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DETERMINATION OF VOLTAGE DEPENDENCE OF CAPACITANCE OF 100 kV AND 300 kV COMPRESSED GAS CAPACITORS USING THE KINETIC METHOD

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Keywords: COMPRESSED, GAS, CAPACITOR, VOLTAGE, DEPENDENCE, CAPACITANCE

Abstract

Measuring voltage dependence capacitance of high voltage compressed gas capacitors is challenging when levels are below one ppm (one Micro-Farad per Farad). Indeed, traditional methods such as direct capacitor comparison, voltage transforming, voltage-doubling, direct voltage, frequency doubling, and simplified tilting are not suitable because they need complex procedures, reference standards with known voltage dependence and accurate capacitance bridges. The kinetic method could be used to determine a possible quasi-zero voltage dependence or at least to detect it. A 100 kV capacitor was studied using this technique at LNE with support from PTB. An excellent initial eccentricity, equal to (0,070 ± 0,010) mm, was determined and which is in accordance with what is claimed by the manufacturer. Quasi-zero voltage dependence (0.45 ± 0.10) ppm, was determined. This low level of uncertainty is difficult to reach with any other method, the internal dimensions of the capacitor have to be estimated. Another 300 kV capacitor was also investigated without any knowledge of its internal dimensions. It was concluded that it has a medium eccentricity despite its good calibration results, equal to (7.0 ± 5.0) ppm.

1 Introduction

High voltage compressed gas capacitors, based on the coaxial cylindrical electrode structure, are widely used in testing and in metrology laboratories as a reference standard for accurate high voltage alternating current measurements. They have usually very low voltage dependence (less than 10 ppm) and very low dissipation factor (less than 0.00001). Manufacturers of compressed gas capacitors have put great effort into improving the electrode coaxiality, which is a determining factor of the voltage dependence [1] [2]. Some of them claim voltage dependence below ppm-level [9]. The measurement of this low level at national laboratory institutes is not an easy task. Indeed, several techniques could be used such as direct comparison of capacitors [3], voltage transforming [4], voltage-doubling [5], direct voltage, frequency doubling [6], and simplified tilting method [1]. Nevertheless, all these techniques need complex procedures, reference standards with known voltage dependence and high precision capacitance bridges. Thus, it is usually very challenging to measure voltage dependence with uncertainties lower than 1 ppm.

An alternative technique to these traditional methods is the kinetic method. It is derived from Latzel's work [7] in the 1980s and 90s at the National Metrology Institute in Gemany (PTB, Physikalisch-Technische Bundesanstalt). On one hand, it is more reliable to detect a possible quasi-zero voltage dependence by qualitative observations. On the other, if the internal dimensions of the capacitor are known, it would be possible to calculate the initial eccentricity and the voltage dependence. These two particular points could be beneficial for compressed gas capacitor manufacturers and national metrology institutes.

Using this technique, the voltage dependence of a 100 kV compressed gas capacitor, was studied at National Metrology Institute in France (LNE, Laboratoire National de Métrologie et d'Essais). For this capacitor, the manufacturer claims a voltage dependence below ppm level up to 100 kV but it has never been validated by calibration because the measurement uncertainties are higher than this value. The mechanical assembly of this capacitor was carefully adjusted by the manufacturer with an accuracy better than 0.1 mm. Thus, the initial eccentricity has to be in the same order. Another 300 kV standard compressed gas capacitor, with known voltage dependence, has also been studied in order to make a comparison with the results of the 100 kV capacitor. The 300 kV capacitor has a voltage dependence of 7 ppm obtained by the direct comparison method with an uncertainty of 5 ppm (95 % of confidence).

2 Kinetic method theory

A typical compressed gas capacitor based on the coaxial cylindrical electrode structure is presented in (Figure 1). The main elements are the high voltage electrode (HVE) mechanically attached to the upper part of the capacitor, external insulating envelope and the low voltage electrode (LVE), mechanically attached to the lower part of the capacitor via its guard electrode and the supporting foot. Their common mechanical link is made through the base of the external insulating case. The Kinetic method consists of vibrating the capacitor in order to determine its resonant frequency. The electrodes are made to oscillate by a mechanical impulse given at the top of the capacitor. Taking into account that the mass of the HVE-attached set is in a much higher mass proportion than the LVE-attached set, it can be assumed that only the LVE is moving. This hypothesis was verified in a lot of research [1] [2]. In other word, the LVE oscillations are at least ten times higher than those of the HVE. Assuming that, the Kinetic method theory is based on the fact that the compressed gas capacitor dependence is obtained only by the displacement of the LVE. This displacement is considered to be perpendicular to the longitudinal axis of the capacitor.

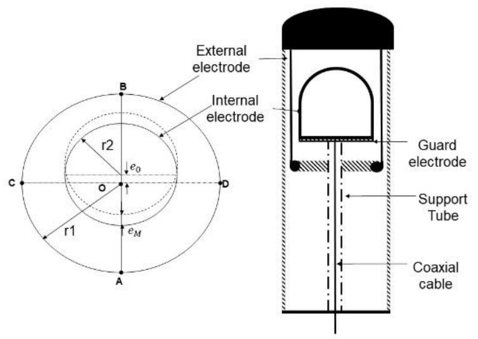


Figure 1: Typical high voltage compressed gas capacitors, based on the coaxial cylindrical electrode structure.

In Figure 1, "e_0" is the initial eccentricity of the compressed gas capacitor, r1 is the radius of the HVE, r2 is the radius of the LVE and (A-B) is the plan of the greatest relative change in capacitance. By neglecting the damping, the LVD oscillates in plan A-B. The variation of the eccentricity as a function of time is written with the equation (1).

$$\mathbf{e(t) = e_M \sin(\omega_M t)} \quad (1)$$

The impulse is applied to point A in such a way that the LVE swings beyond the centre (*Figure 1*). The initial eccentricity will decrease according to the equation (2).

$$e(t) = e_0 - e_M \sin(\omega_M t) \quad (2)$$

e_M is the maximum change of eccentricity.

If the LVE reaches the centre position, the value of the capacitance is equal to the concentric cylindrical capacitance C_c. If the initial eccentricity is much smaller than r1 and r2 (A condition which is generally met), it can be shown that the relative change of the capacitance among the plane of eccentricity could be approximatively expressed by the equation (3).

$$C(t) = C_c[1 + (e_0 - e_M)\sin(\omega_M t)\, b] \quad (3)$$

Where C_c and b could be calculated for coaxial cylindrical structure respectively by the equations (4) and (5).

$$C_c = \frac{2\pi\varepsilon l}{ln\frac{r1}{r2}} \quad (4)$$

$$b = \frac{1}{(r_1^2 - r_2^2)ln\frac{r1}{r2}} \quad (5)$$

Where l is the length of the electrodes and ε is the permittivity of the insulating gas (Generally SF6 or N2).

If the capacitor is charged with a direct voltage U and while the LVE oscillates, an alternating current is generated and could be expressed by equation 6.

$$i(t) = U\frac{dC(t)}{dt} =$$

$$i(t) = UC_c e_0^2 b\omega[-2\frac{e_M}{e_0}\cos(\omega t) + \left(\frac{e_M}{e_0}\right)^2 \sin(2\omega t)] \quad (6)$$

The initial eccentricity could be calculated from the current curve according to equation 7, for example from the points $\omega t = 0$ and $\omega t = \pi/4$.

$$e_0 = \sqrt{\frac{|i(0)|}{4\, UC_c\, b\, w\, |\frac{i(\frac{\pi}{4})}{i(0)} - \frac{\sqrt{2}}{2}|}} \quad (7)$$

For capacitors with large initial eccentricity, the ratio $i(\pi/4)\, /\, i(0)$ has approximatively the value of $\sqrt{2}/2$ according to the co-sinusoidal shape. For a capacitor without initial eccentricity, $i(0)$= 0, the nominator is equal to zero and the denominator becomes infinite.

The calculation of the initial eccentricity will lead to calculating the voltage dependence according to the equation (8). Where S is the spring fitness of the support tube.

$$\frac{\Delta C}{C} = U^2 C_c \frac{b^2}{S} e_0^2 (2 + U^2 C_c \frac{b}{k}) \frac{C_c}{C} \quad (8)$$

From equation 6 and without knowing the internal dimensions of the capacitor, it is usually possible to give a qualitative judgement:

- For a compressed gas capacitor with very large initial eccentricity $e_M \ll e_0$ (Figure 2), the concentric position is not reached while the capacitance and the current change with the amplitude of oscillations. The sinusoidal term in equation 6 is neglected compared to the co-sinusoidal term. In this case, the LVE swings with one natural frequency.

- If there is a capacitor with a small initial eccentricity (Figure 3), for example $e_M = 5\, e_0$, the LVE is found in the concentric position twice during each period of oscillation. The corresponding capacitance relative to Cc leads to two additional zero crossings in the current curve. At a particular point, when $e_M = e_0$ (Figure 4), the concentric position is reached at the maximum amplitudes of oscillation.

- For a perfect capacitor with zero initial eccentricity, $e_0 \approx 0$, any change in the internal electrode position in any direction causes an increase in capacitance. An impact on any direction will lead to a symmetric time dependant change in capacitance. The co-sinusoidal term is neglected compared with the sinusoidal term. In this case, the internal electrode swings with two natural frequencies. This case will probably never be found in practice.

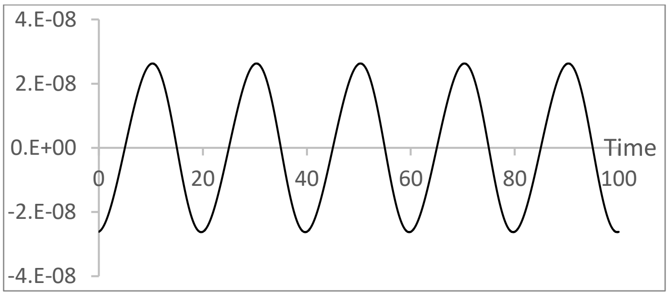


Figure 2: Current wave shape for a capacitor that has large initial eccentricity ($e_0 = 10\ e_M$)

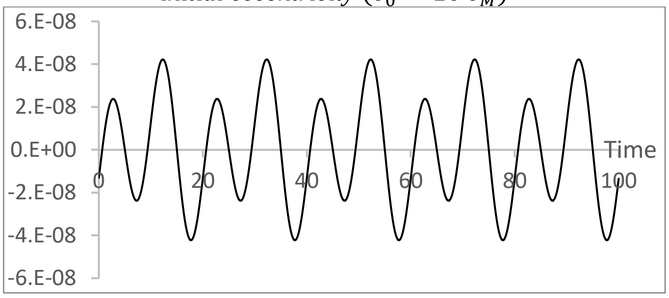


Figure 3: Current wave shape for a capacitor that has excellent initial eccentricity ($e_M = 5\ e_0$)

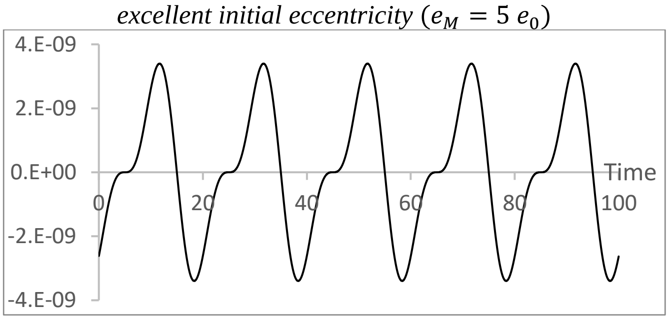


Figure 4: Current wave shape for a capacitor that has good initial eccentricity ($e_M = e_0$)

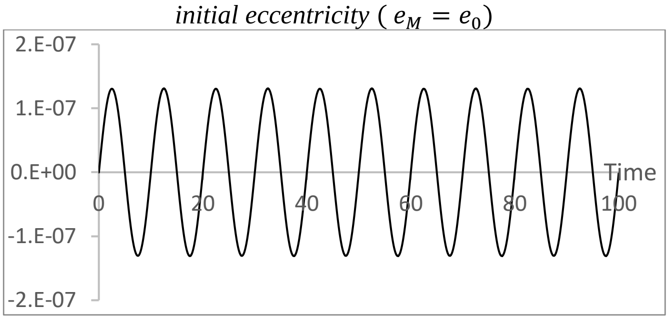


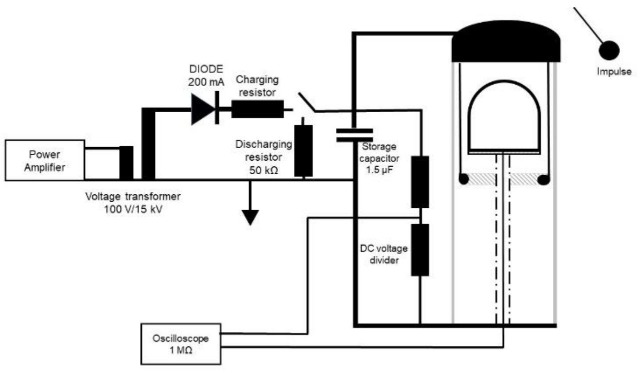
Figure 5: Current wave shape for a capacitor that has a perfect coaxial electrode structure ($e_0 \approx 0$)

3 Procedure and results

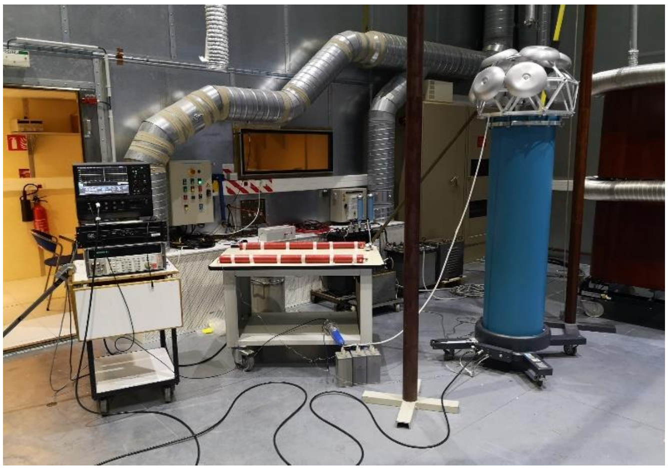
3.1 Procedure

The voltage dependence of a 100 kV capacitor and a 300 kV capacitor was studied in LNE using the Kinetic method. The capacitors was charged by mean of a charging capacitor (1.5 µF/20 kV DC). The charging capacitor was charged by a power source, a high voltage transformer and a high voltage rectifier circuit (high voltage diode, high voltage charging and discharging resistors). It was very important to avoid disturbance and interference because the measured current is very low (in the range of Nano-amperes). The signal to noise ratio was improved by putting the capacitor inside a faraday cage. The charging circuit was disconnected in order to avoid any alternating components.

The LVE oscillates by a mechanical impulse applied to the top of the capacitor. The current flowing though the capacitor is measured across the input impedance of an oscilloscope (1 MΩ ± 1 %) in parallel with the capacitance of a shielded coaxial cable (about 0,5 nF).



a



b

Figure 6: (a): Experimental setup used for the Kinetic method measurements. (b): Measurement of the 300 kV capacitor in LNE Faraday cage to avoid any interference.

A resistive divider (100 MΩ/20 kV) was used to measure the direct voltage during the oscillations (Measured by the same oscilloscope as the current). Due to the resistance of this resistive divider, a discharge time constant to the storage capacitor of about 150 V/min (2.5 %/min) was observed. It was concluded that it is small enough to keep the voltage constant for a few seconds within 1 % while the LVE oscillates. Instead of the resistive divider, it is also possible to use an electrostatic voltmeter in order to decrease the voltage drop down to 1%/min for longer oscillation periods. The DC voltage (U) was chosen between 6 kV and 10 kV to ensure that the signal is high enough to be analysed (at least in the mV range of the oscilloscope).

The mechanical oscillation could be generated by any method. The only condition is that the impulse has to be repeatable (same energy and direction for each impulse). A cylindrical metal suspending from the ceiling was used. The energy was calculated by the mass of the cylindrical metal and the deflection of the pendulum. Precautions were taken in order not to damage the capacitor and to avoid any bouncing and any unwanted disturbance. The impulse was directed from the impact point to the centre of the capacitor.

3.2 Results

Two compressed gas capacitors were evaluated according to the procedure described in this paper and using the setup proposed in (*Figure 6*). The first one is a 100 pF nominal capacitance and 100 kV RMS nominal voltage. The second one is also a 100 pF nominal capacitance but with 300 kV RMS nominal voltage. The voltage dependence for both capacitors was determined with an uncertainty of 5 ppm. It is less than 4 ppm for the 100 kV capacitor and less than 7 ppm for the 300 kV capacitor. This large uncertainty is due, on one hand, by the resolution of the high voltage capacitance bridge at the lowest measurable high voltage (a few kilovolts) when the capacitor is compared with a standard one. And, on the other, by the uncertainty of the relative change of capacitance from the lowest measurable high voltage to the nominal high voltage.

The direct voltage applied to the capacitors was about 6 kV for the 100 kV capacitor and 8 kV for the 300 kV capacitor. Twelve mechanical impulses were applied by rotating each capacitor with its longitudinal axis every 30 degrees. All the impulses were given in a way that the energy would go toward the centre of the capacitors. The first step was to localize the impact point A (*Figure 1*). If the capacitor did not have any initial eccentricity, all the current curves would look like figure 5. If the capacitors had an initial eccentricity, the ratio e_M/e_0 (equation 6) would be minimal when the LVE swings in the plan of eccentricity (A-B). If the impulse was given perpendicularly to the plan A-B, no zero crossing would be observed and the LVE electrode would oscillate symmetrically, the current shape would look like that in figure 5. The sin(2ωt) component would become maximal in this case and decrease relatively fast with the variation of the impulse direction. The impact point was obtained by rotating the capacitor by 90° or 270°. The impulse impact was recognised by the negative sign in the current curve immediately after the impact.

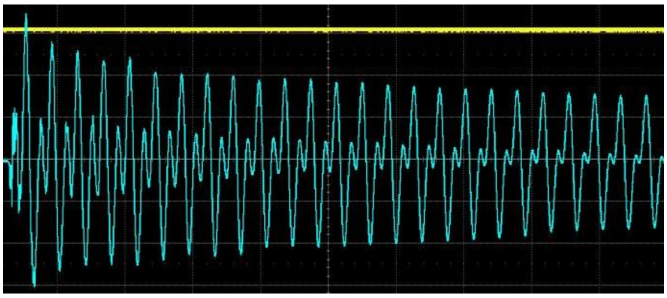


Figure 7: Current curve of the 100 kV capacitor obtained by kinetic method

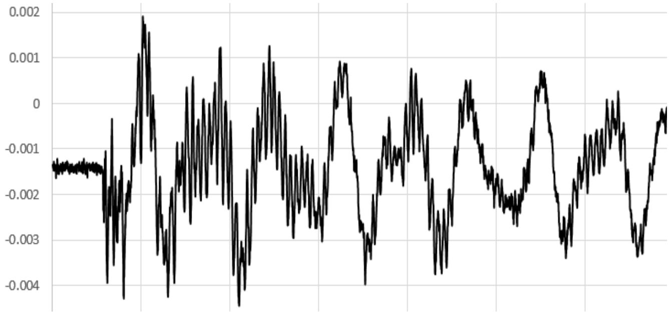


Figure 8: Current curve of the 300 kV capacitor obtained by kinetic method.

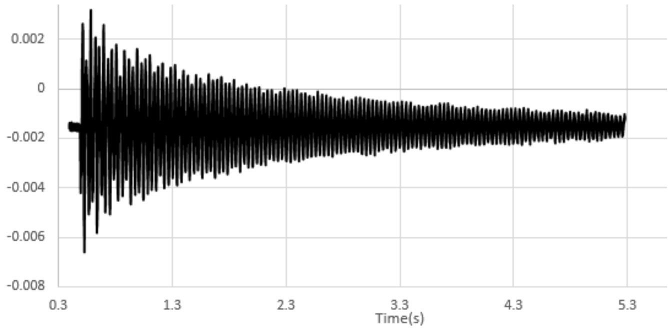


Figure 9: Damping time constant of the 300 kV capacitor support tube.

The measured current curve, when the impulse is applied to point A, is given in (Figure 7) for the 100 kV capacitor and in (Figure 8) for the 300 kV capacitor. The horizontal resolution of the oscilloscope was set to 100 ms/division for the 300 kV capacitor and 50 ms/division for the 100 kV capacitor. The vertical resolution was set to 1 mV/division for the 300 kV capacitor and twenty times higher for the 100 kV capacitor (20 mV/division). The measured natural frequency of the 100 kV capacitor was found to be 52,8 Hz ± 1,0 Hz and 26,04 ± 0,50 Hz for the 300 kV capacitor. The low natural frequency decreases in principle with the mass of LVEs and the mass and length of support tubes. The compressed gas capacitors with high nominal voltage have generally low natural frequency. The oscillations was damped by the support tube for both capacitors. In order to evaluate this damping, an observation was performed up to several seconds (*Figure 9*). For both capacitors, the LVE returned to its initial position in less than 1 minute. For the evaluation, it was important to look only at the first periods. Transitions was observed from currents curves similar to figure 3 and to curves similar to figures 4 and 2. These transitions can be clearly seen in (*Figure 7*).

From the analysis of the current curves of the 100 kV capacitor, it was concluded that the capacitor had a very low initial eccentricity. The centre position (eccentric positon) was reached almost for all the positions expect when the impact impulses were applied perpendicularly to the plan of the initial eccentricity. The component of sin(2ωt) was clearly visible in the first periods. For all other positions, additional zero crossings were clearly visible especially in the first cycles. It could be explained by a very low initial eccentricity or by a possible no-flatness of electrodes. It could also due to the direction of the impact point. Indeed, the impulse was applied towards the centre but it is possible that some fractions of this energy, transmitted to the ELV through the base of the capacitor, could not be dissipated linearly. The ELV could oscillate with elliptical movement if the energy is not directed exactly toward the centre. The impact energies were chosen as low as possible to attenuate these phenomena.

From the analysis of the currents curves of the 300 kV capacitor, it seems that the internal electrode was oscillating with the same frequency for all the impact positions. In contrary to the 100 kV capacitor, the concentric position was not reached clearly, no additional zero crossing was seen despite the voltage and the impact energy being higher than those applied to the 100 kV capacitor. From the results (*Figure 8*) and without quantitative evaluation, the co-sinusoidal shape implies that $e_0 = 0 \; or \; e_0 \gg e_M$. The negative voltage immediately observed after the impact is due to the decrease in capacitance. The influence of the sin (2ωt) is slightly visible in the first cycles despite the disturbance being present just after the impact (the origin of the disturbance was not investigated due to the lack of information about the mechanical internal design). It was clear that the value $e_0 = e_M$ has not been reached. From qualitative observations, it was assigned that the 300 kV capacitor had a medium initial eccentricity compared with current curves of the 100 kV capacitor. Because the calibration results showed very good voltage dependence, we were expecting, before these observations, to obtain current curves similar to (*Figure 3*) or at least similar to (*Figure 4*). The comparison between current curves of the 100 kV capacitor and the 300 kV capacitor could lead to a hypothesis that the 100 kV capacitor will have a very low voltage dependence. A dependence lower than the 300 kV capacitors, but this has never been discovered because the uncertainties are high. This hypothesis is confirmed in 3.3.

3.3 Calculation of initial eccentricity and voltage dependence of the 100 kV capacitor

According to equations 7 and 8, the calculation of initial eccentricity and voltage dependence was performed for the 100 kV capacitor. Indeed, the internal dimensions were supplied by the manufacturer (They are confidential and can not be published). The current curve presented in figure 7 was taken for evaluation. The results and its corresponding uncertainty are presented in the table 1. The factor k in the brackets is the distribution coefficient which is used to calculate the standard deviation of each component according the GUM [8] (k=2.√3 for uniform distribution and k=2 for normal distribution with about a confidence of 95 %). The sensibility coefficients were developed according to the [8] but are not presented in this paper.

The capacitance Cc was calculated according to equation 4 and according to the internal dimensions of the capacitor and taking into account its uncertainties of measurement. It is equal to (95.7 ± 3.3) pF and must not be confused with the measured capacitance which is equal to 99.83 pF (measured at 5 V, 50 Hz). Indeed, the quantity Cc is the concentric cylindrical capacitance. The partial capacitance between the hemispheric top of the LVE and the HVE top plate is independent of the eccentricity. It does not contribute on the voltage dependence according to the mathematic model. It is subtracted from the total measured capacitance. The capacitance between the hemispheric side of the LVE and the HVE side plate was estimated by dimension calculations. In our case Cc is about 96 % of the total measuring capacitance. The value of the permittivity of the gas (SF6. 5 bars, 23 °C) was supplied by the manufacturer. Its uncertainty takes into account the variation with the pressure drop (0.02%/year).

Table 1: Calculation of parameters and their uncertainties of measurement.

Parameter	Value ± uncertainty (k)
R2 (mm)	[redacted] ± 0.10 (3.46)
R1 (mm)	[redacted] ± 0.10 (3.46)
l (mm)	[redacted] ± 1.0 (3.46)
ε(×8,85×10^{-12} F/m)	1.012 ± 0.005 (3.46)
Cc (pF)	95.7 ± 3.3 (2)
f (Hz)	52.8 ± 1.0 (3.46)
i(0) (nA)	-25.6 ± 6.0 (3.46)
i(π/4) (nA)	23 ± 12 (3.46)
U (kV)	6.17 ± 0.10 (3.46)
b(1/m^2)	4161 ± 44 (k=2)
$e_0(mm)$	0.070 ± 0.010 (k=2)
S(N/mm)	360 ± 15 (k=3.46)
ΔC/C at 100 kV (ppm)	0.45± 0.11 (k=2)

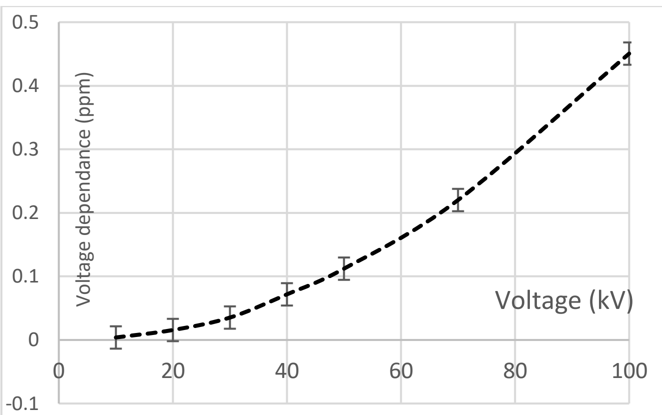


Figure 10: The voltage dependence for the 100 kV capacitor.

The natural frequency was obtained directly from the current curve by using the internal frequency measurement algorithm.

An uncertainty of 1 Hz was reasonably assumed according to the practical observations especially taking into account the repeatability of the natural frequency measurement, depending on impact positions.

The currents at positions ωt=0 and ωt= π/4 were obtained using the –cos(ωt) function as reference. Because of the strong damping, the corresponding voltage was only measured for the first periods. The measurement uncertainty of these positions is large and represents the strongest contribution to the uncertainty budget. Taking into account the sensitivity coefficients, they are about 60 % for ωt=0 and about 38 % for ωt= π/4.They are definitely due to the repeatability of the current curve in (*Figure 7*) and the direction of the impact energy. It is slightly due to the component of the measuring system (coaxial cable and oscilloscope). Possible correlations between temperature and current were not evaluated but could be reasonably neglected because the measurement was performed within a controlled temperature (23± 1)°C. The direct voltage was measured with a calibrated resistive divider, the voltage is controlled within 1 % for each impact.

With the hypothesis that the oscillations of the LVE are assimilated to a simple harmonic oscillator by neglecting the damping, the spring fitness S of the support tube was calculated using $\omega_M \approx \sqrt{S/m}$. Where, m, is the mass of the LVE. The mass of the support tube was neglected because in our case it was much lower that the mass of the LVE.

The initial eccentricity and the voltage dependence of the 100 kV capacitor was calculated according to equations 7 and 8. e_0 is equal to 0.070 mm with a relative uncertainty of less than 14 %. The low value of initial eccentricity is in accordance with what was expected. Indeed, the mechanical structure and the coaxially of the capacitor were adjusted, according to the manufacturer, with an accuracy of 0.1 mm.

The voltage dependence up to 100 kV is given in *Figure 10*. It is equal to 0.45 ppm with an uncertainty of 0.10 ppm. This low level of uncertainty is difficult to obtain with any other method. The relative uncertainty with the Kinetic method is high (about 25 %). It may be concluded that the Kinetic method is particularly suitable for use with capacitors of very low voltage dependence. For capacitors of large voltage dependence, traditional methods could be employed.

4 Acknowledgement

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

5 Conclusions

Two high voltage compressed gas capacitors with coaxial electrode structures were analysed using the Kinetic method. A mechanical impulse excited the oscillations of the electrodes and allowed measuring the natural frequency of the capacitor which is an important quantity when describing a frequency dependence. The initial eccentricity and the voltage dependence could be calculated if the internal dimensions are known. With the first capacitor, 100 kV nominal voltage with known internal dimensions, a voltage dependence below ppm level with an uncertainty of 0,10 ppm was calculated. This last value is difficult to reach with any other method. With the second capacitor, 300 kV nominal voltage, it was possible to analyse qualitatively the results without knowing the internal dimensions. It was considered that the 300 kV capacitor has medium initial eccentricity.

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