Developing a Dissipation Factor Calibration Service for Standard Capacitors at NIST

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Abstract
In response to a growing demand for loss measurements for standard capacitors, staff members in the Quantum Electrical Metrology Division at the National Institute of Standards and Technology (NIST) are working to develop a calibration service for dissipation factor. The demand is driven by increased use of commercial automatic capacitance bridges in the calibration of fused-silica dielectric and other standard capacitors, as well as phase measurement needs in power metrology, characterization of chemical and material properties, among other applications.

The calibration method uses fused-silica standard capacitors of values 1 pF, 10 pF, and 100 pF that have been characterized for dissipation factor against a 0.5 pF cross capacitor, as well as against a 10 pF nitrogen capacitor at frequencies from 50 Hz to 20 kHz. The customer standards are then calibrated against the fused-silica standard capacitors using a substitution method. The method closely follows the technique for calibrating the capacitance of the customer standards, whereby a commercial capacitance bridge is used as a transfer standard.

This paper will briefly describe the calibration procedure, the error analysis, and the details of the calibration service.

1. INTRODUCTION

NIST has recently improved its capacitance calibration services for three-terminal (3T) standard capacitors using a commercial capacitance bridge as a transfer standard [1-3]. A continuation of that work has lead to the push toward offering a calibration service for dissipation factor for these same 3T standard capacitors using the same transfer standard capacitance bridge. NIST primary reference standard capacitors have recently been characterized for dissipation factor [4]. The primary reference standards were then used to characterize the calibration reference standards. This paper presents the procedure for carrying the traceability chain for dissipation

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factor from the calibration reference standard capacitors to the customer fused-silica standard capacitors. The procedure is similar for other types of 3T standard capacitors (air/nitrogen-dielectric, ceramic), although the uncertainty changes slightly, dependent upon the relative quality of the capacitor. Fig. 1 shows the traceability chain for NIST 3T standard capacitor calibrations of dissipation factor.

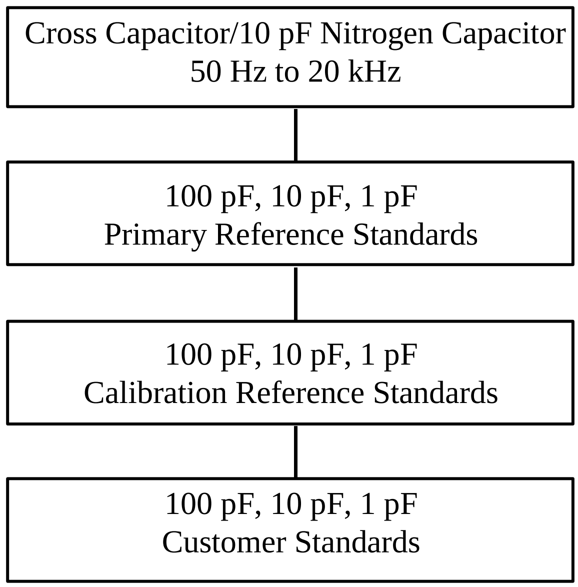

Fig. 1. NIST 3T standard capacitor traceability chain for dissipation factor.

2. CALIBRATION PROCEDURE

The calibration procedure for dissipation factor follows the procedure for capacitance. The calibration reference standard is characterized against primary references. The calibration reference and customer standards are measured. The data are processed using a substitution method, and a report is generated.

2.1. Reference Characterization

For the 1 pF and 100 pF calibration reference standards, the reference data are derived from comparisons against a toroidal cross capacitor using a NIST manual impedance bridge at frequencies from 50 Hz to 20 kHz [4]. In other words, for the 1 pF and 100 pF traceability in Fig. 1, the reference and calibration standards are the same units. For the 10 pF traceability, there are four primary reference standards used to transfer dissipation factor from the toroidal cross capacitor to the calibration reference standard using an automatic capacitance bridge. An average of the four transfers is used; one transfer from each of the four 10 pF primary references to the 10 pF calibration reference.

2.2. Reference and Customer Dissipation Factor Measurements

The automatic capacitance bridge can be used as an effective transfer instrument by measuring the reference and customer standards using a substitution procedure. For each customer calibration, five sets of data are taken for all required frequencies over a period of approximately two weeks, similarly to the capacitance procedure. For each measurement run, data are taken closely in time on the standard under test and the NIST calibration reference standard of the same nominal value. The vector of differences between the measured values of the reference standard and the calibrated values of the calibration reference standard is used, along with the loading correction, as a correction factor to determine the calibrated value of the standard under test. The calibrated value for the dissipation factor of a device under test (DUT) at one frequency is given by

$$DF_{DUTCal} = DF_{DUTMeas} + (DF_{\mathrm{Re}\,fCal} - DF_{\mathrm{Re}\,fMeas}), \qquad (1)$$

where $DF_{DUTMeas}$ is the measured value of the device under test, $DF_{\mathrm{Re}\,fCal}$ is the previously-determined calibrated reference value, and $DF_{\mathrm{Re}\,fMeas}$ is the measured value of the calibration reference standard.

Control software is used to automatically perform the measurements and store the results. The laboratory temperature is maintained at 23.0 ± 1.0ºC. The relative humidity of the laboratory varies seasonally but is held below 50 percent. Ambient temperature, relative humidity, and enclosure temperature are recorded at the time of each customer measurement and the average values over all measurement sets are reported. Customer standards are energized for at least 72 hours prior to measurement and measurements are not performed if the temperature has varied from 23.0 ± 1.0ºC or if relative humidity has increased above 50 percent within the last 72 hours.

2.3. Data Processing

Once the data sets are acquired, they are corrected according to Eq. (1). A dissipation factor measurement correction is obtained for the automatic capacitance bridge by computing the difference between the value of the reference standard previously obtained from calibration against the primary reference standards and the measured value of the reference standard for each of the five measurement runs. This correction is then added to the standard under test measurements to obtain the calibrated dissipation factor for the standard under test. The standard deviation for each frequency is determined over all measurement runs at that frequency and reported as the Type A uncertainty. The ambient temperature, relative humidity, and chassis temperature are also averaged over the five measurement runs and reported.

3. ERROR ANALYSIS

Tables 1 and 2 show the new uncertainty budgets for the 100 pF and 10 pF fused-silica standard capacitor dissipation factor calibration services at NIST. The Expanded Uncertainty for each frequency is the combined standard uncertainty of the calibrated value multiplied by a coverage factor of k=2, consistent with best practices, as recommended by the International Bureau of Weights and Measures (BIPM). The reference uncertainties are the combined standard uncertainties produced from calibration of the reference standards against the NIST cross capacitor and 10 pF nitrogen capacitor. The Type A Uncertainty is a conservative limit describing the behavior of a typical standard. Any standard not performing to within this stability

Table 1. NIST 100 pF fused-silica standard capacitor dissipation factor uncertainty budget.

Frequency (Hz)	Reference Uncertainty C272 (μradians)	Reference Drift (C272) (μradians)	Type A Uncertainty (μradians)	DUT Drift (μradians)	Bridge Thermal (μradians)	Bridge Mechanical (μradians)	Bridge Linearity (μradians)	Bridge Loading (μradians)	Expanded Uncertainty (k=2) (μradians)
50	2.09	0.05	0.20	0.05	0.05	0.05	1.5	0.02	5.18
80	0.84	0.03	0.15	0.03	0.05	0.05	0.8	0.03	2.35
100	0.55	0.01	0.05	0.01	0.05	0.05	0.7	0.03	1.80
160	0.26	0.01	0.03	0.01	0.05	0.05	0.5	0.05	1.14
200	0.20	0.00	0.02	0.00	0.05	0.05	0.4	0.06	0.92
300	0.16	0.00	0.02	0.00	0.05	0.05	0.3	0.09	0.73
400	0.15	0.00	0.02	0.00	0.05	0.05	0.3	0.13	0.74
600	0.15	0.01	0.03	0.01	0.05	0.05	0.2	0.19	0.65
800	0.14	0.01	0.03	0.01	0.05	0.05	0.2	0.25	0.73
1000	0.14	0.01	0.03	0.01	0.05	0.05	0.2	0.32	0.77
1600	0.15	0.01	0.06	0.01	0.05	0.05	0.2	0.51	1.11
2000	0.15	0.02	0.07	0.02	0.05	0.05	0.2	0.63	1.38
3000	0.16	0.03	0.12	0.03	0.05	0.05	0.3	0.95	2.04
4000	0.16	0.03	0.16	0.03	0.05	0.05	0.4	1.26	2.70
6000	0.19	0.06	0.25	0.06	0.05	0.05	0.6	1.90	4.04
8000	0.22	0.08	0.35	0.08	0.05	0.05	1.0	2.53	5.51
10000	0.25	0.10	0.46	0.10	0.05	0.05	1.2	3.16	6.85
12000	0.28	0.12	0.55	0.12	0.05	0.05	2.0	3.79	8.67
16000	0.35	0.13	0.66	0.13	0.05	0.05	3.0	5.06	11.87
20000	0.43	0.11	0.64	0.11	0.05	0.05	4.5	6.32	15.60

limit will be assigned a larger uncertainty. The DUT and reference drift components were determined empirically for the specific types of fused-silica standards used. The Bridge Thermal and Bridge Mechanical components are taken from the standard specifications [5][†]. The Bridge Linearity component is taken from the manual of the commercial capacitance bridge used in performing the calibrations [6]. The Bridge Loading values are derived from measurements evaluating the effects of the loading of the bridge on dissipation factor values. Details of the NIST method of expressing uncertainties can be found in reference [7]. The 1 pF fused-silica dissipation factor uncertainty budget as well as the uncertainty budgets for the 10 pF, 100 pF, and 1000 pF nitrogen-dielectric standards are not yet complete.

4. CALIBRATION SERVICE

The dissipation factor calibration service for fused-silica standard capacitors was developed to coincide directly with the capacitance calibration service for fused-silica standard capacitors. The identical 20 frequencies are offered for dissipation factor as for capacitance, as shown in the uncertainty budget tables. Calibration turn-around time is typically estimated at ten weeks if capacitance calibrations are also required, eight weeks without capacitance.

[†] The identification of a specific commercial product does not imply endorsement by NIST, nor does it imply that the product identified is the best available for a particular purpose.

Table 2. NIST 10 pF fused-silica standard capacitor dissipation factor uncertainty budget.

Frequency (Hz)	Reference Uncertainty C172 (uradians)	Reference Drift (C172) (uradians)	Type A Uncertainty (uradians)	DUT Drift (uradians)	Bridge Thermal (uradians)	Bridge Mechanical (uradians)	Bridge Linearity (uradians)	Bridge Loading (uradians)	Expanded Uncertainty (k=2) (uradians)
50	2.07	0.34	1.21	0.34	0.05	0.05	6.0	0.02	12.97
80	0.83	0.22	0.82	0.22	0.05	0.05	3.0	0.03	6.48
100	0.55	0.14	0.46	0.14	0.05	0.05	2.0	0.04	4.28
160	0.26	0.07	0.26	0.07	0.05	0.05	2.0	0.06	4.08
200	0.20	0.05	0.16	0.05	0.05	0.05	1.0	0.07	2.08
300	0.16	0.04	0.14	0.04	0.05	0.05	0.9	0.11	1.87
400	0.15	0.04	0.14	0.04	0.05	0.05	0.8	0.15	1.69
600	0.15	0.05	0.17	0.05	0.05	0.05	0.9	0.22	1.92
800	0.14	0.06	0.23	0.06	0.05	0.05	1.0	0.29	2.17
1000	0.14	0.08	0.26	0.08	0.05	0.05	1.0	0.37	2.23
1600	0.15	0.13	0.45	0.13	0.05	0.05	1.8	0.59	3.92
2000	0.15	0.16	0.58	0.16	0.05	0.05	2.0	0.73	4.46
3000	0.15	0.25	0.88	0.25	0.05	0.05	3.0	1.10	6.67
4000	0.16	0.34	1.23	0.34	0.05	0.05	4.0	1.46	8.93
6000	0.19	0.51	1.85	0.51	0.05	0.05	7.0	2.20	15.21
8000	0.22	0.69	2.51	0.69	0.05	0.05	7.0	2.93	16.11
10000	0.25	0.84	3.08	0.84	0.05	0.05	9.0	3.66	20.54
12000	0.28	1.01	3.73	1.01	0.05	0.05	15.0	4.39	32.27
16000	0.35	1.22	4.56	1.22	0.05	0.05	17.0	5.85	37.27
20000	0.43	1.33	5.05	1.33	0.05	0.05	18.0	7.32	40.34

Work to characterize 3T nitrogen-dielectric standard capacitors at the same 20 frequencies from 50 Hz to 20 kHz is ongoing. Please contact the authors to inquire about NIST calibration of standard capacitors.

References

1. Y. Wang, "Measurements of frequency dependence of fused-silica capacitors," *Conf. Proc., 2003 NCSL International Workshop and Symposium*, Tampa, FL, Aug. 18-21, 2003.

2. A. Koffman, Y. Wang, and S. Shields, "Optimizing the Use of Commercial Capacitance Bridges in Fused-Silica Standard Capacitor Calibrations at NIST," *Conf. Proc., 2005 NCSL International Workshop and Symposium*, Washington, DC,

3. A. Koffman, Y. Wang, and S. Shields, "Three-Terminal Precision Standard Capacitor Calibrations at NIST," NIST Special Publication, Presently under review.

4. Wang, Y., Koffman, A., FitzPatrick, G., "Dissipation Factors of Fused-Silica Capacitors in the Audio Frequency Range," *IEEE Trans. Instrum. Meas.*, Vol. 56, No. 2, pp. 264-267, 2007.

5. Specification Sheet for Model AH11A Fused-Silica Capacitance Standard, Andeen-Hagerling, Inc., Cleveland, OH.

6. “AH2700A 50 Hz – 20 kHz Ultra-Precision Capacitance Bridge, Operation and Maintenance Manual,” Andeen-Hagerling, Inc., Cleveland, OH, 2003.

7. B.N. Taylor and C.E. Kuyatt, “Guidelines for Evaluating the Expressing the Uncertainty of NIST Measurement Results,” NIST Tech. Note No. 1297, Sept. 1994.