Calibration of Dissipation Factor Standards

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***Abstract*— Working standards for dissipation factor (D) obtained by connecting a shielded three-terminal capacitor in series with a shielded precision resistor have been developed for calibration purposes. Precision conductance boxes have been built for use with a single three-terminal 1000 pF gas capacitor standard to create dissipation factor standards having values from 2×10^{-5} to 1×10^{-2}. The design and testing of these D standards, including precautions in their construction and use, is presented. Calibration procedures using the NIST high voltage capacitance bridge and the measurement uncertainties are discussed.**

***Index Terms*— Calibration, capacitance bridge, capacitor loss measurements, dissipation factor standards, high voltage, loss angle, phase angle, tan delta, transformer loss measurements.**

I. Introduction

The Electricity Division of the National Institute of Standards and Technology (NIST) provides a calibration service for standard capacitors, including both low- and high-voltage devices used in standards laboratories, as well as specialized capacitors used in power industry applications [1]. The dissipation factor (designated as D) or tangent of the loss angle ($\tan\delta$) is expressed as a dimensionless ratio of the loss component to the reactive component of the effective admittance of the device. During recent years, calibrations have been provided for commercially available dissipation factor standards obtained by connecting a shielded three-terminal capacitor in series with a shielded precision resistor. In order to support a calibration service for such devices, NIST has constructed standards of similar design. Although some of the advantages of three-terminal admittance standards such as full elimination of the influence of the shield capacitances are compromised in this configuration, sufficiently low uncertainties can be achieved, ranging from $\pm 2 \times 10^{-6}$ to $\pm 20 \times 10^{-6}$ of the total admittance, depending on the D being measured.

This report presents an analysis of the dissipation factor standards developed for this calibration service, including precautions in their construction and use. It also outlines the calibration procedure using the NIST high voltage capacitance bridge. In the theoretical analysis, the capacitors and resistors have been assumed to have negligible phase angles. This assumption is valid for the resistor, but the capacitor used for the dissipation factor standard has a phase angle of 0.005 ± 0.001 milliradians. The actual value was measured on a fundamental basis using previously developed methods and equipment [2], [3].

II. Circuit Analysis of Dissipation Factor Standards

The NIST dissipation factor standard consists of a series-connected three-terminal standard gas capacitor and a three-terminal conductance, shown schematically in Fig. 1. The two devices are directly connected with a coaxial connector and adaptor, without the use of any extended flexible leads, to ensure a repeatable connector capacitance. The following terminal labeling applies to the circuit points shown in the figure:

1) input;
2) capacitor-conductance junction;
3) output;
4) grounded shield.

Besides the two direct components normally measured in three-terminal networks, C_{12} and G_{23}, there are three stray capacitances to ground, C_{14}, C_{34}, and C_{24}, with C_{24} being the only one that directly affects the value of the dissipation factor standard. Note that C_{24} comprises the sum of the parallel ground capacitances C'_{24} and C''_{24} of the component boxes and coupling connector. It is illustrative to obtain the equivalent π-network shown in Fig. 2 to understand the influence of the series conductance and stray connector capacitances on the effective capacitances and dissipation factors of the standards. The T-network formed by the direct capacitance of the standard capacitor C_{12}, the direct conductance of the precision resistor G_{23}, and the connector capacitance C_{24} is transformed into the equivalent admittance Y_{13}, through the

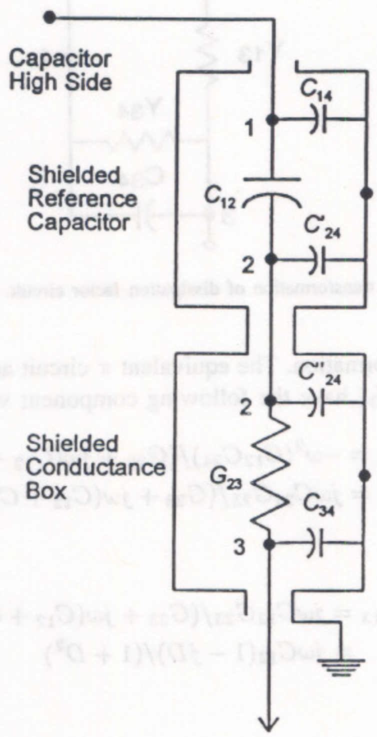

Fig. 1. Dissipation factor standard.

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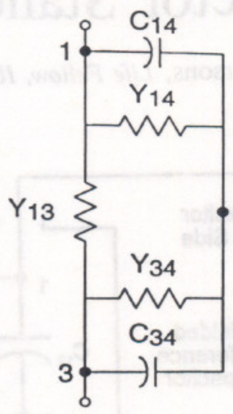

Fig. 2. T-π transformation of dissipation factor circuit.

T-π transformation. The equivalent π circuit admittances Y_{13}, Y_{14}, and Y_{34} have the following component values:

$$Y_{14} = -\omega^2(C_{12}C_{24})/(G_{23} + j\omega(C_{12} + C_{24})) \quad (1)$$

$$Y_{34} = j\omega C_{24}G_{23}/(G_{23} + j\omega(C_{12} + C_{24})) \quad (2)$$

and

$$Y_{13} = j\omega C_{12}G_{23}/(G_{23} + j\omega(C_{12} + C_{24})) = j\omega C_{12}(1 - jD)/(1 + D^2) \quad (3)$$

where

$$D = \omega(C_{12} + C_{24})/G_{23} \quad (4)$$

is the dissipation factor of the network. Also the effective parallel capacitance C_{13} and conductance G_{13} comprising Y_{13} are

$$C_{13} \equiv C_{12}/(1 + D^2) \quad (5)$$

$$G_{13} = \omega C_{12}D/(1 + D^2). \quad (6)$$

The equivalent capacitance, C_{13}, is the original three-terminal capacitance, C_{12}, reduced by a factor of $(1 + D^2)^{-1}$. Fortunately, the difference between C_{13} and C_{12} is negligible for small D ($<10^{-3}$) because of the quadratic contribution of D in (5). The dissipation factor D, as seen from (4), is directly influenced by the presence of the combined stray junction capacitance to ground, C_{24} and therefore a very stable and reproducible value for this capacitance is necessary after reassembling the standard or changing the series conductance box. In normal three-terminal operation, where terminal (2) is at ground potential, the stray capacitances to ground do not affect the measured capacitance C_{12}. For this case, the stray capacitance C_{14} only affects the loading on the power supply. The low-voltage side stray capacitance C'_{24} has a negligible voltage drop across it since terminal (4) is also at ground potential. These stray capacitances therefore do not require the same stability as those for the dissipation factor standards, where C_{24} affects the effective conductance of the π circuit model. As a result, it is desirable to keep the combined stray junction capacitance C_{24} as small as possible relative to C_{12}.

III. Precautions in Construction and Use of DF Standards

The construction and use of the dissipation factor standard should yield accurate and stable values of capacitance C_{13} and dissipation factor D as defined by (5) and (4), respectively. A highly stable capacitance C_{12} consistent with that of laboratory standards should be used. The capacitor should be gas dielectric, hermetically sealed, with a shielding enclosure that is separate from the protective outside box. A nominal value of 1000 pF for C_{12} will yield a range of D between 1×10^{-5} and 1×10^{-2} with resistors that are readily available. The ground capacitances should be small, preferably <50 pF. The resistors should be stable with a temperature dependence of less than 10^{-5}/°C, and have negligible time constant at 50 Hz–60 Hz (time constant $\leq 10^{-7}$ s). The resistance values should be selected to match the measured capacitance values C_{12} and C_{24} and produce D within ± 0.01 of the desired nominal value according to

$$R_{23} = 1/G_{23} = D/\omega(C_{12} + C_{24}), \quad (7)$$

from (4). The direct capacitance C_{12} of the NIST standard capacitor has been determined to be 1000.047 pF. The combined stray ground capacitance value C_{24}, which includes both the internal ground capacitance of the standard capacitor C'_{24} and that for the resistor box C''_{24}, has been determined with the NIST capacitance bridge to be 40 pF within ± 2 pF. Since C_{12} is 1000 pF, the value of the required resistor can be calculated to within $\pm 2 \times 10^{-3}$. The measurement of all component values enabled the adjustment of the actual D to be close to the nominal value; it also provided a cross check of the measured value of the entire standard.

IV. Calibration of Dissipation Factor Standards

Typically, two instruments are required to perform the calibration of dissipation factor standards: a reference standard whose dissipation value has been established on some fundamental basis and a comparison instrument—usually an impedance ratio bridge—for calibrating other dissipation factor standards such as those described here.

The absolute dissipation factor value of a reference capacitor can be determined using a technique described by Astin [2]. This approach uses a parallel plate capacitor operated in vacuum that has a provision for adjusting plate spacing. In such a capacitor the only significant dissipative mechanics are associated with surface coatings and contaminants that contribute an effective resistance in series with the capacitance. As the plate spacing is increased the relative contribution of the series resistance due to surface effects decreases. The dissipation factor vanishes in the limiting case where the series capacitance approaches zero. By taking a set of measurements for several increasing plate spacings and extrapolating to infinite spacing (zero capacitance), the absolute dissipation factor of the reference capacitor is determined. A more recent implementation of this technique and the resulting instrumentation which were used to calibrate the reference capacitor is available at NIST [5]. An alternative fundamental method based on the cross-capacitor is also available at NIST [3], [4].

TABLE I
COMPARISION OF NOMINAL AND MEASURED DISSIPATION FACTORS

Nominal D ($\times 10^{-6}$)	R (Ω)	Mean $D^{\dagger}$ ($\times 10^{-6}$)	Min D ($\times 10^{-6}$)	Max D ($\times 10^{-6}$)
5	0.0	4.7	4	5
25	51.341	24.7	24	25
55	128.35	54.7	54	55
105	256.71	104.7	104	105
205	513.41	204.5	203	205
505	1283.5	503.5	503	504
1005	2567.1	1003	1002	1004
2005	5134.1	2001	1999	2003
5005	12835	4997	4993	5000
10005	25671	9989	9986	9994

† Average of ten measurements

V. DEVICES CONSTRUCTED AND TEST RESULTS

Having achieved absolute determination of D in a suitable standard, it is useful to transfer this value to a working-type standard capacitor, typically having a value of 100 pF to 1000 pF with the latter being the preferable value since it improves sensitivity in the bridge measurements. A set of nine resistor boxes was built and tested with a 1000 pF standard gas-filled capacitor to produce nominal dissipation factors from 2×10^{-5} up to 1×10^{-2} as shown in Table I. The table shows the comparison of the nominal (including an additional D of 5×10^{-6} which is intrinsic to the C_{12} capacitor) and measured dissipation factors along with the resistance values used in the resistor boxes. As measured with the NIST capacitance ratio bridge [6], the actual dissipation factor values differ from their nominal values by $\pm 1.6 \times 10^{-5}$ or less . The agreement confirms the accuracy of the measured combined stray ground capacitance C_{24} that was used for calculating the resistor values from the nominal D values according to (4).

Since the dissipation factor standards are not fixed, but rather use the same standard gas capacitor with all the resistance boxes, it is important to show stability of the standards with repeated disassembly and re-connection. Measurements of the dissipation factor for the standards taken over three months and for temperatures between 17.5°C and 23.0°C agreed to within $\pm 1 \times 10^{-5}$.

VI. SUMMARY OF MEASUREMENT UNCERTAINTIES

The dissipation factor value of the standard is that obtained in the calibration leading to the data of Table I, with the contribution of C_{12} included in these data. The combined dissipation factor uncertainty of the network of Fig. 1 consists of a fixed component, primarily due to uncertainty of the capacitance C_{12}, and a component that is proportional to the actual dissipation factor being measured. This variable component results primarily from the uncertainties of the impedance bridge [6]. The two uncertainties influence the measurement according to

$$D = D_m(1 \pm 2 \times 10^{-3}) \pm 2 \times 10^{-6} \tag{8}$$

where D is the true dissipation factor of the standard and D_m is the measured value.

For small dissipation factors, $\leq 2 \times 10^{-4}$, the fixed component dominates. For large D, 5×10^{-3}, the variable component is the dominant one. In the intermediate region both components need to be combined as the square root of the sum of the squares. The uncertainty estimate is based on the indicated bounds covering the 0.95 or greater probability region—the probability of the uncertainty exceeding the indicated value in either direction is 0.025 or less.

VII. CONCLUSION

A set of nine dissipation factor standards covering a range of $2 \times 10^{-5} \leq D \leq 1 \times 10^{-2}$ have been built and tested. The standards have been measured to have

1) good short- and long-term stability;
2) good temperature stability;
3) good stability with repeated disconnection and reassembly of the component resistor boxes and standard capacitor.

The standards will be used as references for a NIST calibration service for commercially-available dissipation factor boxes and to check the operation of the dissipation factor circuit within the high voltage capacitance bridge.

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