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PREQUALIFICATION OF CAPACITORS FOR HIGH-PRECISION VOLTAGE DIVIDERS

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Abstract

To ensure long-term stability, it is very important to prequalify capacitors used in high-precision voltage dividers. This paper analyzes how film and foil capacitors change due to charge and discharge cycles under different test conditions. The presented experiments aimed at simulating the electric stress associated with high voltage tests in a laboratory. The test procedure considers parameters like magnitude of test voltage, number of impulses, series resistor, test circuit geometry, cooling, self-heating, and temperature. The results indicate that with a variation of up to 500 ppm the change of capacitance caused by repetitive impulse stress can be significant. However, this effect will be smaller when there is natural cooling between test cycles. In this case, the best-suited capacitors showed a variation of less than 200 ppm. In addition, the comparison of different tests shows that the temperature coefficient plays a significant role in the change of capacitance. During the whole test, some of the capacitors show non-recoverable damage. The prequalification testing identified a suitable type of capacitor, which will be used for the realization of a high-precision RCR divider in the European research project "HV-com²".

1 Introduction

Voltage dividers are used in high-voltage measurements to attenuate the input signal suitable for a low-voltage measurement instrument. Various types of dividers are selectively used depending on the test voltage to be measured such as lightning (LI) and switching impulse (SI) voltage, AC and DC voltage [1]. Voltage dividers are usually capacitive, damped-capacitive, resistive type, or mixed type. Resistive types of dividers are typically used for impulse and DC measurements whereas capacitive dividers are typically used for impulse and AC measurements. Mixed type dividers, also known as universal dividers, have both resistive and capacitive branch so that they are able to handle all test voltage types. Universal dividers are ideal for measuring combined and composite voltages where impulse voltages are superimposed on DC or AC [2].

To provide high-voltage measurement and calibration services, high-precision voltage dividers are required. In the European Union funded project HV-com² reference level universal voltage dividers are being developed [2]. One of the key design challenges is related to choosing the optimal capacitor type to ensure long-term stability and the required performance. Therefore, it is very important to prequalify capacitors used in high-precision voltage dividers. In this study, suitability of different types of capacitors (film and foil technology) to be used in the universal voltage divider are tested with various methods. Main focus of the testing was to simulate the electric stress associated with high-voltage testing in a laboratory (Table 1). Especially very fast impulse voltages can damage or age capacitors permanently. For some capacitors, also voltage linearity tests were performed.

Table 1 Investigated capacitors

Type	Technology	Rating	Investigations
Type 1	metallized PP film	22 nF, 20 kV	breakdown, impulse stress
Type 2		47 nF, 2 kV	impulse stress
Type 3		100 nF, 3 kV	impulse stress
Type 4	metallized PP foil	100 nF, 1.25 kV	impulse stress
		10 nF, 4 kV	
		100 nF 1.6 kV	voltage coefficient
		150 nF 1.6 kV	

2 Testing of Type 1 Metallized Polypropylene Film Capacitors ($C = 22$ nF, $U = 20$ kV)

2.1 Test Object

The first type of capacitor to be tested was a metallized polypropylene film capacitor in polyester wrapping with self-healing properties. The low parasitic inductance of this particular capacitor type makes it well suited for the use in high precision dividers. The investigated samples have a nominal capacitance of $C = 22$ nF and a rated voltage of $U_{DC} = 20$ kV and $U_{AC} = 4$ kV.

Fig. 1 Metallized polypropylene capacitor

2.2 Breakdown Test

Before carrying out the impulse stress tests, which are the main focus of this contribution, breakdown tests were performed on three capacitor samples. All samples passed an initial withstand test for $t = 1$ min at 110 % ($U_{test} = 22$ kV) of the rated voltage [1]. Breakdown occurred at $U_{BD} = 33$ kV, 28 kV and 31 kV ($dU/dt = 2$ kV/s).

2.3 Impulse Stress Test

2.3.1 Measurement Circuit: After the breakdown test, impulse stress tests were performed. The aim of this type of test was to analyse how repetitive impulse voltage stress influences the capacitors' capacitance C. For this, the test objects are periodically charged and discharged. The test setup consisted of a DC power supply, a triggerable spark gap and a limiting series resistor ($R = 20\ \Omega$) (Fig. 2). The series resistor R was chosen to meet the designed RC time constant τ of the universal voltage divider. The DC power supply will charge the capacitor and when the spark gap ignites, the capacitor will be short-circuited while the series resistor limits the maximum current. Peak current $\hat{I}$ and the rise time t_r were measured using a Pearson coil together with a fast digitizer. At a charging voltage of $U = 10$ kV the resulting discharge current amounted to $\hat{I} \approx 500$ A ($\tau \approx 440$ ns, $t_r \approx 0.1$ µs, Fig. 3). The estimated rate for voltage change dU/dt is 100 kV/µs.

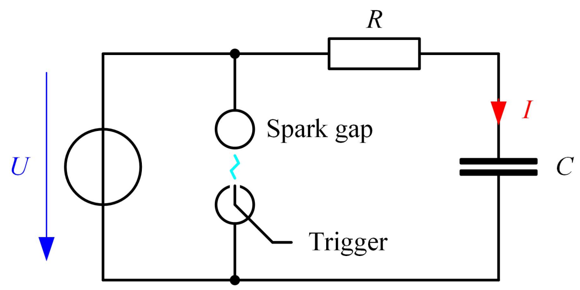

Fig. 2 Impulse stress test circuit with triggerable spark gap

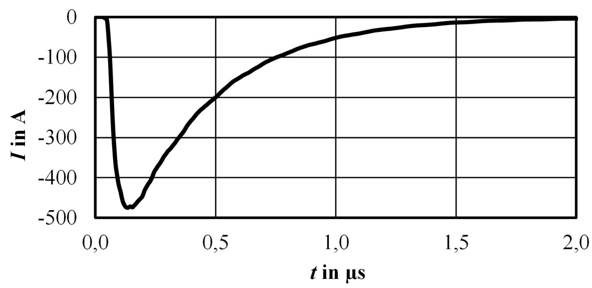

Fig. 3 Typical discharge current I at $U = 10$ kV

2.3.2 Measurement Procedure: To investigate the influence of the repetitive impulse voltage stress outlined in the previous chapter on the capacitors' capacitance C, the test objects were subjected to 100 charge and discharge cycles at constant test voltage U. After 100 cycles, the test voltage U was increased by $\Delta U = 5$ kV (Fig. 4). To assess the change of capacitance ΔC, control measurements were performed with an LCR meter after 50 impulse cycles. As the self-heating of the capacitors can be expected to influence the change of capacitance ΔC, an additional measurement campaign was performed in which the test objects were allowed to cool down for $t = 30$ min between every 50 impulse cycles (Fig. 5).

The outlined measurement procedure was independently carried out at two different laboratories. Both test laboratories performed the investigations on three capacitor samples. Additional three capacitors were used as a control group and were not subjected to any impulse voltage stress.

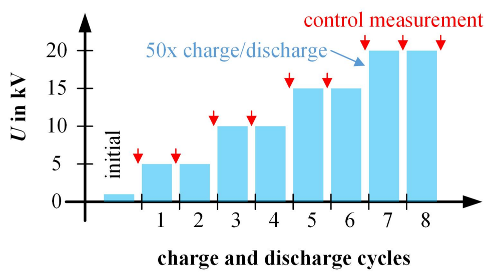

Fig. 4 Measurement procedure without cooling

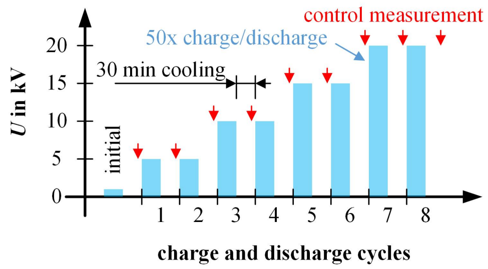

Fig. 5 Measurement procedure with cooling for $t = 30$ min

2.3.3 Results: At laboratory 1 the impulse voltage stress cycles described in the previous chapter led to comparable changes in capacitance in the three test objects. After $n = 400$ impulses, the non-recoverable relative change of capacitance amounted to $\Delta C \approx 500$ ppm in case of no cooling (Fig. 6). With a cooling period of $t = 30$ min between the impulse cycles the relative change of capacitance was $\Delta C \approx 320$ ppm (Fig. 7). Therefore, the change of capacitance due to self-heating is approximately $\Delta C \approx 180$ ppm.

The results obtained from laboratory 2 agree well with those from laboratory 1. The maximum change of capacitance amounts to $\Delta C \approx 300$ ppm in relation to the initial measurements performed in the beginning ($n = 0$) (Fig. 8). The subjection to additional impulse cycles evidently confirm the non-recoverable nature of the damage caused by the impulse voltage stress. This test affirmed the expected behaviour of film capacitors, which usually have quite limited dU/dt specification (10 kV/µs). The tests also confirmed the relatively high temperature coefficient, which complicated the analysis of the test results. Using the control group in laboratory 2 helped to separate the small changes of the ambient temperature from the actual damage.

3 Testing of Type 2 Metallized Polypropylene Film Capacitors ($C = 47$ nF, $U = 2$ kV)

3.1 Test Object

After assessing the experiences obtained from the impulse voltage stress experiments performed on the 20 kV capacitors, it was decided to perform further experiments on capacitors with a lower voltage rating. The capacitors this chapter focusses on are again a self-healing, low-inductive and polyester wrapped type. The manufacturer recommends this type of film capacitor for pulse as well as snubber applications. The investigated samples have a nominal capacity of $C = 47$ nF, and rated voltages of $U_{DC} = 2$ kV and $U_{AC} = 500$ V.

3.2 Impulse Stress Test

3.2.1 Measurement Circuit: The implemented measurement circuit is almost identical to the one described in chapter 2.3.1. However, in this case a limiting resistor of $R = 50\ \Omega$ was used. At a charging voltage of $U = 2$ kV the resulting discharge current was $\hat{I} \approx 23$ A ($\tau \approx 2.35$ µs, $t_r \approx$ 9 ns).

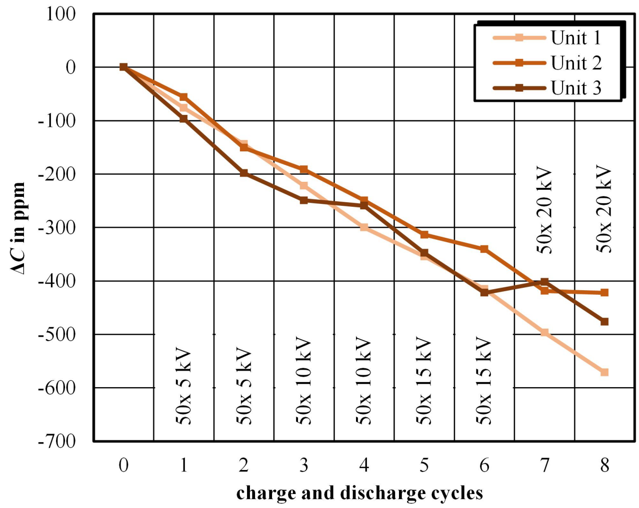

Fig. 6 Relative change of capacitance ΔC without cooling, laboratory 1

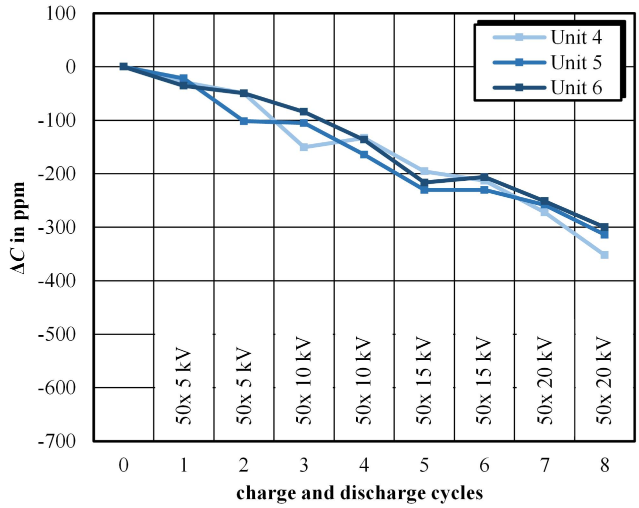

Fig. 7 Relative change of capacitance ΔC with additional cooling periods for $t = 30$ min, laboratory 1

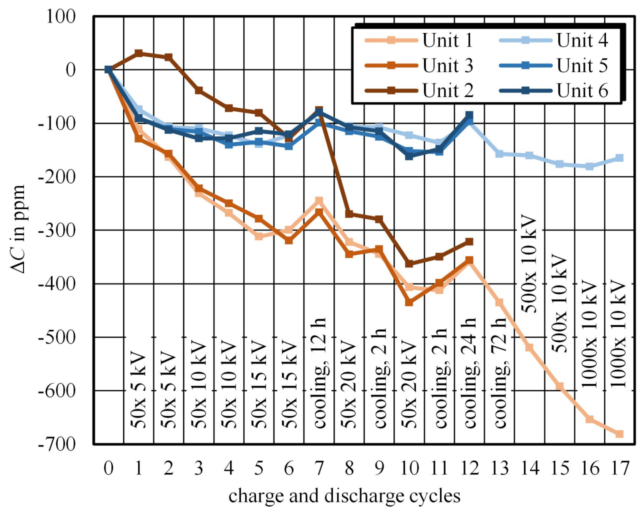

Fig. 8 Relative change of capacitance ΔC, laboratory 2, Unit 1, 2, 3: without cooling, Unit 4, 5, 6: control group

3.2.2 Measurement Procedure: While the measurement procedure is in general similar to that described in chapter 2.3.2, it was decided to perform 500 charge/discharge cycle in every measurement cycle (Fig. 9). The experiments were again performed with and without an intermediate cooling phase. The cooling time itself was extended to $t = 1$ h.

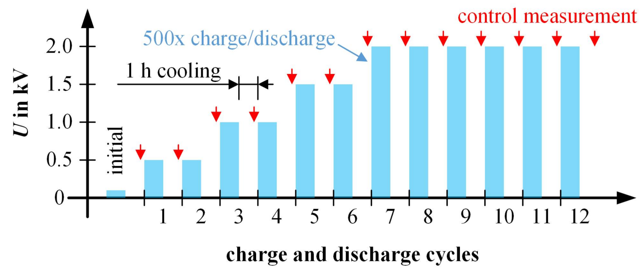

Fig. 9 Measurement procedure with 1 h cooling

3.2.3 Results: After $n = 6000$ impulses, the observed relative change of capacitance was $\Delta C \approx 500$ ppm in case of no cooling (Fig. 10). However, the change of capacitance in reference to the initial measurement at $n = 0$ is around $\Delta C \approx 150$ ppm, when there is a 1 h cooling period between each measurement.

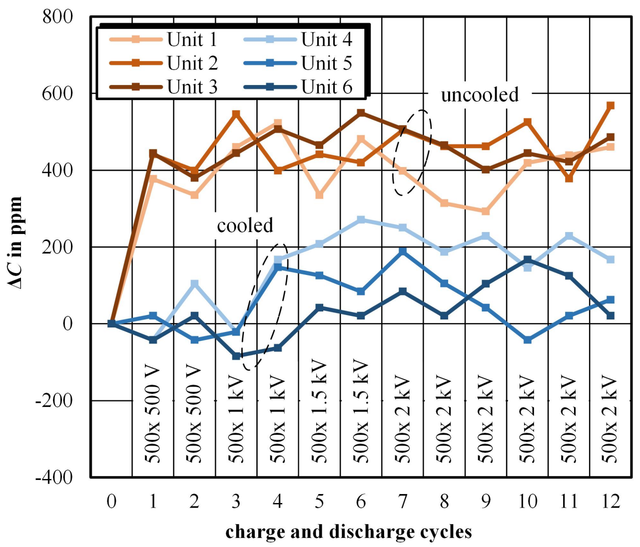

Fig. 10 Relative deviation ΔC at different voltages, unit 1, 2, 3: without cooling, unit 4, 5, 6: with one-hour cooling time

4 Testing of Type 3 Metallized Polypropylene Film Capacitors ($C = 100$ nF, $U = 3$ kV)

4.1 Test Object

Another type of capacitor, which was subjected to impulse voltage stress, a film type, which is explicitly rated for pulse and snubber applications. The nominal capacity was $C = 100$ nF, the rated voltage $U_{DC} = 3$ kV.

4.2 Impulse Stress Test

4.2.1 Measurement Circuit: The limiting resistor used in this case was $R = 5\ \Omega$, leading to a discharge current of $\hat{I} \approx 500$ A at $U = 3$ kV ($\tau \approx 500$ ns, $t_r < 0.2$ µs).

4.2.2 Measurement Procedure: For this type of capacitor the influence of cooling was not investigated. The number of impulses n and the charging voltages U are noted in Fig. 11. Three units were tested and three units were used as a control group without applying any voltage.

4.2.3 Results: Two out of three tested units resulted with a relative change of capacitance of $\Delta C \approx 1500$ ppm. This particular type of capacitor exhibited the highest relative change in capacitance of all capacitor types discussed in this contribution. Measured change was verified to be permanent by repeating the capacitance measurement after 24 hours of cooling. One out of three tested units did not show any permanent damage when compared to the control group. Only the self-heating (~300 ppm) was observed after the impulses. The results indicate that this capacitor might not be the ideal option for impulse applications.

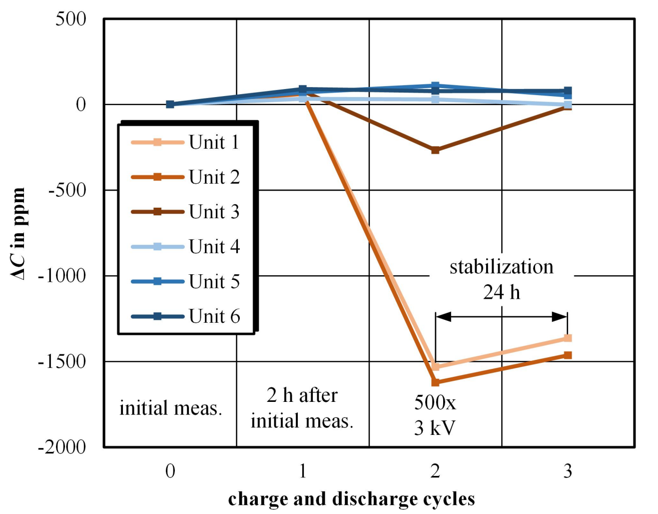

Fig. 11 Relative change of capacitance ΔC at different voltages Unit 1, 2, 3: test objects, Unit 4, 5, 6: control group

5 Testing of Type 4 Very High Pulse Applications Metallized PP Foil Capacitors

5.1 Test Object

After obtaining promising results when investigating the special pulse type film capacitors discussed in chapter 3, it was decided to further examine pulse foil type capacitors. The capacitors this chapter is dedicated to are advertised to be suitable for very high pulse applications and are equipped with metal foil electrodes and metallized internal series connections. To assess the influence of capacitance C and rated voltage U, the experiments were performed on two different capacitor types from the same product ($C_1 = 100$ nF, $U_1 = 1.25$ kV, $C_2 = 10$ nF, $U_2 = 4$ kV).

5.2 Impulse Stress Test

5.2.1 Measurement Circuit: To keep the time constants τ constant, two different values of limiting resistors R were used in this case ($R_1 = 5\ \Omega$, $R_2 = 50\ \Omega$). For $C_1 = 100$ nF the resulting current is $\hat{I}_1 \approx 160$ A at $U = 1$ kV discharge ($\tau \approx 500$ ns, $t_{r1} < 0.2$ µs). For $C_2 = 10$ nF the resulting current is $\hat{I}_2 \approx 70$ A at $U = 4$ kV discharge ($\tau \approx 500$ ns, $t_{r2} < 0.1$ µs).

5.2.2 Measurement Procedure: For this type of capacitor the influence of cooling was not investigated. The number of impulses n and the charging voltages U are noted in the respective results diagrams in Fig. 12 and Fig 13.

5.2.3 Results: In contrast to the previously discussed impulse voltage results, it was not possible to observe a clear trend or measurable difference regarding the change of capacitance ΔC after subjecting C_1 and C_2 to repetitive impulse voltage stress (Fig. 12 and Fig 13). Both types of capacitors stayed relatively stable, which is most likely due to their special very high pulse applications design. This design was found to be durable enough for impulse voltage tests. The downside of this type of capacitor is the relatively high temperature coefficient (~300 ppm/K) which can be seen as capacitance differences in Fig. 12 and 13.

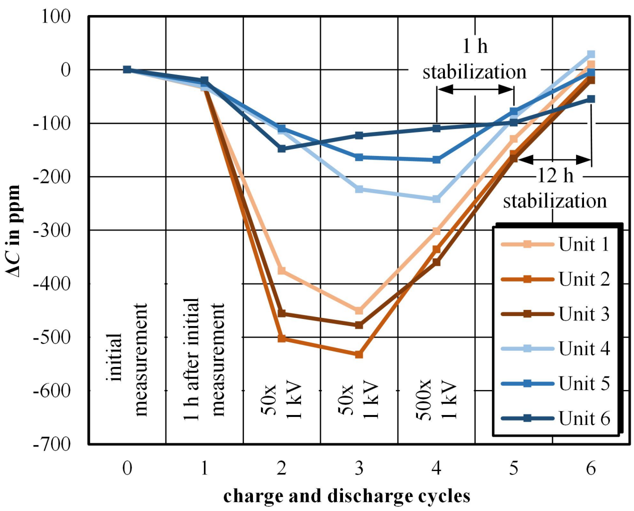

Fig. 12 Relative change ΔC_1 ($C_1 = 100$ nF), Unit 1, 2, 3: test objects, Unit 4, 5, 6: control group

6 Voltage Dependence of Type 4 Metallized Polypropylene Foil Capacitors

6.1 Test Object

Since the impulse stress behaviour of the PP foil capacitors described in the previous chapter indicated good suitability for the use in voltage dividers, further investigations were carried out on this type of capacitor.

These investigation focussed on the voltage dependence, which is one of the key parameters for components in metrology applications. The investigated components' nominal capacitances were $C_1 = 100$ nF and $C_2 = 150$ nF.

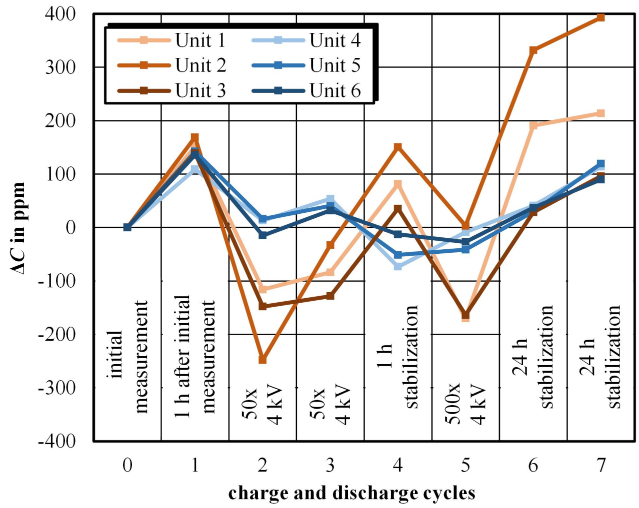

Fig. 13 Relative change ΔC_2 ($C_2 = 10$ nF), Unit 1, 2, 3: test objects, Unit 4, 5, 6: control group

6.2 Measurement Procedure

To investigate the voltage dependence $C = f(U)$, an AC bridge circuit was used ($C_N = 10$ nF). Additionally, the dissipation factor tan δ was determined. Three samples of each type were available for testing.

6.3 Results

For both groups of the investigated capacitors a significant increase in capacitance C was observed for rising test voltages U (Fig. 14a, Fig. 15a). In the case of $C_1 = 100$ nF the change of capacitance amounted to $\Delta C \approx 1250$ ppm at $U = 600$ V (with reference to $U = 15$ V).

For $C_2 = 150$ nF the observed change was slightly higher ($\Delta C \approx 200$ ppm at $U = 600$ V). While the observable increase in capacitance ΔC was rather continuous over the whole test voltage range U, the dissipation factor tan δ exhibited a distinct change of slope for $U > 500$ V (Fig. 14b, Fig. 15b).

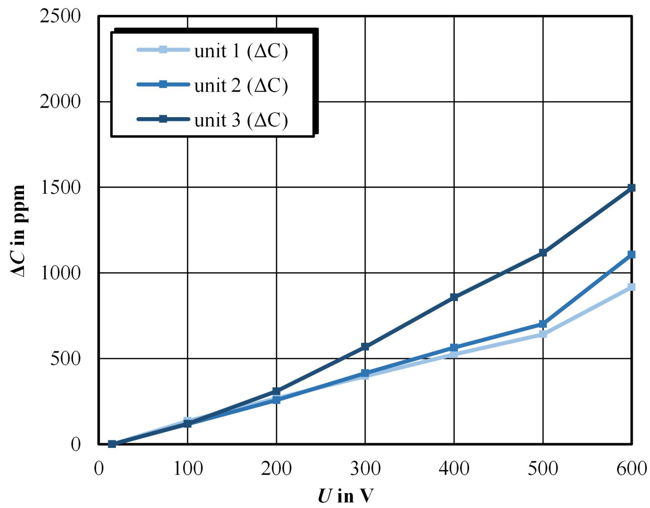

Fig. 14a Relative change of capacitance ΔC as a function of the test voltage U for $C_1 = 100$ nF

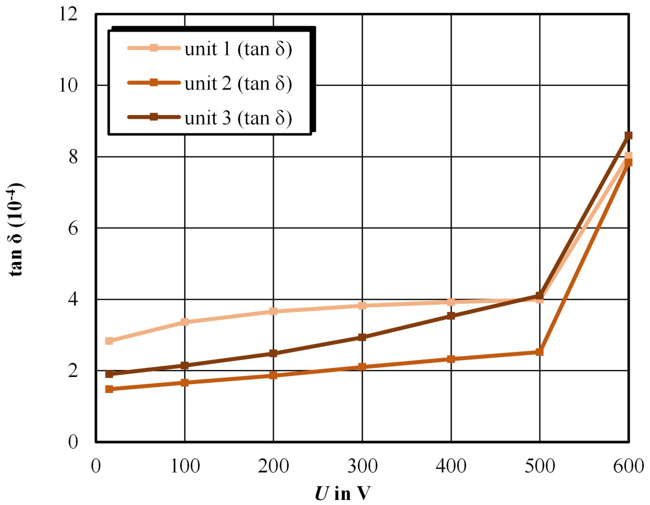

Fig. 14b Dissipation factor tan δ as a function of the test voltage U for C_1 = 100 nF

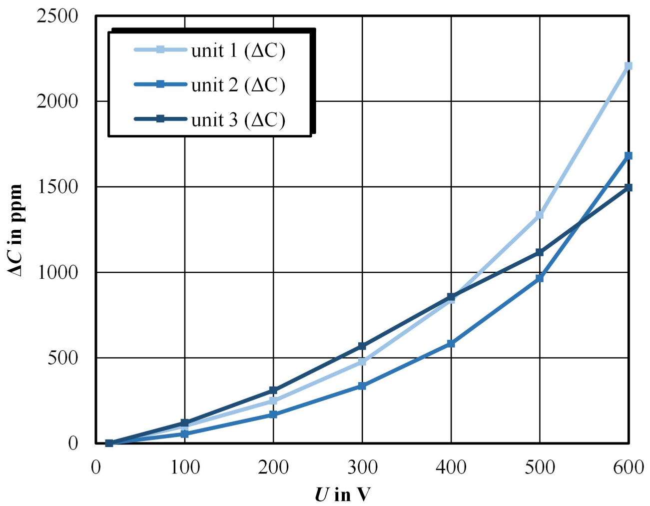

Fig. 15a Relative change of capacitance ΔC as a function of the test voltage U for C_2 = 150 nF

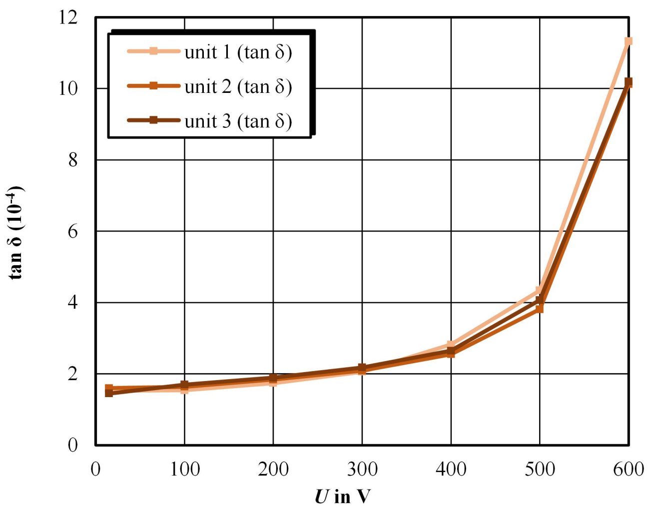

Fig. 15b Dissipation factor tan δ as a function of the test voltage U for C_2 = 150 nF

7 Conclusion

During the impulse voltage stress tests, it was noted that the test geometry affects the peak current as well as the resulting rise time significantly, which complicates reproducibility. Furthermore, the temperature coefficient proved to have a more significant influence than previously anticipated, which made the evaluation of the test rest results more difficult.

The impulse voltage stress led to non-recoverable damage in all investigated film capacitor samples, which makes them unsuitable for the measurement of very fast voltages. The foil capacitors, on the other hand stayed, relatively stable, which makes them a promising candidate for the use in universal voltage dividers. In the investigations regarding voltage dependence, the foil capacitors showed a significant rise of capacitance with increasing voltage

While the significance of the non-negligible temperature coefficient is still somewhat unclear, it was decided that the investigated type of foil capacitor will be used for future prototypes of universal voltage dividers in this project.

8 Acknowledgements

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The data discussed in this contribution can be accessed under https://zenodo.org/record/5047834.

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