Voltage linearity of UHVAC references

E. Houtzager, VSL

The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

Aim and work breakdown

The aim is to develop a new method(s) for linearity determination of HV capacitors with **a target calibration uncertainty for HVAC of 80 µV/V at 800 kV**

1. **Review of methods**
2. **Developments of new methods and reference**
   - Develop new methods for the determination of the voltage dependence (linearity) of HV capacitors.
   - Develop a new reference HV capacitor with ultra-low voltage dependence
3. **Validation of capabilities and uncertainties of new methods**

Review of methods

- **Literature study of voltage dependencies of gas capacitors**
- **Comparison on methods for the determination of voltage dependence of high voltage capacitors based on “Latzel” thesis**

Review of methods
Literature study

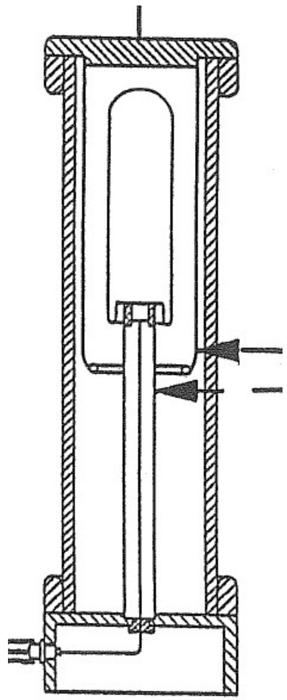
- **Literature study of voltage dependencies of gas capacitors**
  - 55 papers
  - 2 books – Küchler, Schon
  - 8 commercial gas capacitors
  - 15 gas capacitors at NMI:s
  - 8 Field sensors

  - **Overview on poster**

Developments of new methods and reference

Comparison of existing methods

1. **Direct comparison of capacitors** [Schering, 1920]Voltage doubling method [Zinkernagel, 1976]
2. **Direct voltage method** [Kusters, Petersons, 1963] extended for high voltage measurement [Wang, Latzel, 1986]
3. **Voltage doubling method** with capacitive divider [Latzel, 1987]
4. **Tilting** of a high voltage compressed gas capacitor **down to a horizontal position** [Kusters, Petersons, 1963]
5. **Tilting or applying external forces** to the top of the capacitor for displace the electrodes [Rungis, Brown, 1981]
6. **Periodic displacement** of the electrodes of high voltage compressed gas capacitors - caused **by electrical or mechanical forces.** [Kusters, Petersons, 1963], [Latzel, 1987]



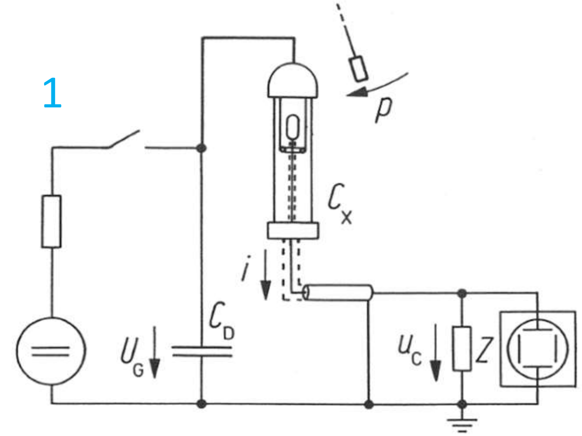
From Latzel

Developments of new methods and reference
Methods used and developed

Six methods evaluated and further developed

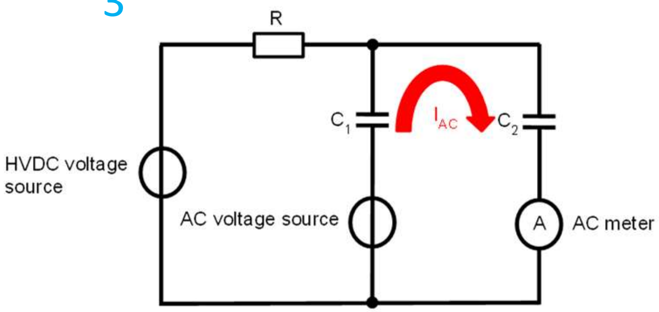
1. Kinetic method (LNE from Latzel)
2. Field sensor (TAU, VTT, VSL)
3. **Three equations method (PTB)**
4. Two harmonics method (VSL)
5. Simplified tilt (NIM from Rungis)
6. **CCD method** (NIM)

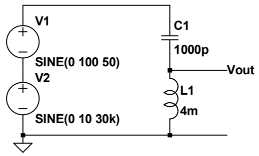
1



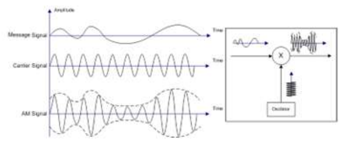
2

3

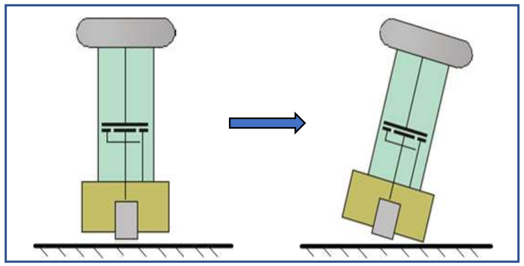




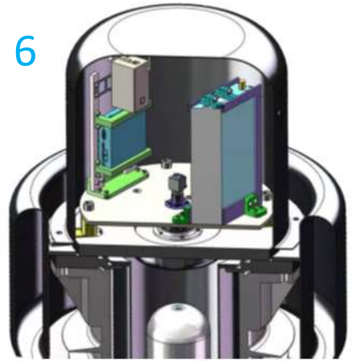
4



5



6

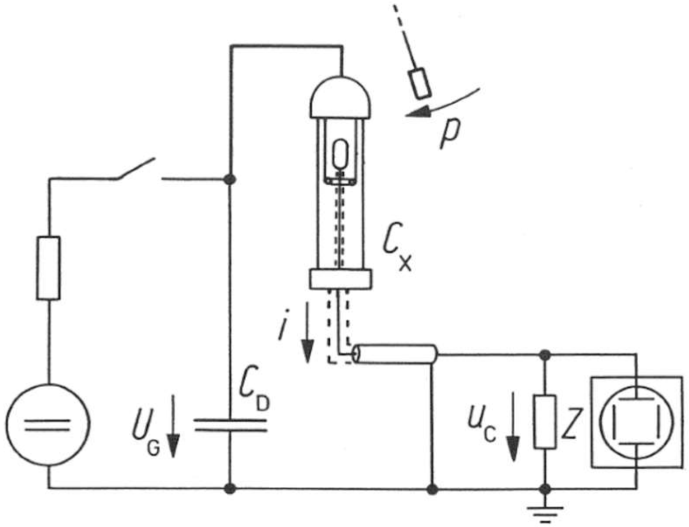


Developments of new methods and reference

1 - Kinetic method (LNE, PTB)

A 100 kV and a 300 kV capacitor characterized

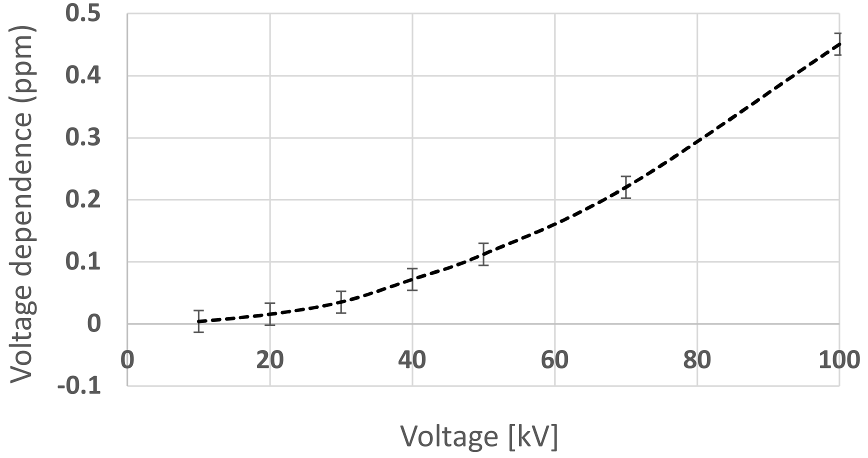
- Apply impulse
- Charge capacitor
- Oscillations measured
- Rotate capacitor, repeat
- Decentering of electrodes detected by difference in signals
- An analysis of the measured alternating current shape gives the resonance and the damping constant.
- In addition, the initial eccentricity is obtained from which the voltage dependence of capacitance may be calculated [Latzel 1987]
- Internal mechanical dimensions needed for calculation
- An expanded measurement uncertainty of 0.11 µF/F/(kV)^2 obtained at 100 kV



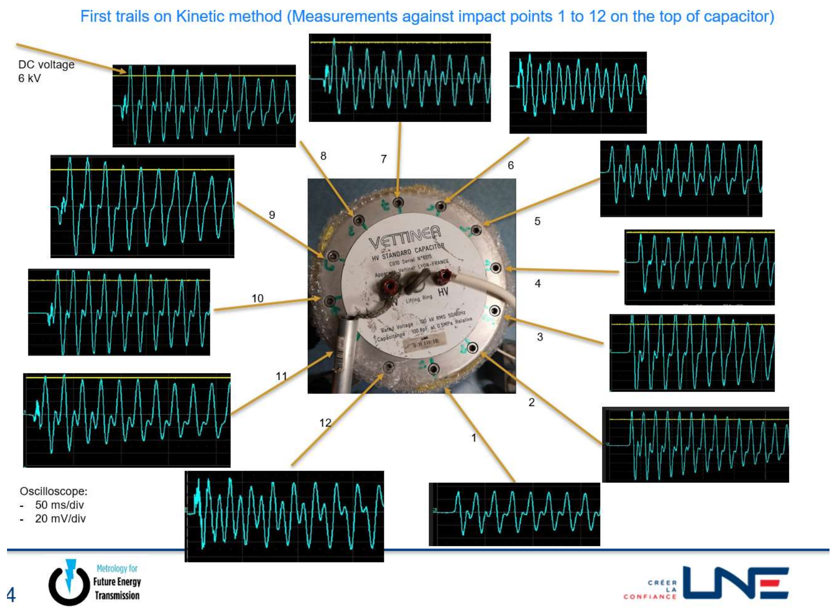
VSL

Developments of new methods and reference
1 - Kinetic method (LNE, PTB)

Result



Voltage dependence of capacitance for the 100 kV capacitor.



Expanded measurement uncertainty (k=2) **0.11 µV/V**

Developments of new methods and reference

2 - Field sensor (TAU, VTT, VSL)

Two arrangements

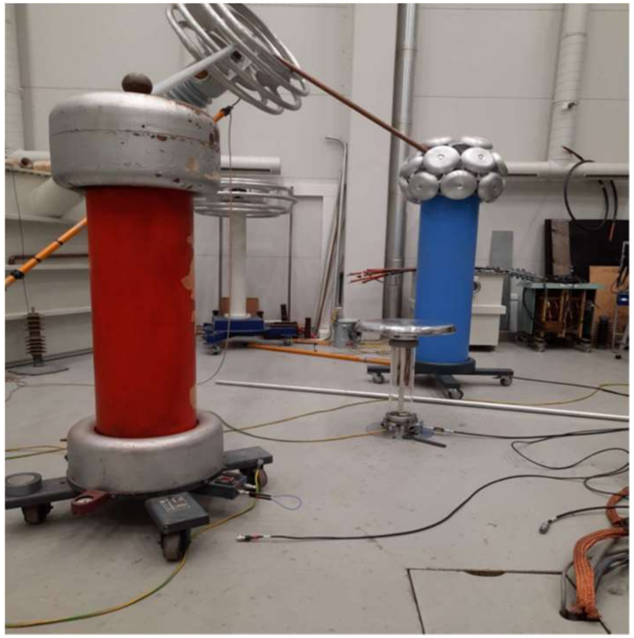
- Voltage ratio measurement (capacitive voltage dividers) → non-linearity of the low voltage arm is known
- Capacitance measurement with capacitance bridge (capacitor)

1

Two field sensors

1. Plate
2. High voltage capacitor

2

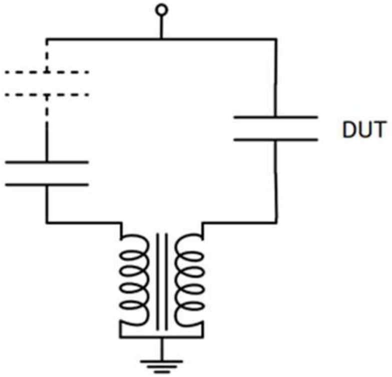


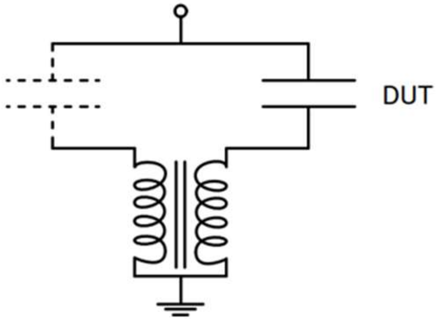
Developments of new methods and reference

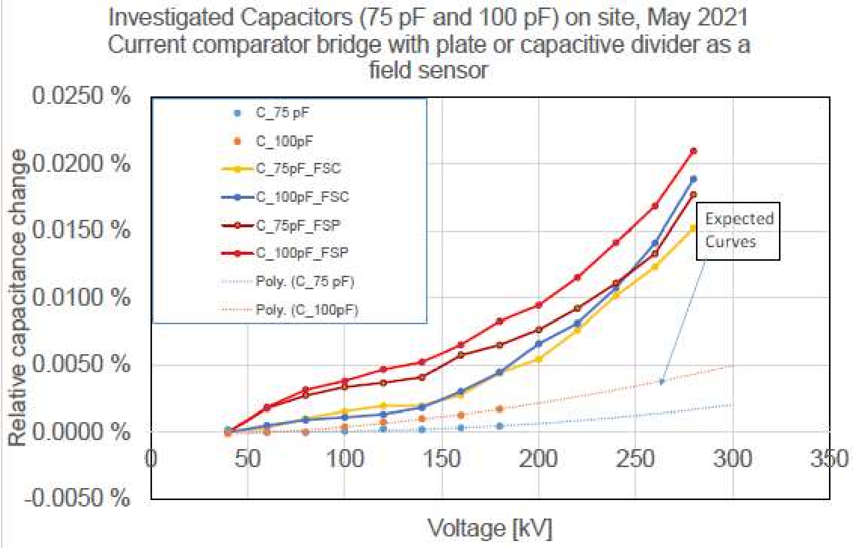
2 - Field sensor (TAU, VTT, VSL)

Capacitance bridge - High voltage capacitor or plate as a field sensor

- Below 140 kV results are good
- Above 140 kV corona may disturb measurement





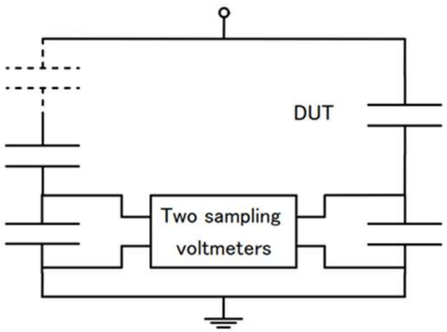


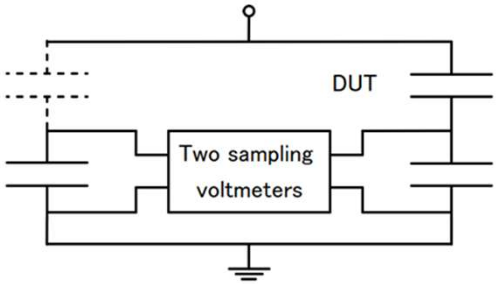
Developments of new methods and reference

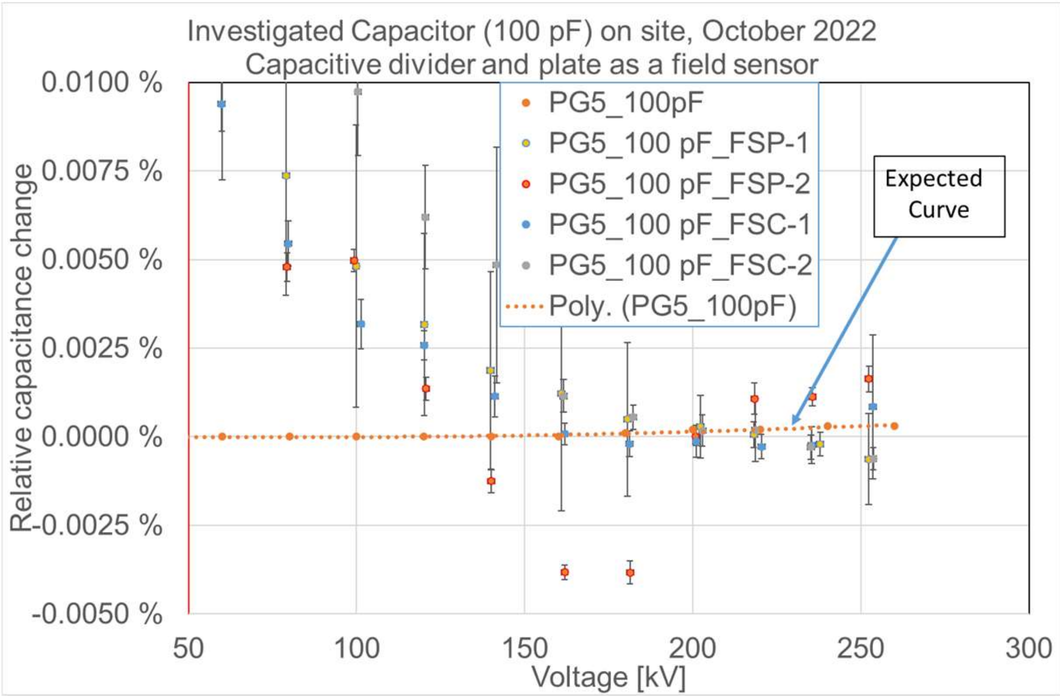
2 - Field sensor (TAU, VTT, VSL)

Voltage ratio- High voltage capacitive divider or plate with low voltage arm as a field sensor, Capacitor (DUT) under investigation with low voltage arm

- Below 50 kV results are not good
- From 140 kV to 260 kV results agree quite well with expected nonlinearity







FSP=plate
FSC=capacitive divider

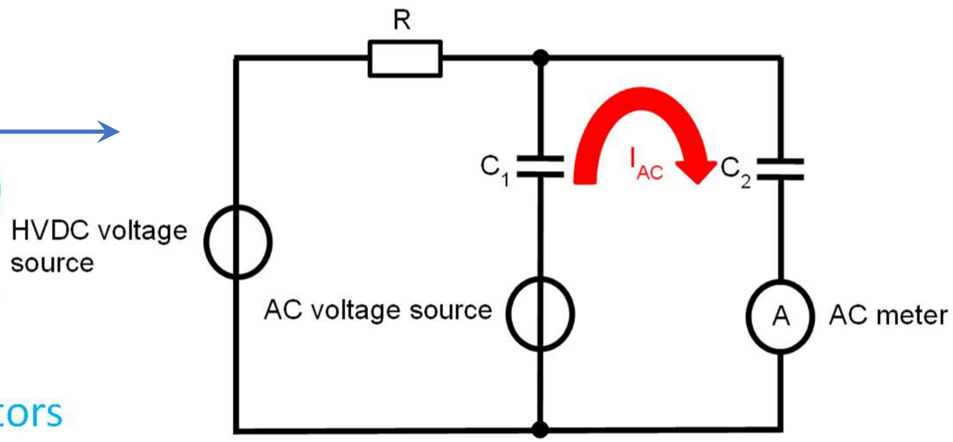
"-1" distance to high voltage about 3 meters
"-2" distance to high voltage about 4 meters

No corona was detected.

Developments of new methods and reference

3 - Three equations method (PTB)

- **Three equations method**
  - Electrical circuit →
  - Use a very stable low AC voltage (c.a. 500 V) with a frequency in the kHz range.
  - Apply different DC voltages to the capacitor (e.g., 0 - 200 kV)
  - Measure the AC current through the capacitors
  - The resistor R is big enough (10^6 times larger than the capacitor impedances), so that the AC current does not flow through the HVDC source.

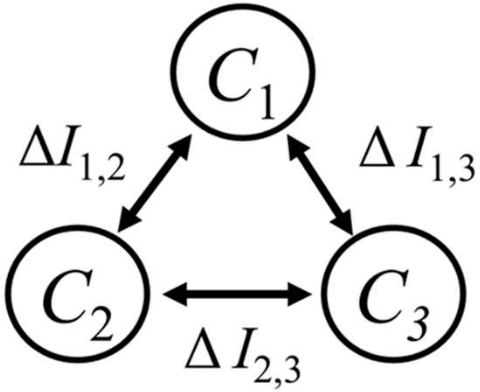


Circuit diagram with two capacitors C_1 and C_2.

Developments of new methods and reference

3 - Three equations method (PTB)

- **Procedure**
  - Method requires 3 capacitors.
  - None of the voltage non-linearities of C1, C2 or C3 are known
  - The relative change of the AC current ($\Delta I_{n,m}$) at different DC voltages caused by respectively two capacitors can be measured
  - The change in AC current is measured for different DC voltages for each pair of capacitors.



Developments of new methods and reference

3 - Three equations method (PTB)

Procedure – the equations

- The shown ΔI is the AC current change caused by the change in capacity due to the DC voltage.
- All three capacitance changes can be given as a function of the DC voltage by the three measured currents $\Delta I_{1,2}(U_{DC})$, $\Delta I_{2,3}(U_{DC})$ and $\Delta I_{3,1}(U_{DC})$.
- Use 3 senior scientists to get three different solutions for equations, and group them to obtain the correct answer

$$\Delta C_1[U_{DC}] = \frac{\Delta C_2[U_{DC}]\Delta I_{1,2}}{U_{AC}\omega\Delta C_2[U_{DC}] - \Delta I_{1,2}}$$

$$\Delta C_2[U_{DC}] = \frac{\Delta C_3[U_{DC}]\Delta I_{2,3}}{U_{AC}\omega\Delta C_3[U_{DC}] - \Delta I_{2,3}}$$

$$\Delta C_3[U_{DC}] = \frac{\Delta C_1[U_{DC}]\Delta I_{3,1}}{U_{AC}\omega\Delta C_1[U_{DC}] - \Delta I_{3,1}}$$

Procedure – three solutions

$$\boxed{\Delta C_{1,DC}} = \frac{2 \cdot \Delta I_{1,2} \cdot \Delta I_{3,1} \cdot \Delta I_{2,3}}{U_{AC} \cdot 2\pi f \cdot \left(\Delta I_{1,2} \cdot \Delta I_{2,3} - \Delta I_{1,2} \cdot \Delta I_{3,1} + \Delta I_{3,1} \cdot \Delta I_{2,3}\right)}$$

$$\boxed{\Delta C_{2,DC}} = \frac{2 \cdot \Delta I_{1,2} \cdot \Delta I_{2,3} \cdot \Delta I_{3,1}}{U_{AC} \cdot 2\pi f \cdot \left(\Delta I_{2,3} \cdot \Delta I_{3,1} - \Delta I_{2,3} \cdot \Delta I_{1,2} + \Delta I_{1,2} \cdot \Delta I_{3,1}\right)}$$

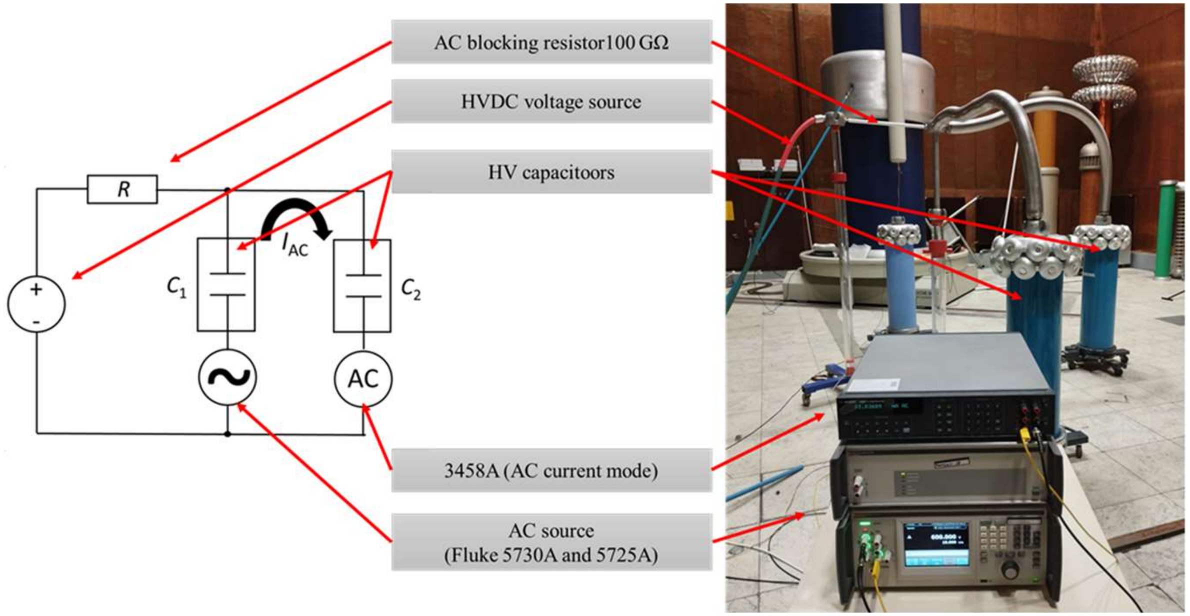
$$\boxed{\Delta C_{3,DC}} = \frac{2 \cdot \Delta I_{1,2} \cdot \Delta I_{2,3} \cdot \Delta I_{3,1}}{U_{AC} \cdot 2\pi f \cdot \left(\Delta I_{3,1} \cdot \Delta I_{1,2} - \Delta I_{3,1} \cdot \Delta I_{2,3} + \Delta I_{2,3} \cdot \Delta I_{1,2}\right)}$$

Developments of new methods and reference

3 - Three equations method (PTB)

Measurement set-up

- Three identical compressed gas capacitors MCP200 with a rated voltage of 200 kV and 100 pF where used.
- DC Voltages from 0 V to 160 kV were applied to each pair of capacitors in 40 kV steps.
- A resistor of 100 GΩ was used to block the HVDC source from the circuit.
- An AC voltage of 600VRMS at a frequency of 10 kHz was generated using a Fluke 5730A with a Fluke 5725A.

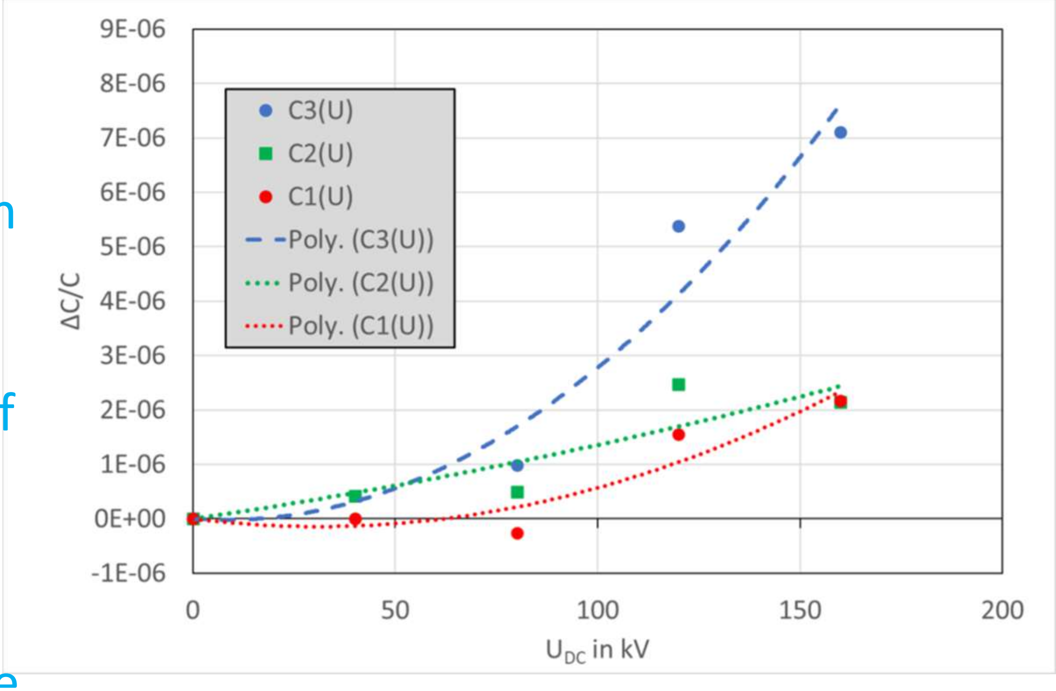


Developments of new methods and reference

3 - Three equations method (PTB)

Results for three 200 kV capacitors

- The measured currents, which are dependent on the DC voltage were used to calculate the voltage dependency of the capacity by solving the three equations to obtain three ΔC.
- The results are plotted and highlighted using poly nominal fits of 2nd degree
- C1 and C2 have a low voltage dependence. C3 was repaired and expected to have higher dependence



Developments of new methods and reference

3 - Three equations method (PTB)

Ongoing work

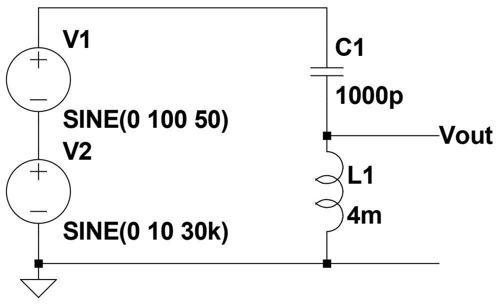
- Verifying that the method fulfill the target uncertainty of 80 μF/F @ 800 kV using three 800 kV capacitors (two from PTB and the new design from VETTINER)
  - A 500 kV capacitor was used instead of the VETTINER capacitor, limited to 240 kV because of corona onset.
  - Delay in production of 800 kV capacitor from Vettiner
- Measurement uncertainty estimate points towards 10 uF/F
- Improve the current measurement to improve the measurement uncertainty

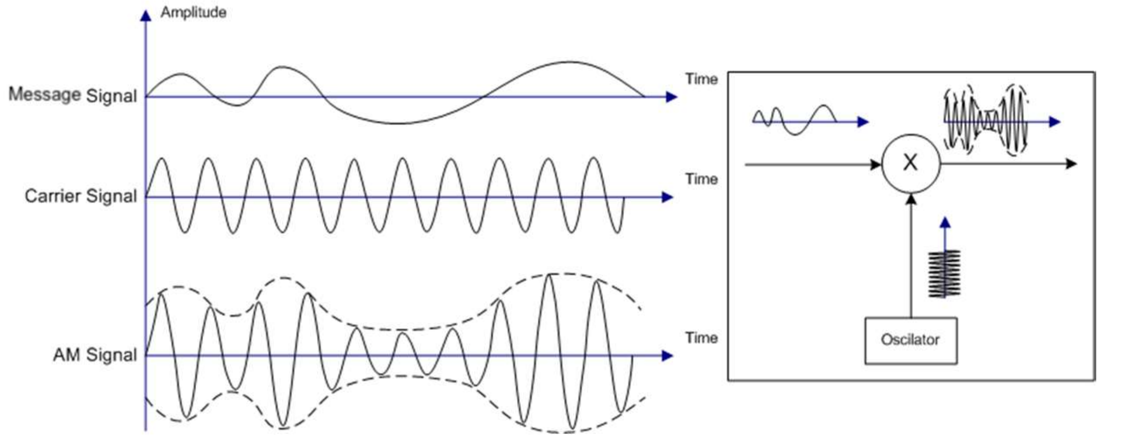
Developments of new methods and reference

4 – Two harmonics method (VSL)

Procedure

- Apply two AC voltages
  - 100 kV 50 Hz
  - 10 kV 30 kHz
- The beating of the two signal produces side lobes in the frequency spectrum which are measure of decentering
- Decision not to develop further within this project



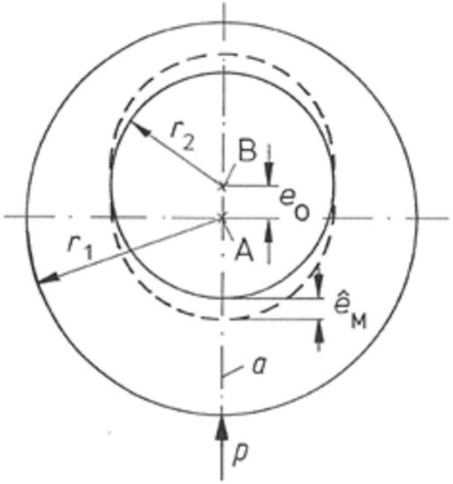


Developments of new methods and reference

5 - Simplified tilt method (NIM)

- Tilting of the gas capacitor and rotating it the non-linearity can be evaluated
- The tilting cause a displacement of the high and low voltage electrodes
- Mechanical knowledge needed

$$\beta(U) = \frac{\Delta C}{C} \approx \frac{\beta(U,\Phi) - \beta(U)}{2\frac{e_N}{e_0} + (\frac{e_N}{e_0})^2} = \frac{\frac{\Delta K}{K}(U,\Phi) - \frac{\Delta K}{K}(U)}{2\frac{e_N}{e_0} + (\frac{e_N}{e_0})^2}$$

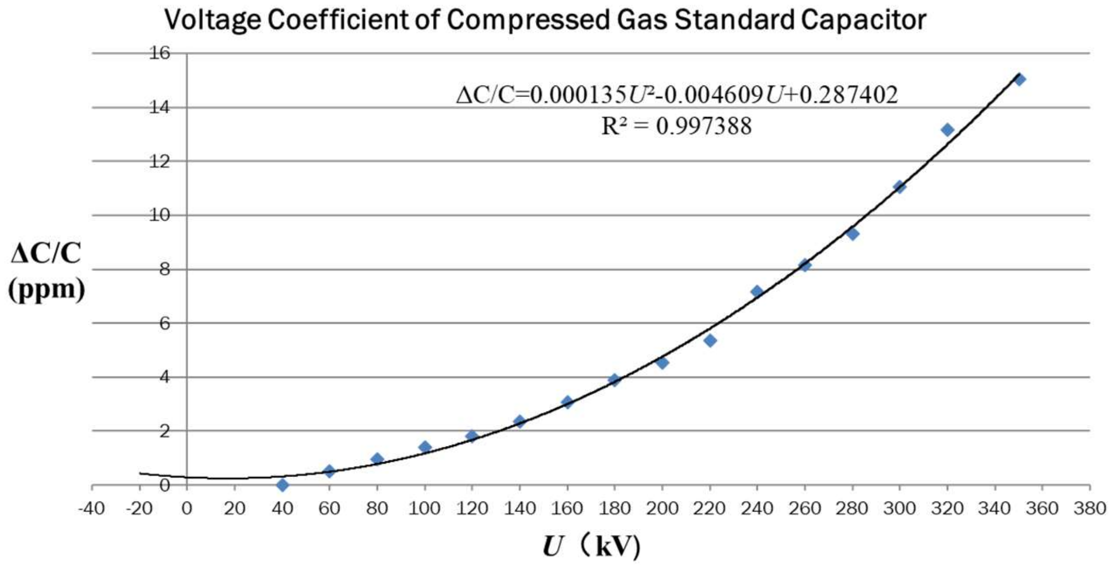


Developments of new methods and reference

5 - Simplified tilt method (NIM)

Result – simplified tilting method

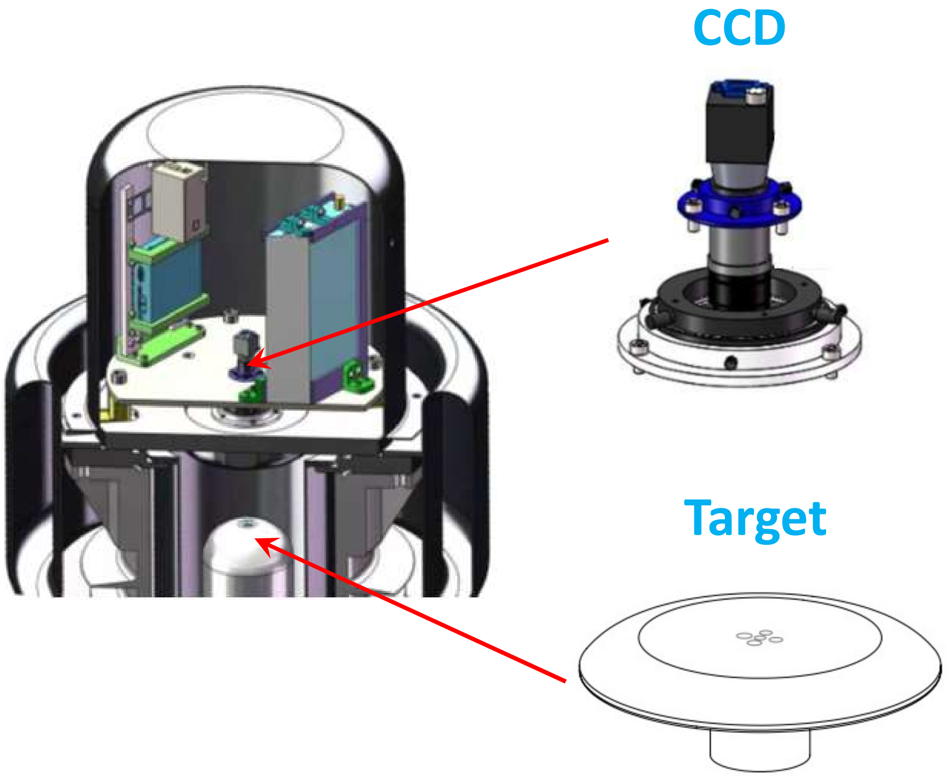
- Voltage coefficient: 20×10^{-6} at 400 kV
- Expanded uncertainty (k=2) = 9.8×10^{-6}



Developments of new methods and reference

6 - CCD method

- A camera (CCD) is detecting movements of the electrode by monitoring a target pattern through a window
- No mechanical knowledge needed

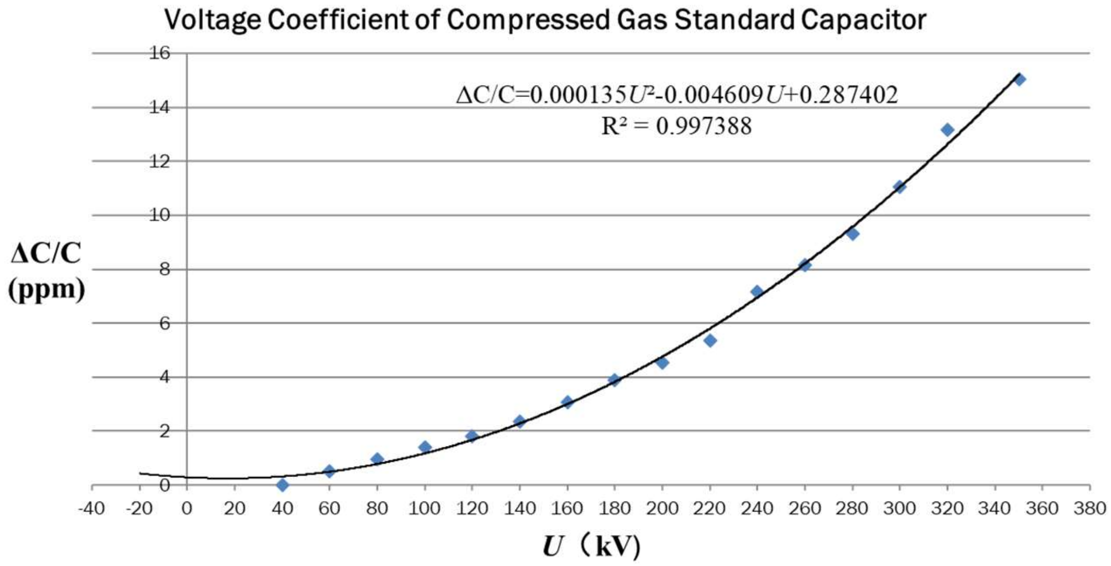


Developments of new methods and reference

5 - Simplified tilt method (NIM)

Result – simplified tilting method

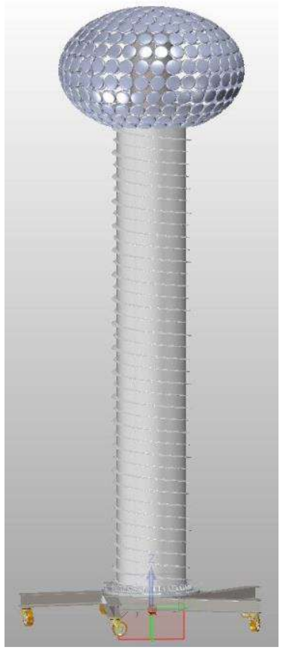
- Voltage coefficient: 20×10^{-6} at 400 kV
- Expanded uncertainty (k=2) = 9.8×10^{-6}



Developments of new methods and reference

New 800 kV gas capacitor

- Validation of a 100 kV and a 200 kV with new design successful – voltage dependence and dissipation factor lower than measurement uncertainties
- An 800 kV capacitor prototype Jan 2022
  - Several parts improved
  - Change of suppliers
  - Assembly process improvements
- Delays in supplier chain until June 2023
  - Aluminium raw material availability
  - Excess workload



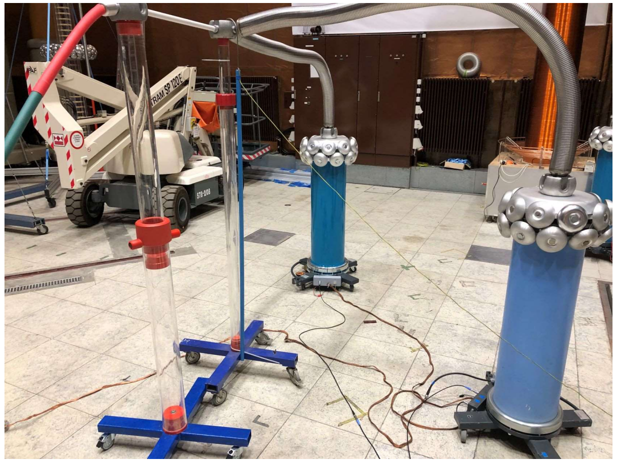
Original 800 kV design

New 800 kV design

Validation of two methods

Three equations method (PTB)

- First measurement campaigns carried out up to 200 kV AC with selected and characterized gas capacitors.
- Final measurement campaign at PTB w16 April 2023 up to 500 kV (lacking the Vettiner 800 kV capacitor)

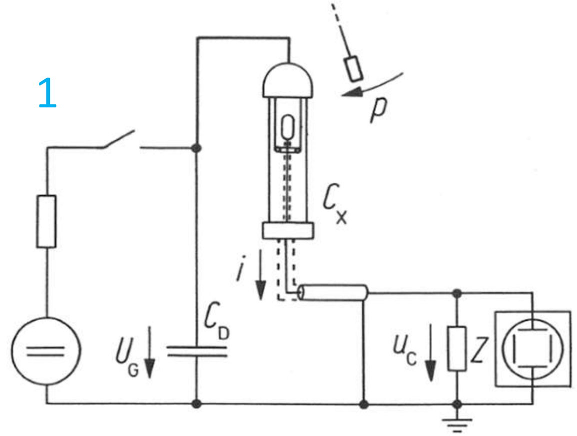


Validation of methods

Measurement uncertainties

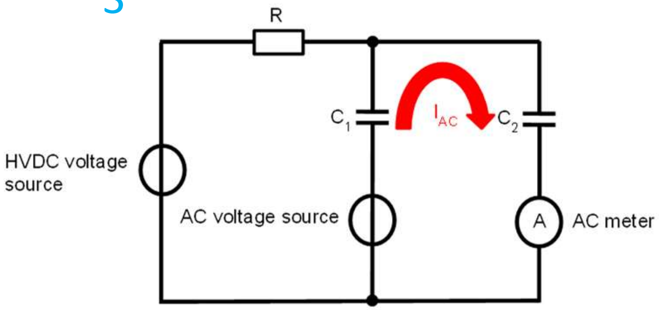
1. Kinetic method (LNE from Latzel) - 0.11 μF/F
2. Field sensor (TAU, VTT) – 50 μF/F
3. Three equations method (PTB) – 10 μF/F
4. Two harmonic method (VSL) – not developed
5. Simplified tilt (NIM from Rungis) – 10 μF/F
6. CCD method (NIM) – 6 μF/F

1

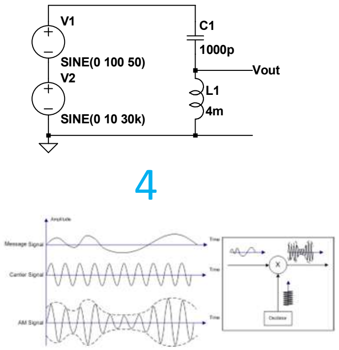


2

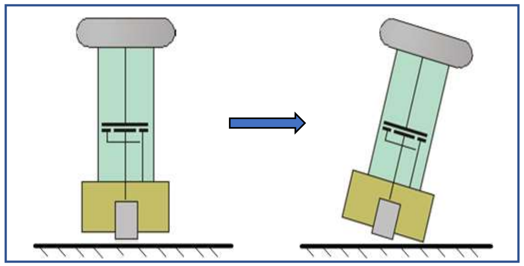
3



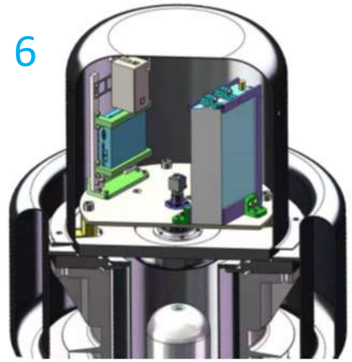
4



5



6

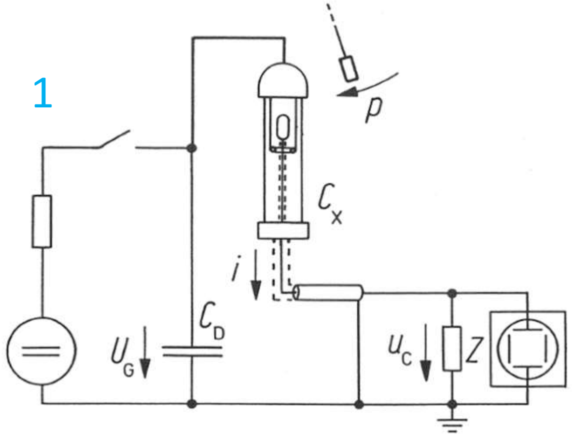


Conclusions

Five of the six methods have been developed/analysed

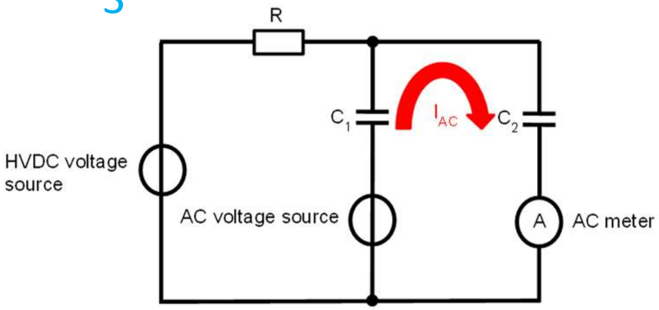
1. Kinetic method – low unc., only gas capacitors, time consuming
2. Field sensor – simple, sensitive to corona, any capacitor, **can meet defined target 80 µF/F at 800 kV**
3. Three equations method (PTB) – no prior knowledge of capacitance, any capacitor, three capacitors needed, **meets defined target 80 µF/F at 800 kV**
4. Simplified tilt – special arrangement, primary lab
5. CCD method (NIM) – intrusive

1

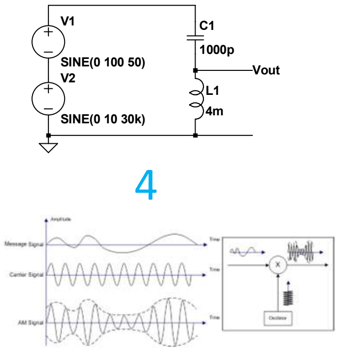


2

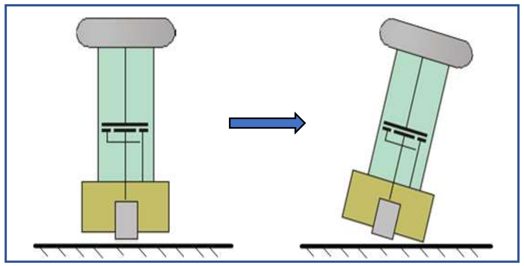
3



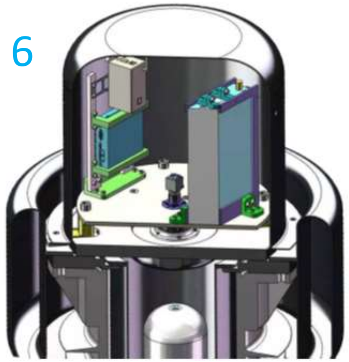
4



5



6



Partners of the work package

Acknowledgements

This research was performed within the project 19ENG02 FutureEnergy "Metrology for future energy transmission". The project received funding from the EMPIR programme co-financed by the Participating States and from the European Union's Horizon 2020 research and innovation programme.

The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States