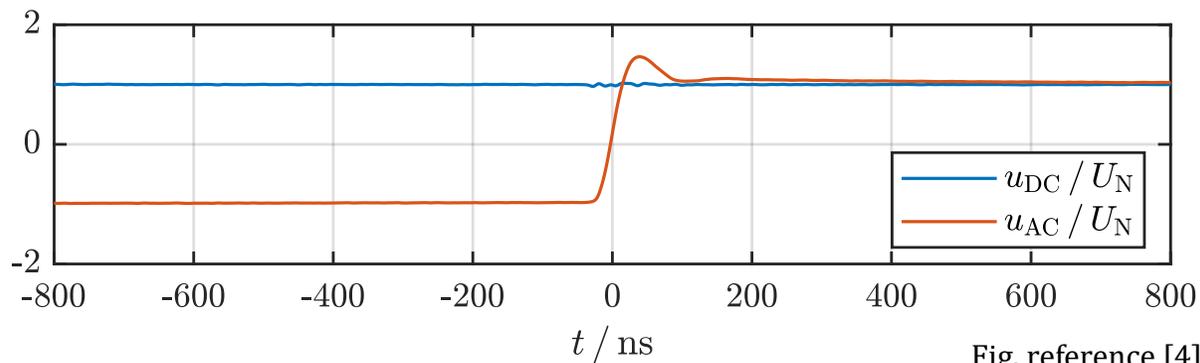→ Suitability for the comparison of power meters with typical sampling frequencies from 1 MHz to 10 MHz
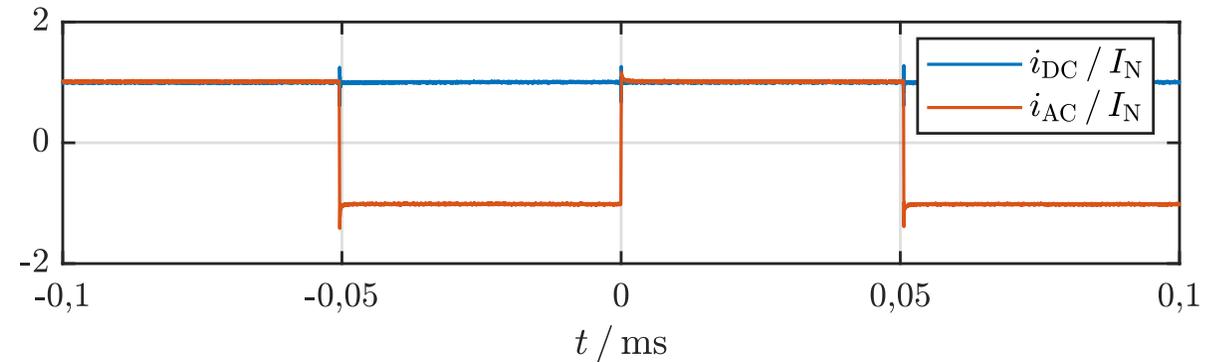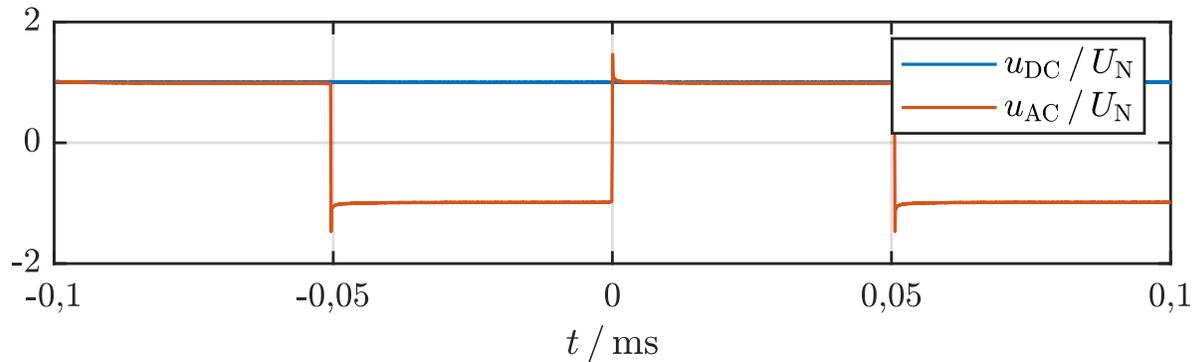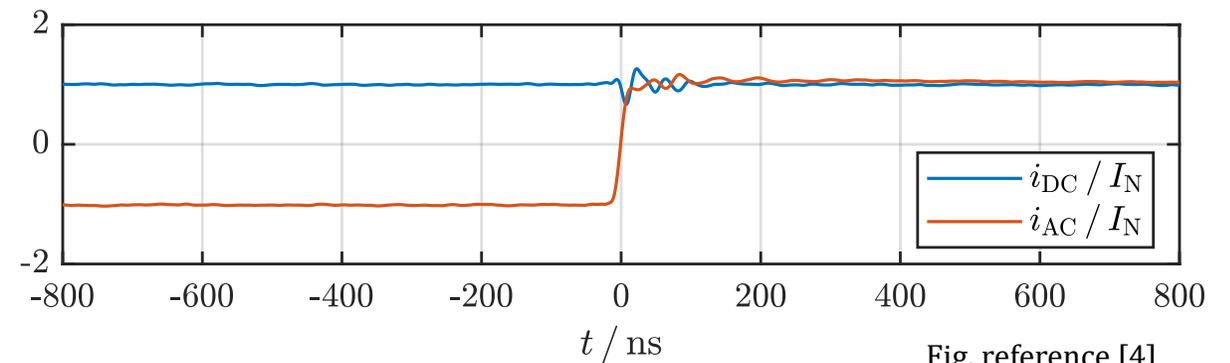

Fig. reference [4]

Fig. reference [4]

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Summary

- Challenges in measurements on the powertrain

  - **time-synchronous** acquisition of **various physical quantities**

  - fundamental **cycle-based parameters** and **instantaneous values** (raw data)

- All **measured quantities** contain a certain **measurement uncertainty (MU)**

- **Analytical approach** of MU estimation for **DC quantities** and **sinusoidal** quantities well-known, see [1]

- **Analytical error propagation** approach for **arbitrary dynamic signals** is a challenge
  → solution based on discrete samples introduced

- **Hardware-based methods** for verifying the **dynamic measurement uncertainty**

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Thank You

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