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New proposed method for traceability dissemination of capacitance measurements

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ABSTRACT

Capacitance measurements at the National Institute of Standards (NIS), Egypt, are traceable to the Bureau International des Poids et Mesures (BIPM). It calibrates the main NIS standard capacitors, AH11A. In this paper, traceability of the BIPM capacitance measurements could be used to evaluate a new accurate measurement method through an Ultra-Precision Capacitance Bridge. The new method is carefully described by introducing some necessary equations and a demonstrating chart. Verification of this new method has been realized by comparing its results for the 10 pF and 100 pF capacitance standards with the results obtained by the conventional substitution method at 1 kHz and 1.592 kHz. The relative differences between the two methods are about 0.3 µF/F, which reflect the accuracy of the new measurement method. For higher capacitance ranges, the new measurement method has been applied for the capacitance measurements up to 1 µF at 1 kHz. The relative differences between the two methods are in the range of 5.5 µF/F on the average which proves the acceptable accuracy and the reliability of the new method to be used.

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1. INTRODUCTION

Reference values of the capacitance standards are primarily determined in terms of the quantized Hall resistances using a quadrature bridge through some consecutive measurements [1-6]. They are carried out for different capacitance standards at different frequencies [7-13]. Accurate dissemination of the capacitance unit in a wide range of the measurement is a very important issue in the calibration laboratories. Therefore, traceability chains of the capacitance measurements are established for different accuracy levels to develop capacitance scaling systems. However, it is difficult to construct a very accurate capacitance scaling system due to the lack of perfect linearity commercial instruments. So, there are some limitations on the capacitance range and the operation frequency range for any capacitance scaling system. One of these systems was mainly constructed by a commercially available four-terminal-pair LCR meter and an inductive voltage divider (IVD) [14]. Generally, the LCR meter is used as a transfer device with minimum linearity errors [15]. The IVD and the LCR meter can be calibrated by comparing two calibrated 4TP air capacitors with known frequency dependence [16, 17]. Therefore, a capacitance scaling system is established by using different components, and it should be evaluated and verified [18].

Capacitance measurements at the National Institute of Standards (NIS), Egypt, are mainly traceable to the Bureau International des Poids et Mesures (BIPM). It calibrates three of the NIS standard capacitors, Fused Silica capacitors model AH11A, which have capacitance standard values of 1 pF, 10 pF, and 100 pF. For higher capacitance ranges, the NIS measurements are traceable to the National Physical Laboratory (NPL) which is the National Metrology Institute (NMI) of UK.

A Bilateral comparison between the NIS and the BIPM was carried out from November 2015 to March 2016. Two 10 pF and two 100 pF traveling standards belonging to the BIPM were measured at 1592 Hz and 1000 Hz, with a maximum uncertainty of 0.7 ppm, using a coverage factor k=2, for the NIS measurements were obtained by a direct substitution method. [19]. The NIS measurement results were obtained using AH 2700A - Opt. E & Opt. C, Ultra-precision Capacitance Bridge [20, 21].

In this paper, a new accurate method has been introduced for disseminating the traceability of the capacitance measurements over a wide range. This method depends on applying the correction factor obtained at 20% of the value to be calibrated to compute its actual value from its measured value. Full demonstration of this new calibration method has been presented in detail. Starting from the 1 pF capacitance standard value that is calibrated at the BIPM, the actual values of the proceeding standards up to 1 µF could be determined at 1 kHz with their associated expanded uncertainties using the new measurement method. Validation of this new accurate method up to 100 pF range has been obtained by comparing its results with the results obtained by the originally used substitution method at 1 kHz and 1.592 kHz through the BIPM traceability. Whereas the validation of the new accurate method for higher ranges up to 1 µF at 1 kHz has been obtained by the same comparison but through the NPL traceability. All measurements have been carried out using our Ultra-Precision Capacitance Bridge, which is the newest product of the Andeen-Hagerling Corporation. Most of the NMIs, including NIS, take a capacitance value at 1 kHz frequency as standard value for capacitance calibrations. So, many researches are carried out to improve the capacitance measuremtns and uncertainty at different frequencies [22, 23]. The uncertainty calculations of the NIS capacitance measurements are carried out according to the international statements [24-26], and the expanded uncertainties are computed for 95.54% confidence level at a coverage factor k=2.

2. METHODOLOGY OF THE NEW ACCURATE METHOD

The new method based on having two calibrated capacitance standards of the same value at every range. The method proves that applying the correction factor obtained at 20% level of the value to be calibrated to compute its actual value can be performed with a good level of accuracy. Firstly, we should have two calibrated equal standard capacitances, $C_{X_1}=C_{X_2}$, which their parallel measured value, C_{2X_m}, is equal to 20% of the standard capacitance to be calibrated C_Y, where:

$$C_Y = 10\, C_{X_1} \tag{1}$$

Accordingly, C_{2X_m}can be measured, using a suitable capacitance measuring device, and expressed as given in (2).

$$C_{2X_m} = C_{X_1} + C_{X_2} \tag{2}$$

Then the corresponding computed value, C_{2X_C}, for the reference values of the two capacitances, $C_{X_{1R}}$ and $C_{X_{2R}}$ obtained from the calibration certificates, can be computed using (3).

$$C_{2X_C} = C_{X_{1R}} + C_{X_{2R}} \tag{3}$$

Therefore, the deviation between the measured and the computed values, $D_{20\%}$, is determined as stated in (4).

$$D_{20\%} = C_{2X_m} - C_{2X_c} - D_{\mathrm{S}} \tag{4}$$

This deviation, $D_{20\%}$, represents the deviation in the measurement device at the value of 20% of the standard capacitance to be calibrated, and it is used to determine the actual value, $\grave{C_{Y_2}}$, of the measured value, $C_{Y_{2m}}$, of the standard capacitance to be calibrated, C_Y, as presented in (5). The drift in the used standards, D_S , should be taken into consideration while determining D_{2X}. D_S, represents the deviation of the measured value of the two calibrated standard capacitors from their calibration certificates. It can be neglected by performing the measurements in a relatively short period which is very close and near to the standards calibration. In this case, the measured values of the standards can be directly compared to certified values without any required drift corrections. Therefore, $D_{20\%}$, represents the deviation due to the measurement device only. Nevertheless, the per year standards drift should be also taken into consideration during the uncertainty estimations. Two examples are demonstrated in detail below to present the uncertainty components for low and high capacitance values.

$$\grave{C_{Y_2}} = C_{Y_{2m}} - D_{20\%} \tag{5}$$

Then the actual value of the standard capacitance that is required to be calibrated C_{Y_2} is obtained by using the deviation, D_{Y_1}, determined by substitution method through a reference certified value of another standard capacitance, $C_{Y_{1R}}$, having the same value of the capacitance to be calibrated. Its measured value, $C_{Y_{1m}}$, obtained by the same measuring device as described in (6) and (7).

$$D_{Y_1} = C_{Y_{1m}} - C_{Y_{1R}} \tag{6}$$

$$C_{Y_2} = C_{Y_{2m}} - D_{Y_1} \tag{7}$$

To verify this new method, the obtained value, $\grave{C}_{Y_2}$ from the 20% deviation is compared to the obtained actual value, C_{Y_2}, form the substitutional method, to specify the relative accuracy, A, of the new method as given in (8).

$$A = (\grave{C}_{Y_2} - C_{Y_2})/\ C_Y \tag{8}$$

3. PRACTICAL CONFIRMATION OF THE NEW ACCURATE METHOD

NIS has two sets of the AH11A capacitance standards that have capacitance values of 1 pF, 10 pF, and 100 pF. The first set is calibrated at the BIPM, as mentioned before, and it is used through the substitution method to calibrate the second set. The NIS capability to use the substitution method has perfectly checked through the pre-described bilateral comparison with the BIPM. To validate the new introduced calibration method, the actual values of the 10 pF and 100 pF, of the second standards set, have been determined also by using the new method and the results are compared to those obtained by the substitution method. Therefore, in the new method, the two 1 pF capacitance standards are used to calibrate the 10 pF. Then, the two 10 pF calibrated standard capacitors are used to determine the actual value of the 100 pF as, for example, demonstrated in the chart depicted in Figure 1. The correction factor obtained at the 20-pF value is applied to the measured value of the 100 pF to compute its actual value, which is compared to that obtained by the conventionally used substitution method as demonstrated in Figure 1. All measurements in this paper have been carried out using an Ultra-Precision Capacitance Bridge "AH2700A Option-C+E Multi-Freq. Capacitance/Loss Bridge", shown in Figure 2. It has specific Gold-Plated Low Noise Coaxial Cables and connections, AH-DCOAX-TPG1-BNC.

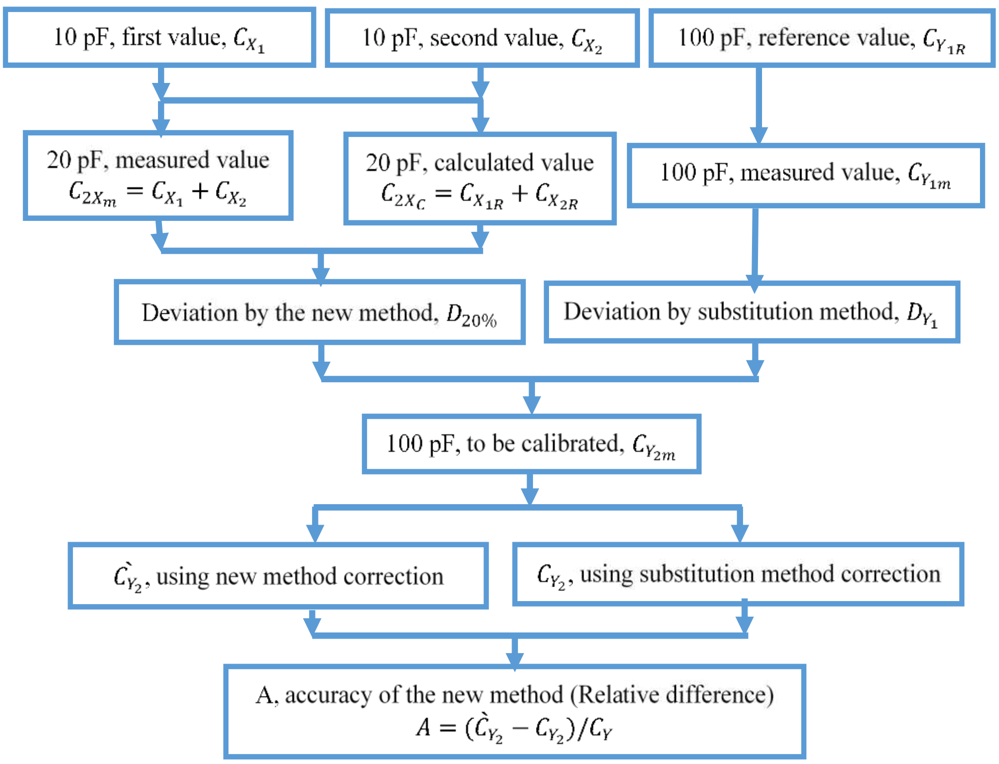

Figure 1. Chart for confirmation of the new accurate method

Figure 2. NIS capacitance measurement system formed by the latest AH bridge and the two highly accurate capacitance standards sets

4. RESULTS AND DISCUSSIONS

The new proposed calibration method has been experimentally implemented at electrical quantities metrology laboratory, NIS, EGYPT. The traceability of the lower values capacitance standards has been disseminated to higher capacitance values as well be investigated in the following sub-sections.

4.1. Confirmation of the new accurate method

The new proposed calibration method has been applied, at NIS, by using the previously described method to calibrate the capacitance of 10 pF and 100 pF values at 1 kHz and 1.592 kHz. The results obtained by the two methods, new proposed method and conventional substitution method, are compared to validate the proposed method. The differences between them where found to be about 0.3 µF/F as listed in Table 1. The obtained 0.3 µF/F accuracy level result proves that the new proposed calibration method is accurate and can be reliably used to disseminate the measurement traceability in such low capacitance values.

Table 1. Relative differences between the new accurate calibration method and the conventional substitution method using the BIPM traceability

Nominal Value	A, relative accuracy using the BIPM traceability at 1kHz, (µF/F)	A, relative accuracy using the BIPM traceability at 1.592 kHz, (µF/F)
10 pF	0.289	0.288
100 pF	0.305	0.281

4.2. Confirmation of the new accurate method at higher capacitance values

The new validated calibration method has been applied, at NIS, by using the previously described method to calibrate the capacitance ranges up to 1 µF at 1 kHz. Firstly, the parallel value of the two 1 pF calibrated standard capacitors, capacitance value of 2 pF, are used to calibrate two capacitance standards each has a capacitance value of 10 pF. Subsequently, the recently calibrated capacitance value of 20 pF, two parallel 10 pF, is used to calibrate two capacitance standards each has a capacitance value of 100 pF. The obtained actual values of the used 10 pF and 100 pF capacitance standards at 1 kHz are shown in Table 2 with their relative expanded uncertainty. The approximated relative difference between the new accurate calibration method and the conventional substitution method using the BIPM traceability is written in Table 2 on the average for the clarity.

Table 2. Calibration of the NIS capacitance standards up to 100 pF at 1 kHz using the new accurate confirmed method

Nominal Value	Actual Value, New Method	A, relative accuracy using the BIPM traceability at 1kHz, (µF/F)	Relative uncertainty (µF/F), k=2
10 pF	9.9999985 pF	0.297 (on the average)	0.68
100 pF	100.00002 pF		0.70

Consequently, the calibrated capacitance standard value of the 200 pF is used to calibrate capacitance values of 1 nF. And so on by repeating the same procedure of the new calibration method at higher values, then the actual values of other NIS capacitance standards, 10 nF, 100 nF and 1 µF, could be obtained and presented in Table 3 with their related uncertainties. Above 100 pF, our standards are calibrated at the National Physical Laboratory (NPL), the NMI of the UK, which is the NIS traceability source for these ranges. Therefore, the linearity of the bridge at such higher capacitance values could be also verified by comparing the actual values obtained by the new method with those obtained by the conventional substitution method using the NPL traceability. The relative difference between the two methods is in the range of 5.5 µF/F on the average which reflects the acceptable accuracy and the reliability of the new method to be used also for such higher capacitance ranges as shown in Table 3.

Table 3. Calibration of the NIS capacitance standards above 100 pF at 1 kHz using the new accurate confirmed method

Nominal Value	Actual Value, New Method	A, relative accuracy using the NPL traceability at 1kHz, (µF/F)	Relative uncertainty (µF/F), k=2
1 nF	1.0000222 nF	5.5 µF/F (on the average)	0.83
10 nF	9.9840598 nF		1.13
100 nF	100.10557 nF		1.20
1 µF	1.001797 µF		4.36

The uncertainty budget of the 100 pF and 1 µF measurements are introduced in Table 4, as examples for the details of the computed uncertainty values given in Tables 1 and 2. The effect of the cables when connecting two capacitors in parallel has been evaluated for all cases, and it could be neglected for capacitance values up to 1 nF. Above that value, the cables effect does not exceed 3.7 ppm on the average. Uncertainty evaluation for the cables effect contribution has been taken into consideration in the uncertainty budget as shown in Table 4

It can be noticed that the uncertainty of the 1 µF value is relatively high due to its high repeatability value and cables effect, while the uncertainties of the other capacitance values are relatively small. They are comparable to the uncertainties obtained using the substitution method during the BIPM bilateral comparison which were about 0.7 µF/F as previously mentioned.

Table 4. Uncertainty budget for measurement of 100 pF and 1 µF obtained by the new method

Source of Uncertainty	Distribution/Type	Relative uncertainty (µF/F), for 100 pF	Relative uncertainty (µF/F), for 1 µF
Repeatability	Normal / A	0.001	2.076
Capacitance standard certificate (including cables effect)	Normal / B	0.090	0.470
Bridge resolution	Rectangular / B	0.003	0.288
Drift of the used standard	Rectangular / B	0.110	0.173
Stability of the bridge	Rectangular / B	0.290	0.289
Temp. stability of the bridge	Rectangular / B	0.003	0.003
Nonlinearity of the bridge	Rectangular / B	0.130	0.127
Combined uncertainty		0.348	2.177
Expanded uncertainty (k =2)		0.696	4.355

5. CONCLUSION

The new calibration method has been verified by comparing its results for the 10 pF and 100 pF capacitance values with the results of the conventional substitution method using the BIPM traceability for the same values at 1 kHz and 1.592 kHz. The accuracy of the new calibration method is about 0.3 µF/F in these low ranges. For higher capacitance ranges, the new method has been verified by comparing its results with those obtained by the conventional substitution method using the NPL traceability. In this case, the relative difference between these two methods is in the range of 5.5 µF/F on the average.

The obtained results prove that the introduced new calibration method is accurate and can be reliably used to disseminate the measurement traceability over a wide range up to 1 µF with acceptable uncertainties. It colud be also recommended that the new calibration method should be used in calibration laboratories that don’t have sufficient standards to cover all ranges required to calibrate capacitance meters using the conventional method.

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