Study Collection

Measurements on (standard) capacitors

Kees Pronk & Piet Trimp

The readers of this magazine are probably well aware of what a capacitor is: two conductive plates with an isolating dielectric in between. The purpose of this article is to present a number of special capacitors available in the EEMCS Study Collection in Delft and to discuss equipment to effectuate precise measurements of capacitor values.

An ideal capacitor has a capacitance according to the following formula: $C = (\varepsilon_0 \cdot \varepsilon_r \cdot A) / d$, where C is the capacitance in Farad, ε_0 is the dielectric constant (a.k.a. vacuum permittivity) of vacuum ($8.854187 \cdot 10^{-12}$ F·m^{-1}), ε_r is the dielectric constant of the insulating material, A is the surface of the plates (in m^2) and d is the distance (in m) between the plates. To give an idea: with A = 1 m^2, d = 10^{-3} m, and using vacuum as dielectric, the capacitance is 8.85 nF.

Whereas in an ideal capacitor voltage and current are 90 degrees out of phase, unfortunately the dielectric material is not an ideal (leak free) medium; some leakage of electrons is always present. We model this leakage with a resistor parallel to the capacitor (see figure 2). The impedance of the circuit is $Z = R / (1 + j\omega RC)$, and is therefore frequency dependent. Consequently, voltage and current are not precisely 90 degrees out of phase and we find a loss factor (a.k.a. capacitor loss tangent) which is commonly known as tan δ (see figure 2). It should be noted that the loss factor is frequency dependent; the frequency used during a measurement should always be specified.

Of course, as with other units of International Standards, standard organizations like NIST (National Institute of Standards, USA) and NMI (Nederlands Meet Instituut, Netherlands Measurement Institute) maintain high precision reference capacitors against which other capacitors can be calibrated. This article is not the place to discuss various forms, applications and use of capacitors. Reference [1] gives many useful details on that subject. Instead we will emphasize precision capacitors, their use and carrying out measurements using precision capacitors.

Fixed value capacitors

The Study Collection has a few Standard capacitors of which two examples are given in figures 3 and 4. This standard capacitor from General Electric has a value of 1 µF and is accurate to +/- 0.05%. This specification is only valid for frequencies below 17 kHz. The maximum voltage is 500 Volt. The capacitor in figure 3 from Sullivan Ltd in London has a capacitance of 0.1 µF. Its dielectric material is mica, an insulating mineral found in volcanic areas. Mica has a high dielectric constant and is a very stable crystal-like material. Of course there do exist also switchable capacitors banks (similar to the well-known resistor banks). These banks have less precision and stability but are more flexible in experiments. Here we show one made by General Radio (USA). It has a range from 1 nF to 1.1 µF, the maximum voltage is 500 Volt peak; the zero capacitance is 40 pF. (figure 7)

Variable value capacitors

In electronic practices around WW II, it was necessary to have variable capacitors having good accuracy and stability. Figures 5 and 8 show two capacitors available in the Study Collection.

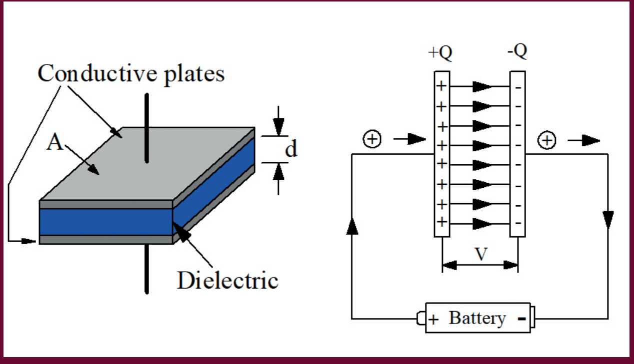

Figure 1. *Model of a perfect capacitor*

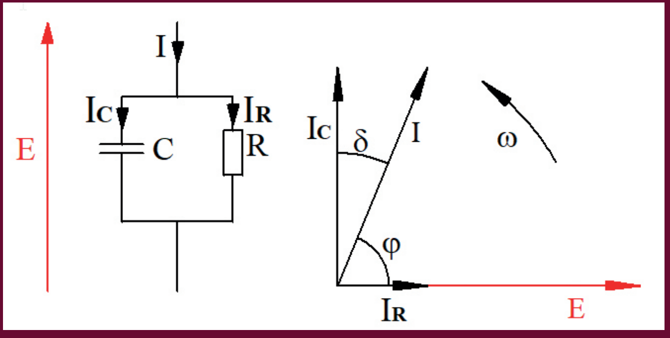

Figure 2. *Adding imperfections to the model*

Figure 3. *Standard capacitor from Sullivan Ltd. (UK)*

Figure 4. *Standard capacitor from General Electric (USA)*

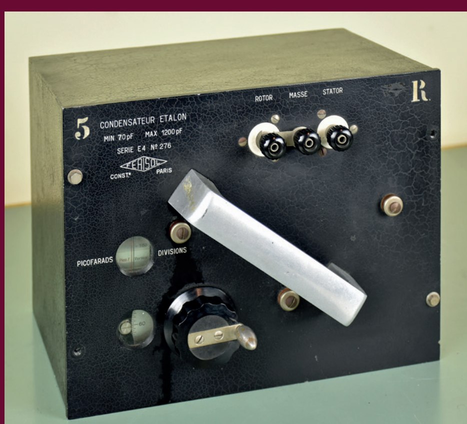

Figure 5. *Variable precision capacitor (external view)*

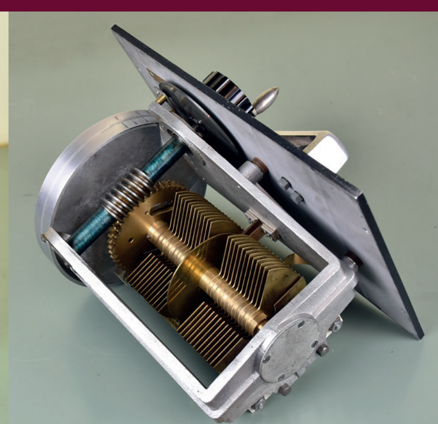

Figure 6. *Variable precision capacitor (internal view)*

Figure 7. *Decade condenser (Capacitor)*

Figure 8. *Philips GM 4352 standard capacitor*

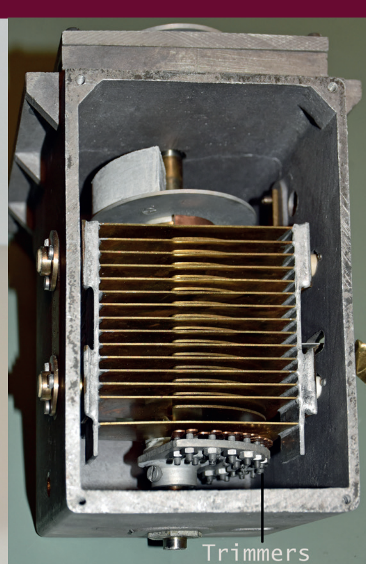

Figure 9. *Internal view of Philips GM4352; Notice the trimmers*

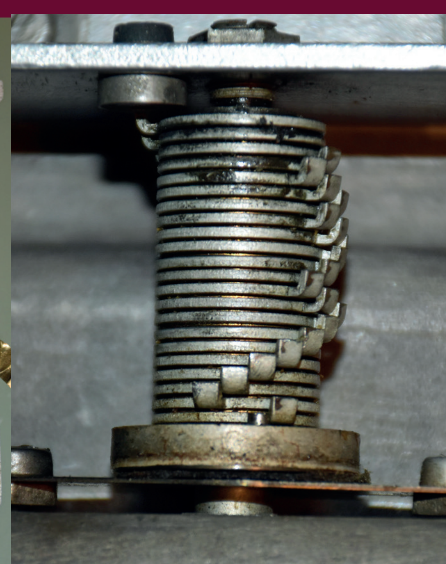

Figure 10. *Twenty turn rotation mechanism*

These capacitors look internally like standard variable capacitors as used in radios but they are more stable and accurate.

The variable capacitor in figure 5 and 6 (Condensateur Etalon) was made by the French firm Verisol (in Paris). The capacitance can be adjusted on the front panel from 70 .. 1200 pF by means of a coarse and fine adjustment dials. By turning the dials the half-round blades are rotated 'in between' the fixed blades. Due to parasitic capacitances, these capacitors need a calibration chart. It should be noted that the creation of a calibration chart requires the availability of higher precision capacitors and a measuring device able to measure the difference between two capacitances.

Another example of such a variable capacitor is the Philips GM 4352 standard capacitor that was introduced by Philips around 1952. This standard capacitor (figure 8) has a variable capacitance ranging from 60 to 300 pF. No calibration chart is needed for this device because of the use of many trimmers (see figure 9).

Thanks to the purely mechanical 20-turn mechanism shown in figure 10 there is only one knob for adjusting the value of the capacitor. To increase the readout accuracy a mirror and a hairline are provided as in well-known high precision volt and ampere meters. The data sheet is available on the web in ref. [2].

Measuring capacitance values

To measure the capacitance value of a capacitor usually a bridge circuit derived from the well-known Wheatstone bridge is being used. The Wheatstone bridge (figure 13) is operated by adjusting the potentiometer until the bridge is balanced and the meter reads zero. The value of the of R_x can be calculated from the value of a known Resistance R_2 and the potentiometer ratio. Both alternating current and direct current can be used to feed the bridge.

When the resistors R_x end R_2 are replaced by the capacitors C_2 and C_x, alternating current must be used to feed the bridge. When using a frequency in the audio spectrum, a headphone having a high impedance can be used for zero detection. The circuits for this can be seen at ref. [3] and in figure 13. When the bridge is balanced, the value of the capacitance C_x can be expressed as $C_x = C_2 \cdot (R_1 / R_2)$ where C_2 is a standard capacitor having a high accuracy. The above reasoning is perfected in a capacitance measuring device from Siemens, to be described below.

As an example of a device capable of high precision capacitance measurements we shortly discuss the Siemens Kapazitäts Meßbrücke (capacity measuring bridge) type Rel. 3 116 (see figures 11 and 12) which was bought around 1958 by the Laboratory for High Voltage Technology in Delft and which is now in the Study Collection. This bridge measures capacitor values from 0.001 pF to 100 µF and is directly readable for frequencies of 200, 800, 2000 and 5000 Hz. The measurement of tan δ is possible from 0.5 .. 100. 10^{-3}. The accuracy in the range from 10 pF to 10 µF is 1 ‰. The schematic diagram is given in Figure 12. This box only contains the bridge circuit. There are no electronic devices in this box. The input measurement signal is to be provided through the connectors 'Sender'. The output signal of the bridge appears at the connectors 'Empfänger'. Both Sender and Empfänger are coupled to the bridge circuit via transformers and therefore the bridge is floating with respect to the signal earth. With these kind of measurement it is vital to provide for proper double shielding of parts of the bridge as can be seen in the schematic diagram in figure 12. The reference element of the bridge is a capacitor CN of 10,000 pF. In this Siemens bridge circuit the usual bridge resistors are replaced by coils with taps. The switches S_1 to S_4 are used to determine the measurement range. These switches form a so-called Kelvin-Varley voltage divider (see ref. [4]). The switch S_5 is used for measuring tan δ. Using coils is much more expensive than using resistors but leads to an extended measurement range and a better accuracy. Capacitors to be measured are connected to pins a and m on the front panel. Differential measurements are possible by connecting a second capacitor to the pins m and b. Additional documentation is available from the author; see ref. [5].

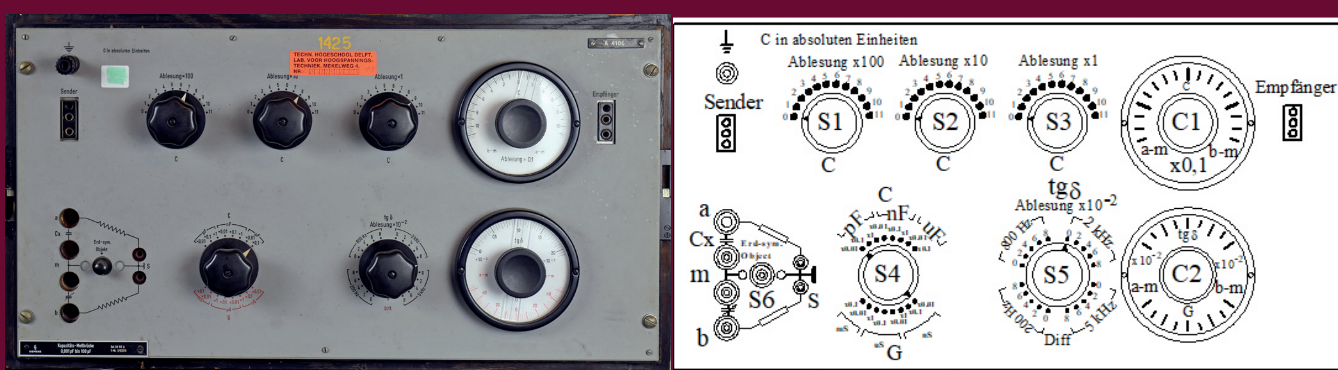

Figure 11. *Siemens Rel. 3 116 high precision capacitance bridge, and the interface's manual entry*

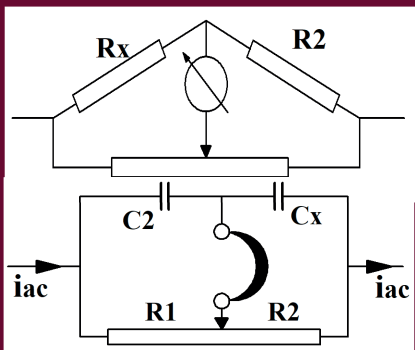

Figure 13. *A wheatstone and the derived Capacitor bridge.*

Figure 14. *Andeen-Hagerling Capacitor Measurement System*

Two final remarks will be made here: (1) Normally, a signal generator using vacuum tubes will be used to provide the signal to the Sender connectors and at the Empfänger connectors a (possible tuned) vacuum tube voltmeter will be used to provide for more accurate nulling (2): It is rather unclear what use can be made of a measurement range down to 0.001 pF. The Siemens documentation only mentions one application area: the measurement of capacity between electrodes in a vacuum tube (e.g. between a grid and the anode).

Modern developments

Nowadays capcitance measurements are done with modern equipment such as the Andeen- Hagerling Inc. AD 2700A shown in figure 14. This machine has an outstanding accuracy and stability traceable to NIST-standards. Some specifications are: Accuracy at 1kHz of 5 ppm; Stability better than 1 ppm/year; True Resolution at 1kHz of 0.5 attofarad (0.000 0005 pF) and 0.15 ppm; Reportable resolution of 0.1 attofarad (10^{-7} pF); Temperature coefficient of 0.03 ppm /°C; Measures extremely low loss at 1kHz down to a dissipation factor of $1.5 \cdot 10^{-8}$ tan δ, a conductance of 3×10^{-7} nanosiemens or a resistance up to 1.7×10^{6} gigohms; Operating frequency is 50.000Hz-20.000kHz ±0.0025% in discrete steps.

Such a machine also allows for automated measurements using a GP-IB (IEEE-488) bus. A few application areas are copied from the above web page: Capacitance measurements on Carbon nano tubes, on Liquid Cristal Displays and on Superconductivity.

The machine shown here is in use at the group Electronic Instrumentation in the EEMCS faculty for measurements on capacitive gas sensors.

Conclusion

This article has provided a short overview ofa the use and measurement of (standard) capacitors. Measurements of capacitors has been important from the early twenties of the previous age and is still important in these days for determining capacitances of many kinds of sensors.

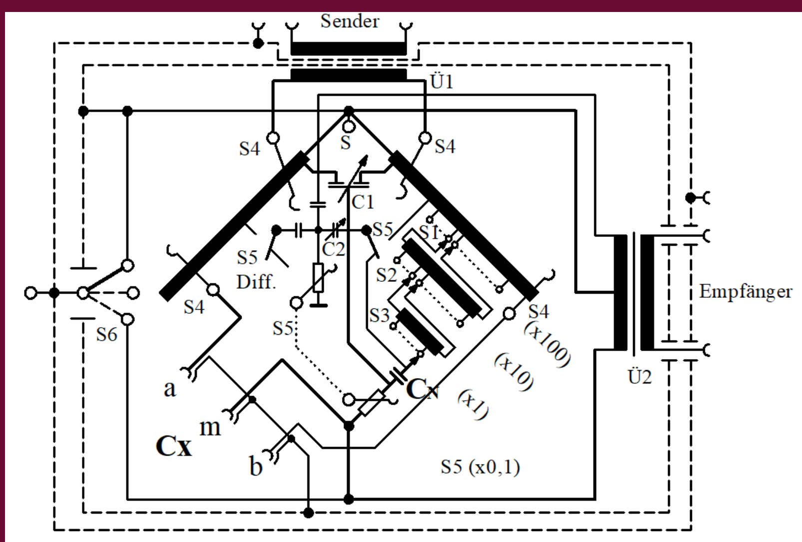

Figure 12. *Circuit diagram of the Siemens capacitor bridge*

[1] http://www.breem.nl/TechThemas/Condensatoren.htm (in Dutch)
[2] Variable Standaardcondensatoren Philips GM 4352: [https://elektrotanya.com/philips_gm_4351_4352_4353_100_300_1000pf_variable_standard_condensators_1952_sm.pdf/download.html]
[3] Meting van condensatoren, in: Meetinstrumenten; De Muiderkring, 4th printing, pp (46-49), 1953 (in Dutch)
[4] https://en.wikipedia.org/wiki/Kelvin%E2%80%93Varley_divider
[5] Siemens Kapazitäts Meßbrücke type Rel. 3 116, 200 bis 10.000 Hz; Beschreibung und Bedienung (in German), 1959