EMRP
European Metrology Research Programme
Programme of EURAMET
The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union

# Methods for characterization and correction of transducer response in presence of actual MV distorted waveforms

G. Crotti, D. Giordano,
M. Modarres, M. Zucca
Istituto Nazionale di Ricerca Metrologica
Torino, Italy

D. Gallo, C. Landi, M. Luiso
Department of Information Engineering,
Second University of Napoli,
Aversa, Italy

Joint Workshop *Grid Sens and Smart Grid II*, Glasgow (UK), 3rd February 2016

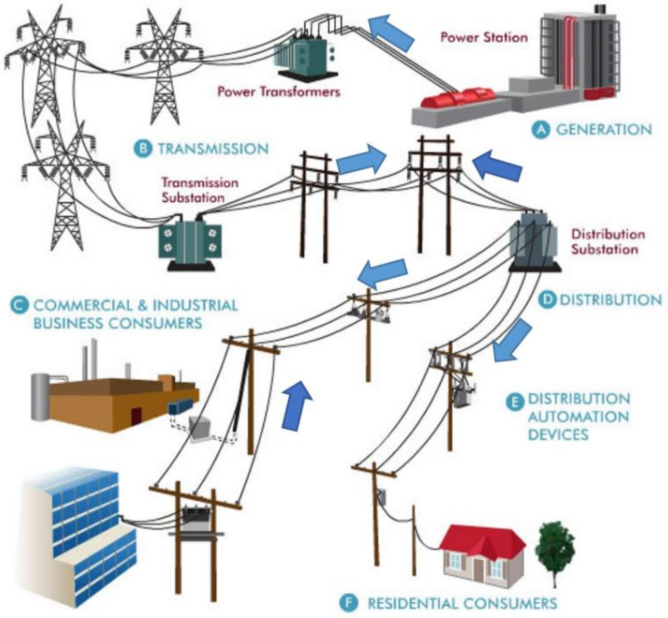
# Outline

- ✓ Rationale and scope
- ✓ Circuits for frequency response characterization of MV voltage measurement transformer
- ✓ Method for the real-time compensation of voltage transducer frequency response
- ✓ Experimental validation
- ○ Discussion and conclusions

# Motivation

**Use of power electronic devices and DG from renewable is modifying the transmission and distribution grid conditions with reference both to power flow and its quality**

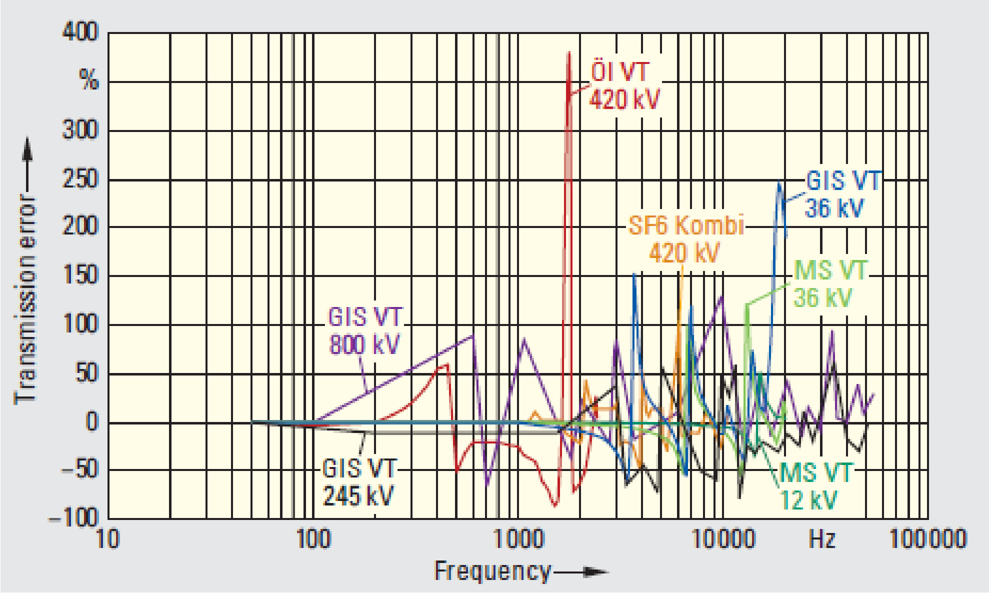
T



- ✓ **Information from PMUs and knowledge of the quality of the transferred power play a basic role in ensuring accurate evaluation of grid state**

# Motivation

- ✓ **Used instrument transformers do not always accurately scale and input to the PMU/PQ measuring instrument the voltage/current levels**



K. Kunde at al., Components & Periphery 3 Heft 6/2012, ETZ

- ✓ **Need for the use of most accurate, extended performances transducers with reference to the on-site measurement conditions.**

# Smart Grid II…

- ✓ Optimization of performances of non-invasive current transducers
- ✓ Voltage transformers (VTs) calibration systems for determining frequency response at rated voltage
- ✓ Methods for real time compensation of voltage transducer frequency response
- ✓ Modelling for the uncertainty propagation through the PMU/PQ measurement chain

# Calibration set-up requirements

**Generation of realistic distorted voltages (fundamental at rated voltage with superimposed harmonics/interharmonics/subharmonics,…).**

**Operating frequency range:**

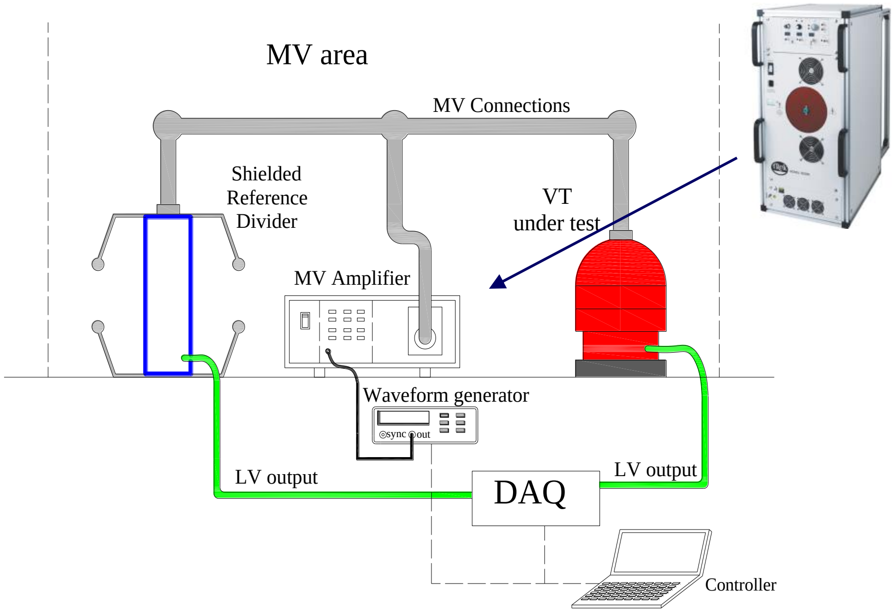
**up to the 50th harmonic (minimum requirement)**

**Traceable measurement of ratio and phase errors**

**Uncertainty: two orders of magnitude better the indicated accuracy limits for VTs in PQ measurements (IEC 60044-8)**

# Calibration circuit layout:

## i) Comparison with a reference voltage transducer



**Supply:**

**Arbitrary Waveform Generator**

**+ MV Amplifier**

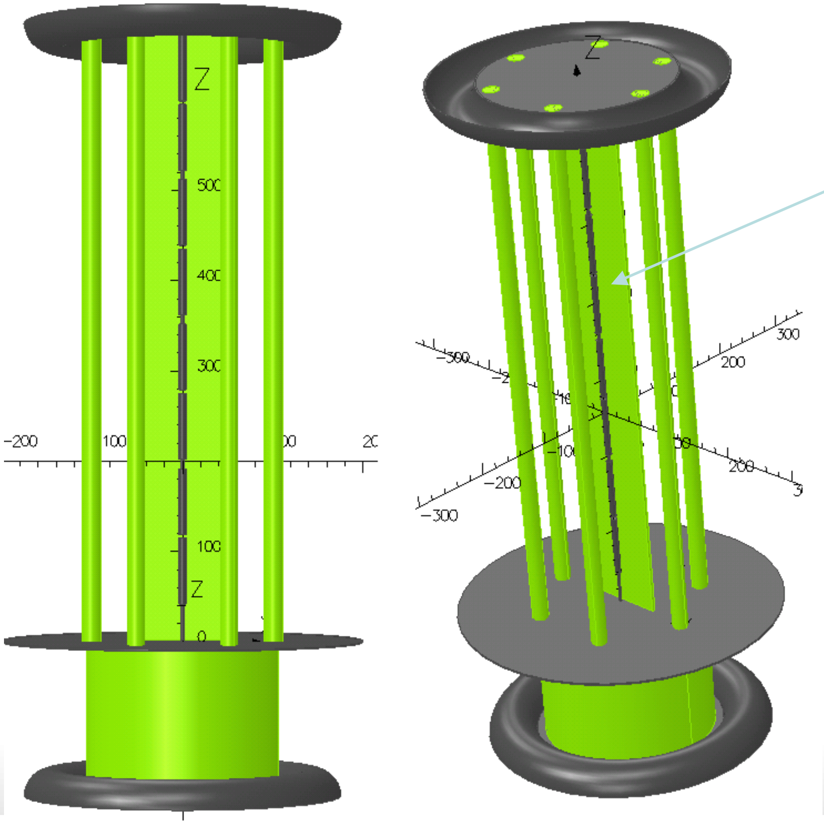
**(+ step-up transformer)**

**Measurement:**

**Reference divider**

**DAQ system (Agilent 3458/NI)**

# 30 kV Compensated reference resistive divider



**DC to 30 kHz**

**Ratio error variation $<2\cdot10^{-4}$**

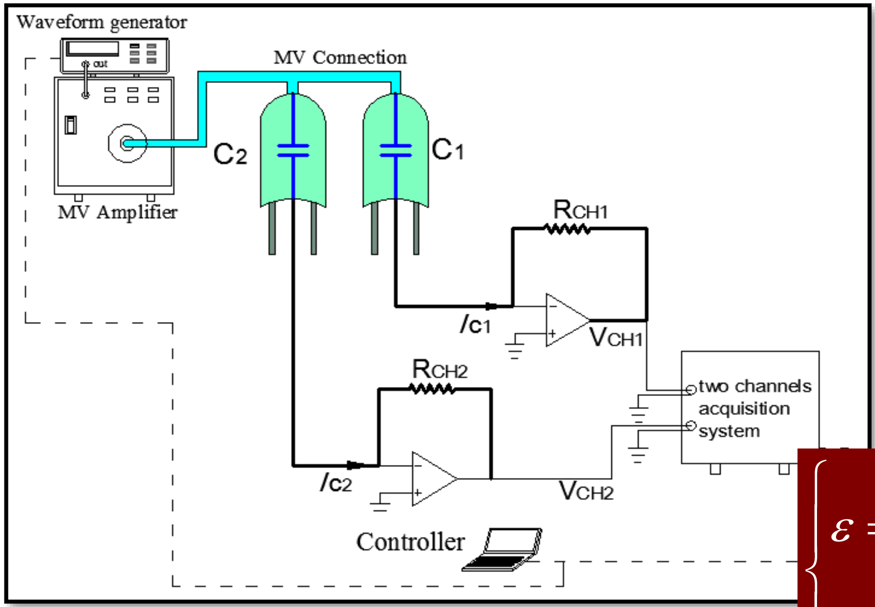
**Phase error $<110\ \mu$rad**

**(with compensation stage)**

# Calibration circuit layout:

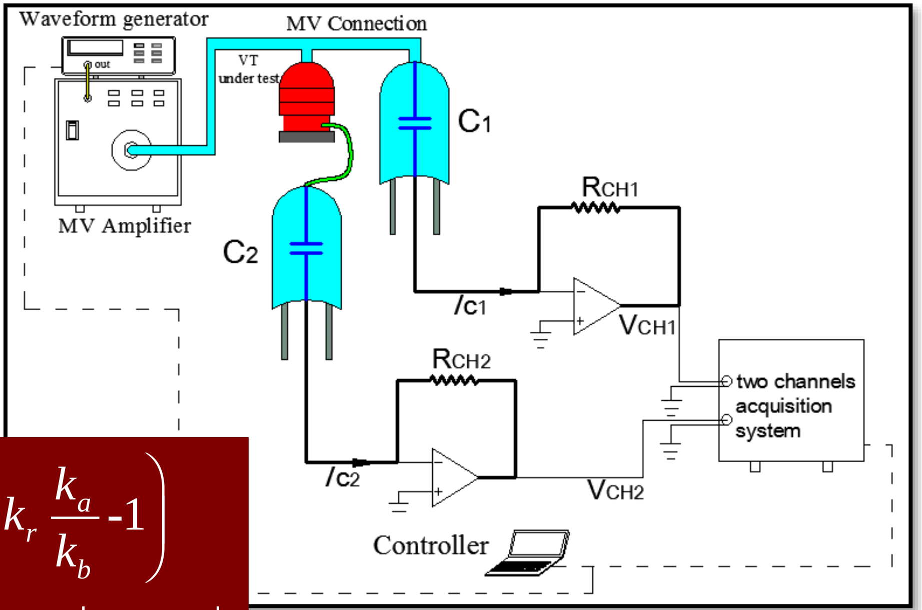
## ii) Calibration by HV capacitance bridge

- First step (a)



Output:
$$\begin{cases} k_a = \dfrac{|V_{CH1}|}{|V_{CH2}|} \\ \Delta\varphi\big|_a = \varphi(V_{CH2}) - \varphi(V_{CH1}) \end{cases}$$

- Second step (b)



Output:
$$\begin{cases} k_b = \dfrac{|V_{CH1}|}{|V_{CH2}|} \\ \Delta\varphi\big|_b = \varphi(V_{CH2}) - \varphi(V_{CH1}) \end{cases}$$

$$\begin{cases} \varepsilon = \left( k_r \dfrac{k_a}{k_b} - 1 \right) \\ \Delta\eta = \Delta\varphi\big|_b - \Delta\varphi\big|_a \end{cases}$$

# *Uncertainty component analysis*

**Ideal conditions:**

**Supply voltage linearity of $C_2$ and $R_{CH2}$ under step a) and b) conditions**

**No loading effect of C2 on the VT under calibration**

⇩

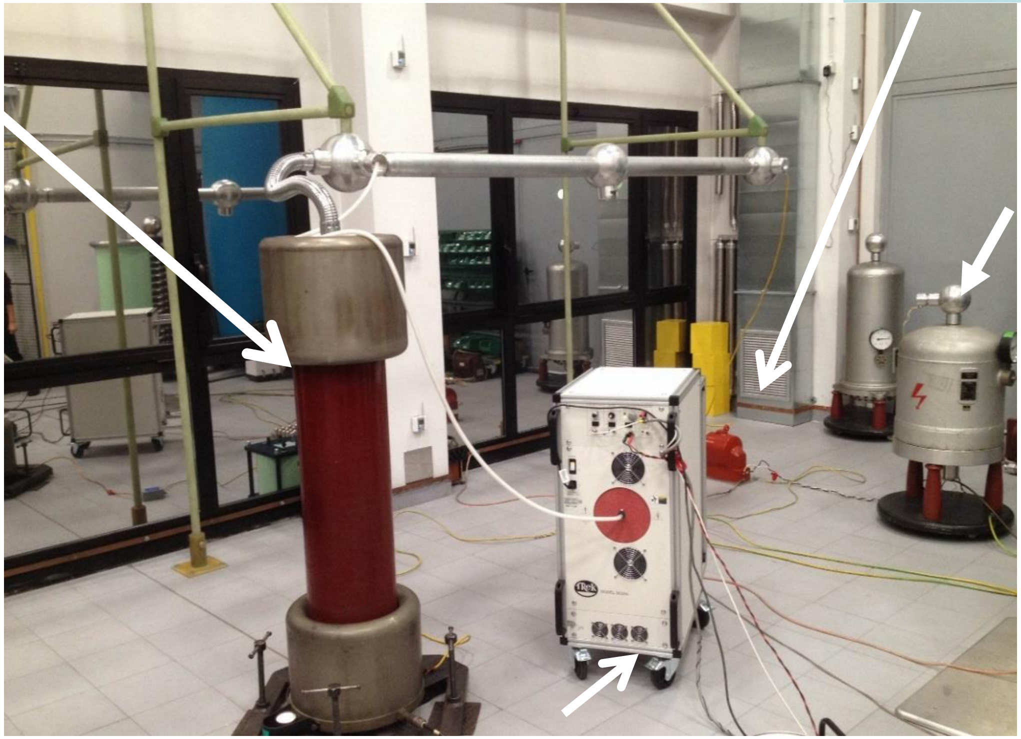
$$G_{VT}(f)\cdot e^{i\varphi_{VT}(f)} = \frac{(V_{CH1}/V_{CH2})_a}{(V_{CH1}/V_{CH2})_b}$$

| Quantity/ influence factor | Standard Uncertainty | Evaluation method |
|---|---|---|
| C2 non linearity<br>(up to 40 kV, 50 Hz):<br>Capacitance<br>Dissipation factor | $< 2\cdot10^{-5}$<br>< 1 µrad | Comparison with a 700 kV capacitor |
| C2 loading effect<br>( 50 Hz to 2.5 kHz):<br>ratio error<br>phase errror | neglible up to 1 kHz<br>400 µV/V at 2.5 kHz<br>< 10 µrad | Computation and measurements on a 20 kV/100 V VT |
| Digitizer ($V_{CH1}=V_{CH2}$)<br>(50 Hz to 3 kHz)<br>Ratio error:<br>Phase error: | 20 ppm to 40 ppm<br>2 µrad to 30 µrad | Generation of known signals |
| Digitizer ($V_{CH1}=100\cdot V_{CH2}$)<br>(50 Hz to 3 kHz)<br>Ratio error:<br>Phase error: | 30 ppm to 100 ppm<br>4 µrad to 100 µrad | Generation of known signals of different amplitudes |

# Calibration of a 20 kV/√3 VT

**VT under test**

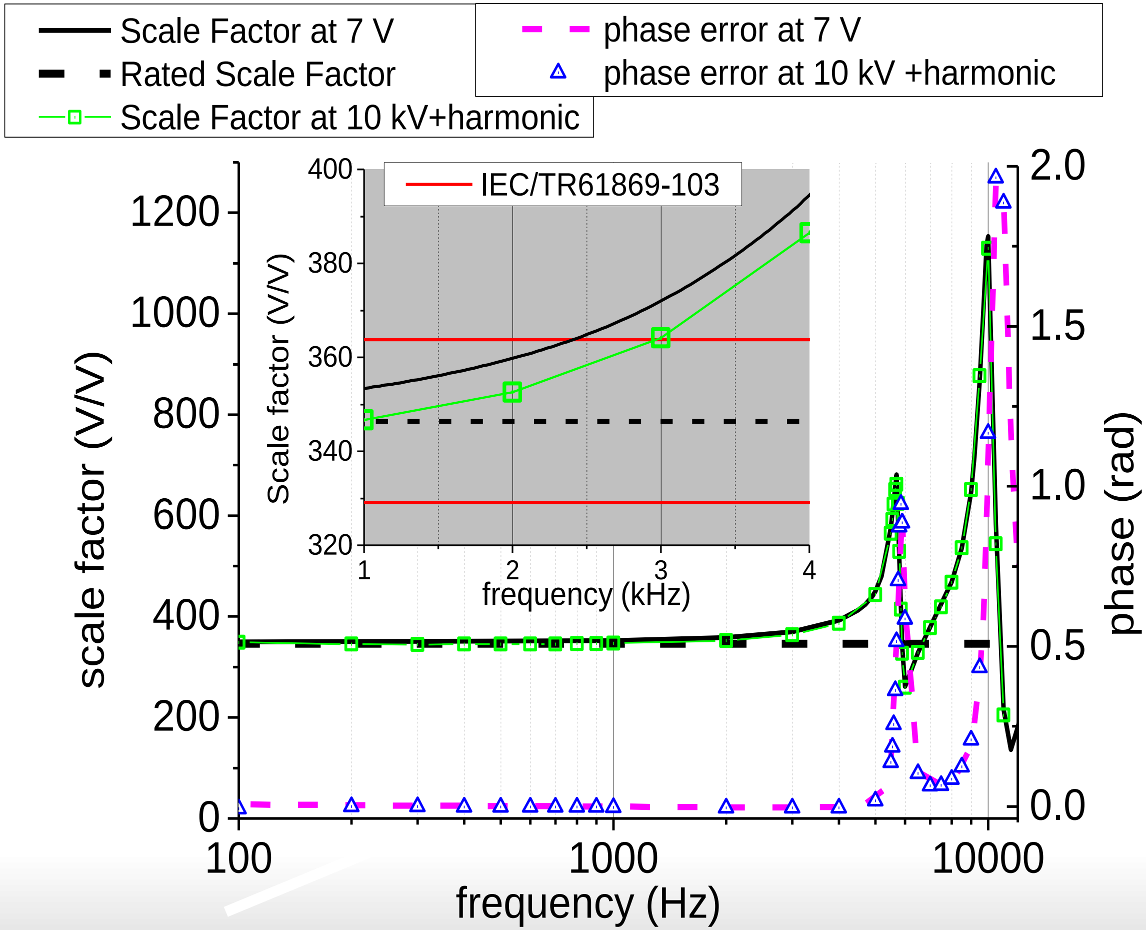
**Compressed gas capacitor $C_1$**
Max voltage: 200 kV
$C_1$: 103.54 pF
tan$\delta$: $1 \cdot 10^{-5}$



**Compressed gas capacitor $C_2$**
Max voltage: 60 kV
$C_2$: 1.0467 nF
tan$\delta$: $1 \cdot 10^{-5}$

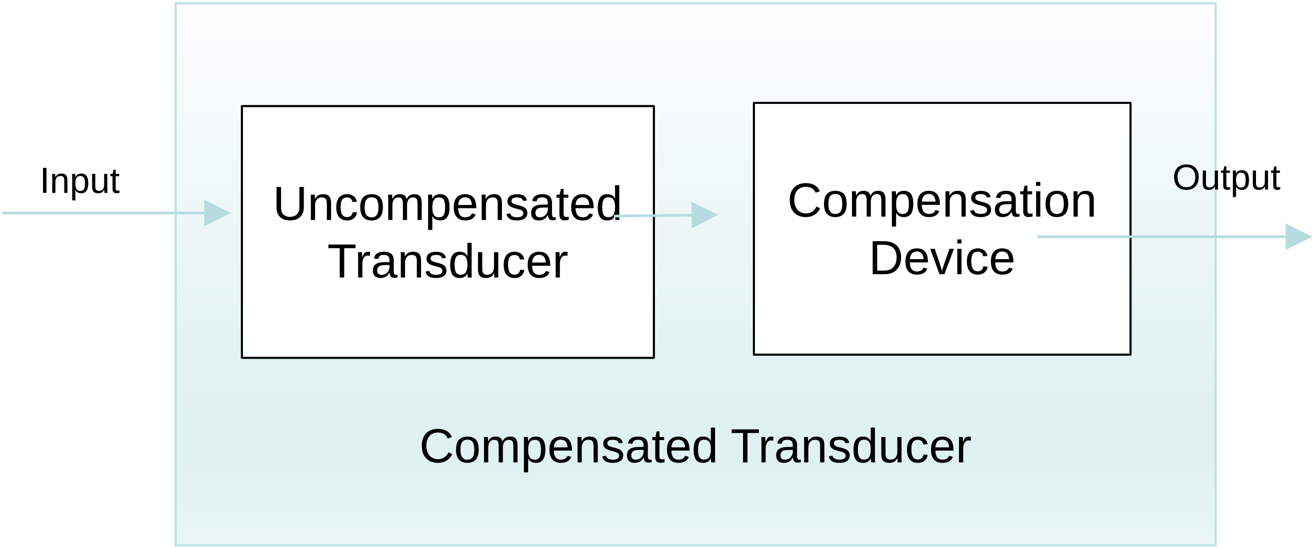
**MV amplifier (30 $kV_p$, 20 mA)**

# Frequency response of a 20 kV/√3/100 V VT



# Transducer error compensation

Once errors are known, they can be corrected cascading to the transducer a compensation device



Input

Uncompensated Transducer

Compensation Device

Output

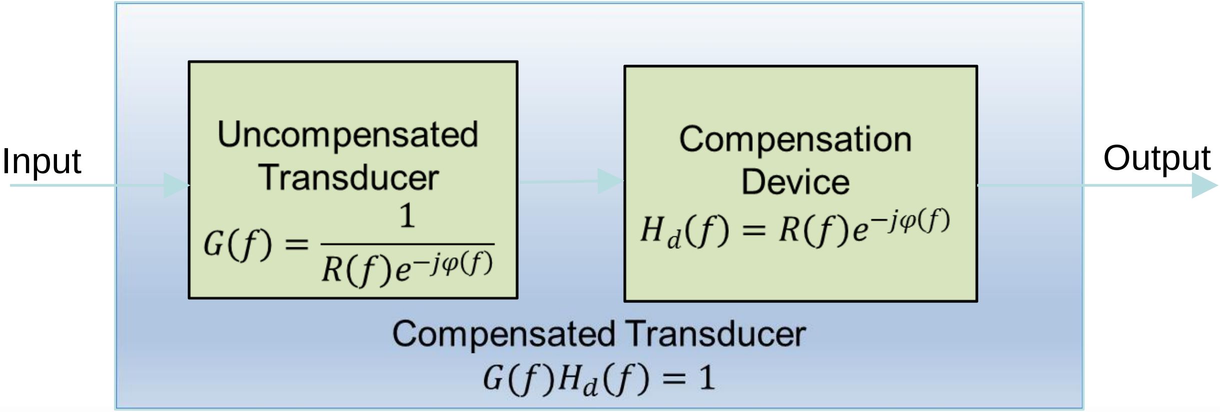
Compensated Transducer

# Working hypotheses for of compensation of VTs and CTs

## ➢ Linearity of transducer

**Voltage measurement transformer assumed linear from 80% to 120% of rated voltage and with high impedance load.**

**…the compensation device should implement transducer inverse frequency response!**



Input

Uncompensated Transducer

$$G(f) = \frac{1}{R(f)e^{-j\varphi(f)}}$$

Compensation Device

$$H_d(f) = R(f)e^{-j\varphi(f)}$$

Output

Compensated Transducer

$$G(f)H_d(f) = 1$$

# Compensation through a filter

- Analog implementation drawbacks
  - acceptable results only on a very limited range of frequencies
  - inherent variability of the physical components (resistors, inductors, and capacitors)
  - rigidity of the compensator that is not reconfigurable except by replacement of hardware components, preventing the possibility of real-time changes (non-adaptive filters)
- Digital implementation drawbacks
  - time discretization of the input variables;
  - numerical quantization, that is amplitude discretization of the input variables;
  - delay of execution

# Filter function identification

1) **Measurement of the transducer frequency response in $N_f$ points ($H_\mathrm{d}(f_\mathrm{i})=V_{LV}(f_i)/V_{HV}(f_i)$)**

2) **Modelling of an infinite impulse response filter (IIR), as a product of *N* Second Order Sections:**

$$H\left(z\right)=K\prod_{k=1}^{N}\frac{1+b_{1,k}z^{-1}+b_{2,k}z^{-2}}{1+a_{1,k}z^{-1}+a_{2,k}z^{-2}}$$

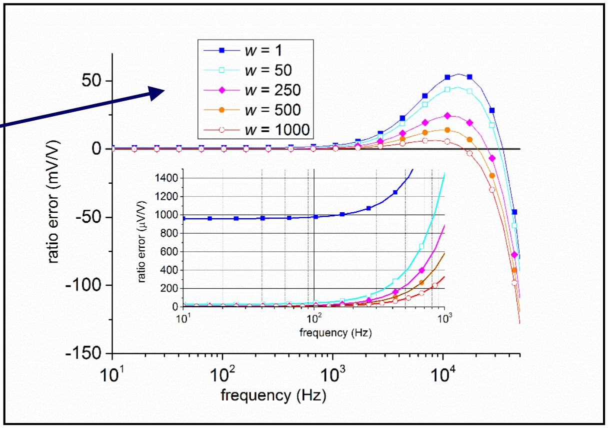
3) **Identification of the 4·N+1 filter coefficients (P), by minimizing the objective function C(P):**

$$C\left(\mathbf{P}\right)=\frac{1}{2}\sum_{i=1}^{M}W\left(f_i\right)\cdot\left[\log_{10}\frac{H\left(f_i,\mathbf{P}\right)}{H_d\left(f_i\right)}\right]^2\cdot\left[\log_{10}\frac{f_{i+1}}{f_{i-1}}\right]$$

**$W(f_\mathrm{i})$=weight**

# Settings of the optimization algorithm

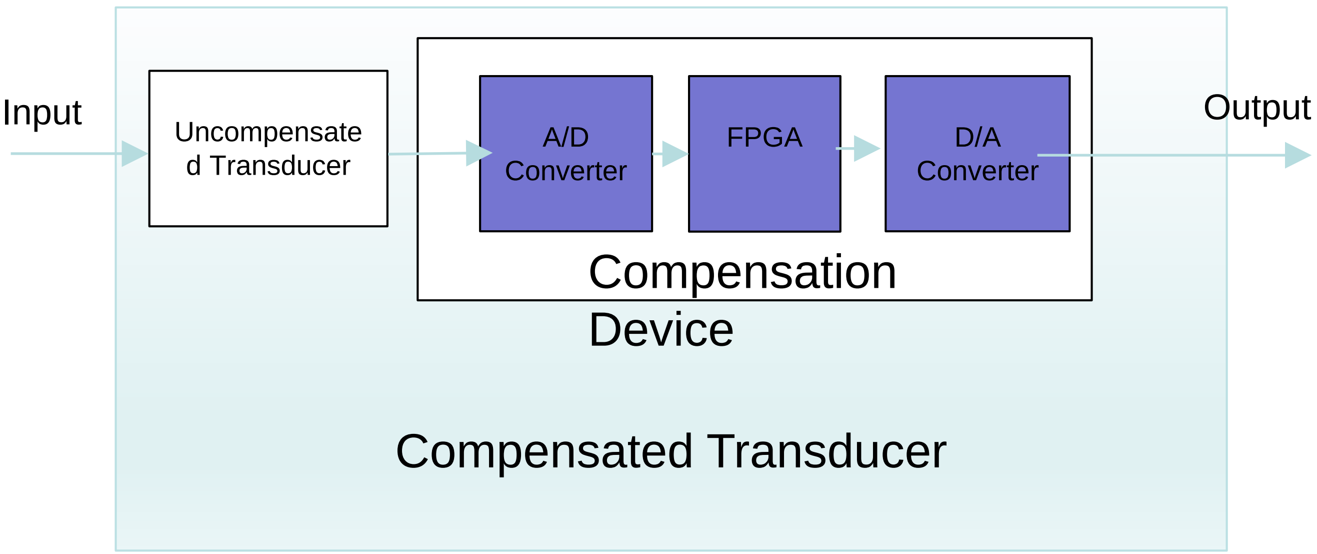
1. **Choose the weights of the objective function**
    - Weights have influence on the algorithm performance
2. **Choose a range for number of SOS (e.g. 1 to 10)**
    - Typically, higher filter orders reach better compensation performance but higher order means <u>slower convergence</u> of the optimization algorithm and <u>higher computational burden</u> for real-time filter execution
3. **Choose a number of iterations for every SOS**
    - Since the algorithm has a stochastic section, two identical runs give different results
4. **Choose performance indexes to evaluate results of optimization algorithms**



$$I_R = \frac{\overline{\Delta R^2}}{\overline{\Delta R_C}^2} = \frac{\sqrt{\frac{1}{N_f}\sum_{k=1}^{N_f}[\Delta R(f_k)]^2}}{\sqrt{\frac{1}{N_f}\sum_{k=1}^{N_f}[\Delta R_C(f_k)]^2}}$$

$$I_\varphi = \frac{\overline{\Delta\varphi^2}}{\overline{\Delta\varphi_c}^2} = \frac{\sqrt{\frac{1}{N_f}\sum_{k=1}^{N_f}[\Delta\varphi(f_k)]^2}}{\sqrt{\frac{1}{N_f}\sum_{k=1}^{N_f}[\Delta\varphi_c(f_k)]^2}}$$

# Compensation with Real-Time Digital Signal Processing



Input

Uncompensated Transducer

A/D Converter

FPGA

D/A Converter

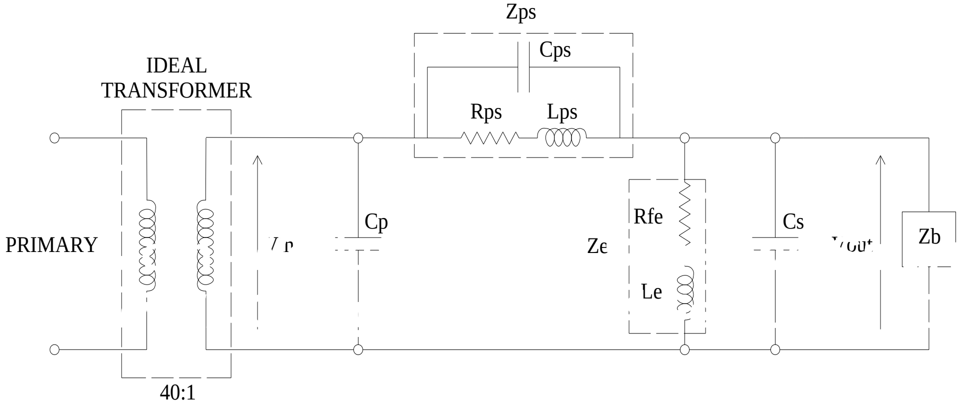
Output

Compensation Device

Compensated Transducer

FPGA implements the **DIGITAL FILTER**

# Model of a Voltage Measurement Transformer

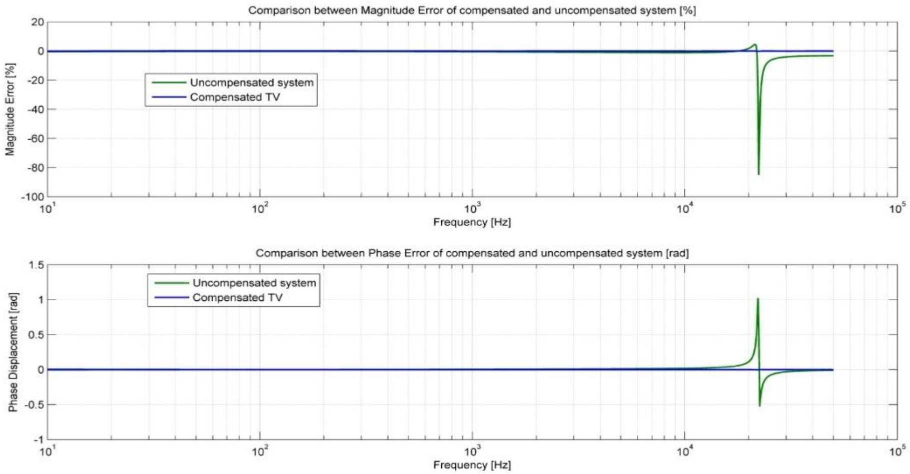


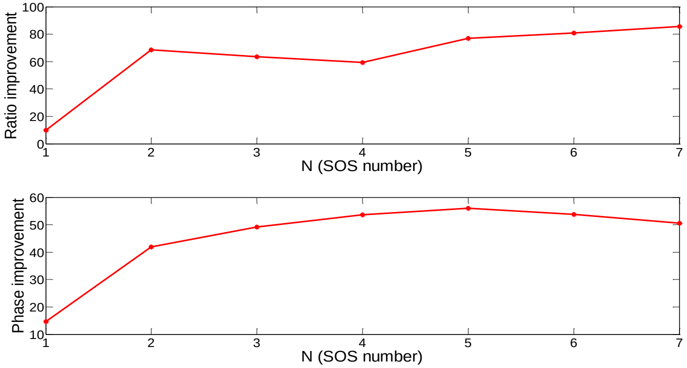
**VT ratings**: 4800 V primary, 40:1 turns ratio, ANSI accuracy class 0.3, 120 V secondary output rated frequency 60 Hz.

**Circuit parameters**: $C_P = 160\ \text{nF}$, $R_{ps} = 1\ \Omega$, $L_{ps} = 1.7\ \text{mH}$, $C_{ps} = 30\ \text{nF}$, $R_{fe} = 35\sqrt{f}\ \Omega$, $L_e = \frac{5.6}{\sqrt{f}}\ \text{mH}$, $C_s = 1\ \text{nF}$, $Zb = 1\ \text{M}\Omega$.

# Compensation of simulated VT response

**weights: f<100 Hz w=5000    100Hz<f<2500Hz  w=2000    f>2500Hz   w=1000 Hz**





| freq [Hz] | Ratio error [%] |  | Phase displacement [mrad] |  |
|---|---|---|---|---|
|  | Comp | Uncomp | Comp | Uncomp |
| 50 | 0,0613 | -0,3072 | 1,1639 | -0,9456 |
| 100 | 0,0754 | -0,2939 | 0,3522 | 0,0824 |
| 1000 | -0,0747 | -0,5217 | -0,2232 | 4,3203 |
| 10000 | 0,0505 | -1,1063 | -0,5056 | 18,7441 |
| 20000 | 0,0293 | 1,7130 | -1,0460 | 111,1353 |
| 22275 | -0,9256 | -84,9464 | -6,7732 | 557,7878 |
| 50000 | -0,0621 | -3,2076 | 1,2385 | -8,2199 |

# Application to the compensation of a 1 kV VT response

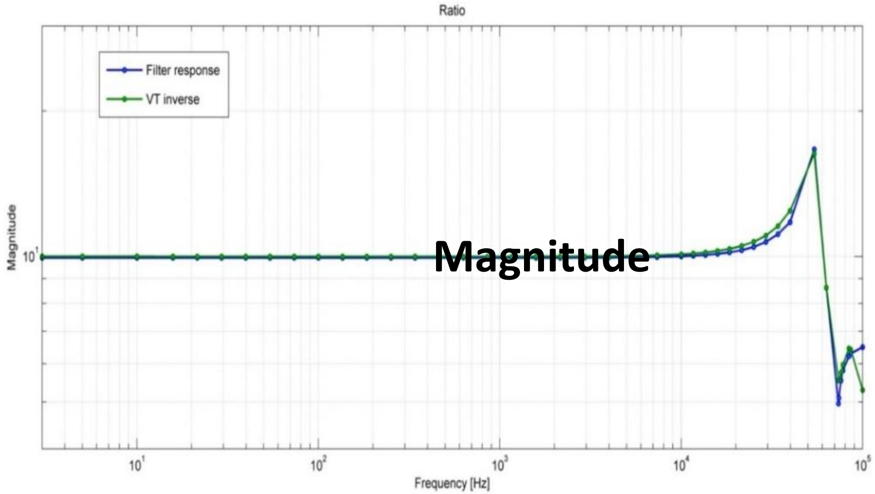
1. Fluke 5500A calibrator
2. DAQ board, 4 synchronous 16 bit inputs, ± 10 V, maximum sampling rate 1 MHz
3. Application of sinusoidal signals from 3 Hz to 250 kHz:
   - 7 V up to 100 kHz
   - 3 V above 100 kHz
4. Acquisition and elaboration software in Python

**1 kV/100 V VT**

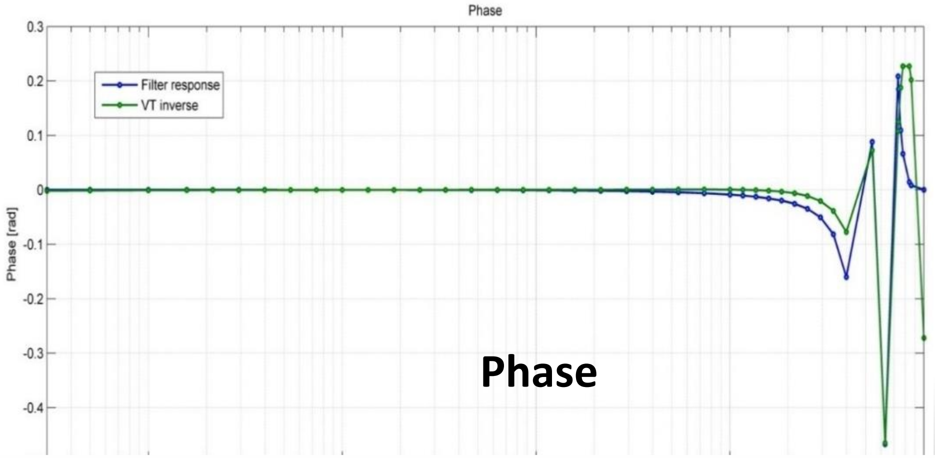
# MatLab implementation of digital filter (1)

**First resonance frequency**

**Comparison measured and inverse computed frequency response**



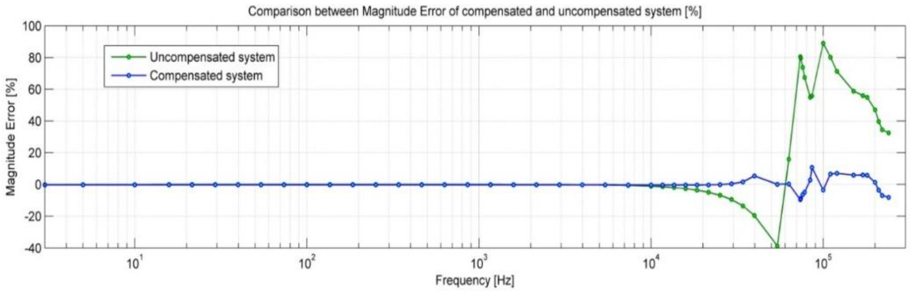
**Magnitude**

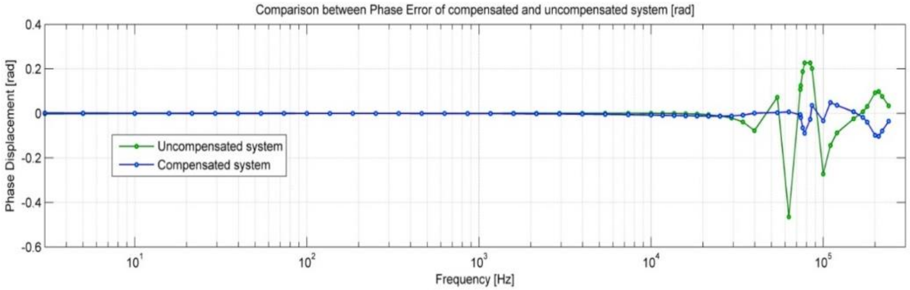


**Phase**

# MatLab implementation of digital filter (2)

## Compensated and uncompensated system





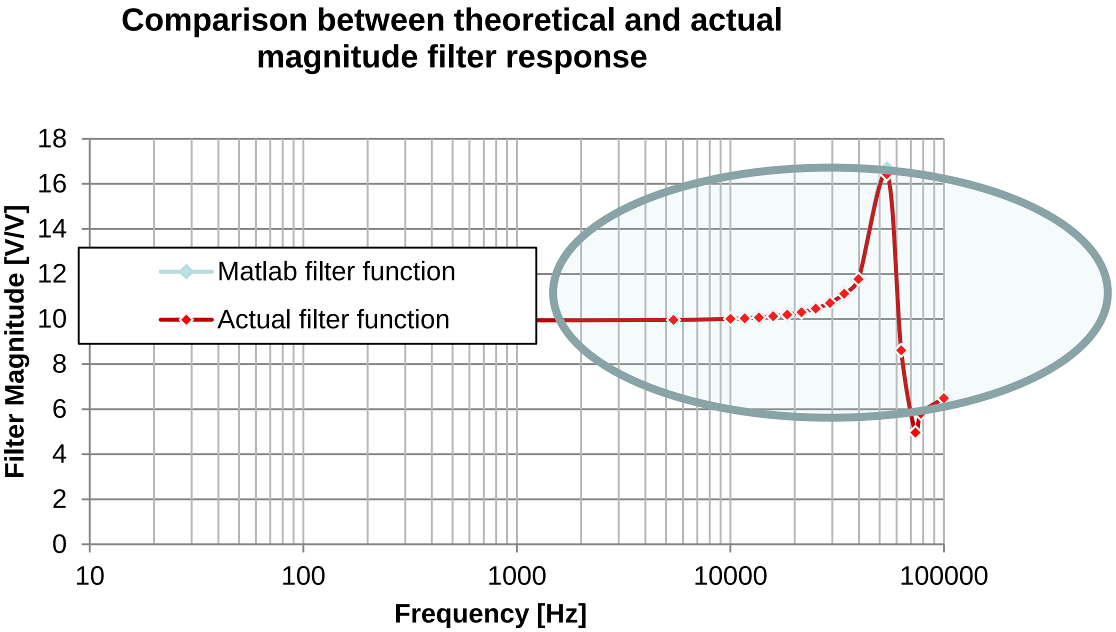
# Experimental characterization of FPGA compensated VT

1. Fluke 5500a calibrator
2. DAQ board

**NI CompactRIO**: AC signals 3 Hz to 250 kHz:

   a. 7 V up to 100 kHz
   b. 3 V above 100 kHz.

1. Software: **LabVIEW FPGA**



# Conclusions

- ☐ Systems for the measurement of frequency response of MV VTs are being experimented with distorted waveform up to some ten kilohertz.
- ☐ Method for the real-time compensation of voltage transducer frequency response by digital filter have been developed.

# Next steps

- ➢ Extension of the VT characterization up to 30 kV
- ➢ Investigation on frequency response of VT of the same type as those operating in MV substations
- ➢ Implementation of the real time compensation procedure
- ➢ Compensantion of the unsatisfactory response of VTs
- ➢ Provide input data to the model for the propagation of the uncertainty through the PMU/PQ measurement chain