Capacitance Standards and their Calibration

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Abstract

Selection and calibration of capacitors for use as Standards is a challenging task, especially since the accuracies required, depening on the application, can be very demanding for the test gear as well as for the secondary- and working-standards used. Few capacitance meters are suitable if a higher accuracy needs to be achieved, and also few secondary- and working-Standards support such high accuracy. The meteres suitable comprises traditional manually operated capacitance bridges as well as a few selected capacitance meters. Also taken into account has to be the traceability accuracies to National Standards.

This document gives general explanations about key aspects of Capacitance Standards, measurement accuracy related topics and also describes our approach in calibration of the Capacitance Standards we build.

1. Capacitance Working Standards - Background

In this paragraph, a brief summary is initially given related to the use and selection of capacitance technologies, as applied by us. This is especially in view of our baseline to produce cost efficient Capacitance Standards, based on readily available components, eliminating some of the more exotic or extremely expensive technologies such as e.g. fused silica or (hermetic) air, which are consequently not covered here.

For the calibration of capacitance- (or LCR) meters, Capacitance Standards with accurately known values for C and D at a given frequency are required. While it is possible to determine these values very precisely at lower frequencies (1kHz is mostly used), this gets harder at higher frequencies due to the increasing impact of parasitic parameters. We therefore use 1kHz as the calibration frequency, although we could also use others, e.g. on special request. To achieve higher accuracy there, we can reference the measurements to the GR capacitors and do a relative measurement, circumventing to a certain degree the lower accuracy at higher frequencies. This is possible because the GR air capacitors have a specified behaviour over frequency.

Generally, the prerequsite for achieving a high accuracy is to use coaxial Standards, as we only offer them, see also further below in para. 2.

Capacitance Standards are characterised by a couple of parameters:

- calibration uncertainty
- temperature drift
- aging drift
- absolute value

- calibration frequency

While the calibration uncertainty, temperature- and aging-related drifts are critical for the use of the Standard, the absolute value is not. An absolute deviation from a nominal value of e.g. 5%, although usuall not used for Standards, would not be of concern at all, provided the calibration uncertainty is sufficiently low. We use reasonable deviations from nominal for cost efficiency reasons (for details see our Calibration Standard data sheets). However we take great care that the calibration uncertainty is generally low, and we do offer several versions of uncertainty in some cases.

The next parameter impacting the overall uncertainty of a Capacitance Standard is drift related to temperature and aging. Primary Standards are based on fused silica or hermetic invar air dielectric, are low capacity, and pretty expensive and thus not further considered here. But temperature drifts can also be minimized by using appropriate readily available capacitor technologies such as mica or low drift ceramics, thin film or foil (for higher capaciances where mica is not available or very expensive/exotic). Foil today is not a preferable solution, there is better solutions available. Mica and COG ceramic capacitors are available with low thermal drifts down to 30ppm/K for COG (mica is typically worse than COG, arround 70ppm, also depending on the manufacturing process), making them well suitable for Standards with respect to temperature related drifts. Hermetic glass mica capacitors are available, although not cost-efficiently in ROHS-versions. These hermetic capacitors have typically lower aging drifts thn normal mica capacitors, simply because the impact of environmental effects such as e.g. humidity or chemicals is minimized through the hermetic case. But the impact of humidity can also be generally reduced by using a sealed metal housing for the Standard in combination with an appropriate dissicant. This has been done in the industry for quite a while. We apply this technology, not using silica gel however but another material, achieving lower humidity levels. Normal mica capacitors show low drifts anyway, and have been used in Standards for decades. COG capacitors are low drift too, they do not show the known aging/drift effects of ferroelectric (class II and III) ceramic material capacitors and also no microphonic effects, and overall are a good solution for laboratory Standards. They are now available also in higher capacitances. A relatively new class of readily available capacitors are thin film capacitors in SMD-version, using SiO_2 as dielectric material. They show low dissipation factors, relatively close tolerance also in low capacitance ranges even below 1pF and are available with the same low temperature coefficent as COG. Which technology has been used where in our standards is specified in the related datasheets.

2. Capacitance Calibration

The precision measurement of capacitors for the purpose of calibration is generally based on a national primary standard of high accuracy, secondary/working Standards derived from it, and a capacitance- (or LCR-) meter used for the measurement (i.e. calibration) of the devices under test (DUT). This meter is normally calibrated with reference to the secondary Standards, and thus the traceability chain is maintained.

It is important that the measurement uncertainties for the various steps are known. In addition, drift rates related to aging and temperature for the various Standards and the measurement gear needs to be known. These values are usually specified for the standards and meters used.

Our focus in calibrating the working Standards we build and sell was to base our measurements on one, precisely calibrated secondary laboratory Standard that we maintain, which has a known low aging and temperature drift rate. This ensures good traceability and limits the costs of Standards used as well as that for external calibration. From this standard we derive (calibrate) our other working standards, which in turn are used as the verification/calibration Standards for any other meters used.

The measurement and calibration of the D-factors (dissipation factors) is ususlly based on precise resistors used to simulate D-factor equivalent series- or parallel-resistances. These resistors can be calibrated with a precision resistance meter, ensuring traceability to National Standards also for the D-factor.

The selection of suitable equipment to perform the tasks described above is as important as the selection of appropriate capacitors for the Capacitance Standards we offer. This relates to the accuracies of the meters and standards used, the interconnections supported (to achive high accuracy) and the procedures applied.
The Capacitance Standards we build, in order to achieve high accuracy, are generally of coaxial (also called 'three terminal') type. That means that each of the two terminals of our Capacitance Standards is brought out through a BNC connector, with the shield of the two connectors forming the third terminal. This setup ensures that parasitic capacitances within the Standard are essentiallly eliminated as a source of error (the mathematical explanation of the background of this principle goes beyond the scope of this document, but such information is generaly available). As a consequence, all test gear used has to support this setup (precision gear anyway does).

Meters requiring 4-Terminal BNC interfaces (actually 5-terminal, including the shield) such as those on e.g. Keysight capacitance meters, can also be calibrated with these standards by using suitable adapters (BNC-Tees) directly at the Standard terminals, and coaxial cables, although we do also offer special 4-(5-)terminal BNC Capacitance Standards for these meters. Low precision meters, only having two terminals, can be interfaced by using two BNC to Banana adapters.

3. Methods, Technologies and Equipment
Our lab Secondardy Standard is a hermetically sealed SC1000 coaxial air capacitor with 1000pF, calibrated to a low uncertainty. The laboratory working Standards used in our calibration chain are Genrad (GR) air capacitors (type 1403; 1pF to 1000pF; also exhibiting excellent high frequency behaviour), a Genrad GR1615-P1 10nF hermetic Mica standard and a lab-built Mica low drift hermetic 100nF capacitor.

The working standards are calibrated using a precision manually operated IET/Genrad 1620 capacitance bridge, on the basis of the SC1000. This bridge, despite being a several decades old design, is still inproduction and is one of the most accurate capacitance meters available with a basic accuracy of 0.01% (100ppm) at 1kHz and a resolution (capacitance) of 6 digits (1ppm!). The advantage of this bridge is that the base of its accuracy are switchable transformers (i.e. switched transformer taps), thus the accuracy is essentially only dependent on the transformer winding ratios, (adjustable) drifts of internally used hermetic capacitors, plus certain parasitic effects. This bridge is capable of measuring down into the attofarad range and includes a self-calibration mechanism, allowing capacitance calibration of all its ranges derived from one known precise external capacitor. We use our SC1000 Secondary Standard for this.

This bridge is used to directly calibrate the most accurate Capacitance Standards in our product line.

It is also used to calibrate, by means of the GR Standard Capacitors, our precision IET/Genrad 1689 digibridge, which has a basic accuracy of 0.02%. This bridge is used for all calibrations not requiring the highest precision. The reason for distigushing is that the use of the 1620 manual bridge, while being extremely accurate, is also much more time consuming and thus costly, so an automatic bridge (capacitance meter) such as the 1689, is the more efficient approach. This is also the reason why manual bridges are rarely used today, it is simply expensive due to labour costs.

It should be noted that other precision capacitance meters, frequently used in calibration labs, in comparision, usually have a basic accuracy of 0.1 to 0.05%, at best. Only very few calibration labs use the Andeen Hagerling or IET 1621 bridges, the most acurate bridges available commercially today, which are about an order of magnitude better.

4. Uncertainty Contributors
3.The following contributors are relevant for the calibration procedures applied (max. values

listed):

- SC1000 calibration uncertainty: 32ppm
- SC1000 anual drift: 20ppm; here ½a assumed
- SC1000 temperature drift (1K): 5ppm
- IET1620 C-uncertainty: 100ppm + 30aF
- IET1620 C-drift (1K): 5ppm
- IET1689 C-uncertainty: 200ppm
- IET1689 C-drift (1K): 5ppm
- IET1689 D-uncertainty: 0.0002
- IET1689 D-drift (1K, 1kHz): 5ppm
- GR1403, 1615-P1 temp. drift (1K): 30ppm
- Temperature drift during test: 2K (+/-)

For the analysis of the absolute measurement uncertainty of the 1620 bridge, we assume that all uncertainties are of rectangular distribution (divider ? 3 = 1,73).

With K=2 (equals 95% confidence level), the calculated absolute measurement uncertainty U of the IET 1620 bridge (per RSS summation due to uncorrelated parameters), is therefore:

$U(IET1620) = 2 * \sqrt{((32/1.73)^2 + (10/1.73)^2 + (10/1.73) + (100/1.73)^2 + (10/1,73)^2)} =$
$2 * \sqrt{(346 + 33.4 + 33.4 + 3341 + 33.4)} =$
123 ppm or 0.0123%

Consequently, the GR1403 capacitors used for the calibration/verification of our IET1689 digibridge have this uncertainty (plus the related temperature drift uncertainty for a +/-2K temperature uncertainty; normal distribution). Thus, these capacitors are calibrated to 133ppm or 0,0133% worst case. The verification of the 1689 bridge is made shortly after the calibration of the GR capacitance standards so that we can avoid the impact of any aging-related drift,

To be conservative, we use 150ppm / 0.015% (instead of 0,0123%) or higher as the datasheet specified uncertainty value for the factory calibration of our Capacitance Standards we calibrate with the IET1620 bridge (see data sheets for applied value).

For the calculated uncertainty U of the IET1689 bridge, as calibrated with these GR Standards, within a +/-2K temperature window, the following applies (K=2):

$U(IET1689) = 2 * \sqrt{((200/1.73)^2 + (10/1.73)^2 + (150/2)^2)} =$
$2 * \sqrt{(13365 + 33.4 + 5625)} =$
276 ppm or 0.0276%

To be conservative, we round to 300ppm or 0.03% or higher as the datasheet specification value for the calibration uncertainty of our Capacitance Standards which we calibrate with the IET1689 bridge (see data sheets for applied value). The correct meter setting of course is furthermore prerequsite (slow measurement, 1kHz...) to ensure this uncertainty.

The calibration/verification of the dissipation factor D of our Capacitance Standards is always performed with the IET1689 bridge. This is due to the calibration of this meter, which is substantially less complex and time consuming. The calibration is performed using an adjustable decade resistance, adjusted to the values specified in the 1689 calibration manual, and verified with a calibrated 3458A multimeter, which allows to well exceed the 0.01% uncertainty required.

Dissipation factor D uncertainty of our IET1689 is therefore as specified with 0.0002.