ASEE 2004

Standard Capacitor Calibration Procedure Implemented Using Control Software

Svetlana Avramov-Zamurovic[1], Brian Waltrip[2], Andrew Koffman[2] and George Piper[1]

[1]United States Naval Academy, Annapolis, Maryland, USA avramov@usna.edu

[2] National Institute of Standards and Technology*, Gaithersburg, Maryland, USA

Introduction

A capacitance scaling method is used to calibrate standard capacitors. This is a very powerful technique that was introduced by Aoki and Yokoi in 1997 [1]. Reference [1] describes the general method and provides a detailed uncertainty analysis. Aoki and Yokoi developed a calibration procedure based on [1] but this reference is insufficient for duplication of the measurement system and implementation of the calibration procedure.

The capacitance scaling procedure involves reference point measurements and a series of "scaling" measurements. A commercial capacitance bridge is used in order to obtain reference measurements at 1 kHz. An inductive voltage divider (IVD) with the ratio of 10:1 is used to scale a known capacitance for comparison with a capacitance under test. The measurements are performed over a range of frequencies.

This paper will present the capacitance scaling procedure in detail and demonstrate the developed software program that controls the calibration procedure. The challenge of this presentation is to explain a rather sophisticated precision measurement technique in such a way that it may be taught to an interested group of undergraduate students. The software development provides an opportunity to teach the calibration process: from taking measurements to producing a calibration report.

Capacitance Scaling Method

Modern instrumentation is designed for automated control in order to create custom calibration procedures. In the case when very precise and specialized tests are necessary within the metrology community, it is particularly challenging to establish computer control of an entire procedure. Accurate calibration of capacitors that range from 1nF to 100 μF over a wide frequency range (100 Hz to 100 kHz) is a demanding task.

There are several instruments commercially available to measure the impedance of a capacitor. LCR meters are general impedance-measuring instruments that have limited

---

* Electronics and Electrical Engineering Laboratory, Technology Administration, U.S. Department of Commerce. Contribution of the U.S. Government. Not subject to copyright in the U.S.

accuracy, while automatic capacitance bridges are commercially available with very high accuracies but with more limited measurement ranges.

An automatic capacitance bridge is very convenient for measuring standard capacitors with precision, reliability, and uncertainty at metrological levels. Measurement errors are on the order of parts in 10^{-6}. The measurement accuracy depends directly on the standard capacitor that resides in one branch of the bridge as well as on the inductive voltage divider used to scale the measured capacitance to that standard. The limitations of the automatic bridge include a limited frequency band and limited capacitance range. A single-frequency commercial capacitance bridge has been available for several years. Recent versions allow measurement from near dc to 20 kHz. The capacitance measurement limit is typically 1 μF.

LCR meters have been widely available for many years. The LCR meter operates on the principle or sourcing a known current through an unknown impedance and measuring the voltage drop. The impedance is determined based on the magnitude and phase of the known current and the measured voltage. This instrument has a very broad frequency span (up to MHz) and can measure inductors, capacitors, and resistors with a wide range of values and very high dissipation factors. The limitation of the instrument is a large measurement uncertainty. It is on the order of fractions of a percent for the most accurate meters.

These two instruments play the major role in evaluating capacitors. The goal is to calibrate capacitors up to 100 μF over the frequency range from near dc to 100 kHz. The reference measurements are made using an automatic capacitance bridge at 1 kHz. All of the remaining measurements are performed using the LCR meter and are traceable to the reference measurements.

The goal of newly developed measuring procedures is to use commercially available instrumentation as much as possible and design specialized equipment so it is easily integrated in an automatic measuring system.

The capacitance scaling system consists of an LCR meter, an automatic capacitance bridge and custom-made interface (see Fig 1.)

Capacitors calibrated using this procedure have values of 10 nF, 100 nF, 1 μF, 10 μF and 100 μF. This information is important because the decade property is incorporated in the interface design.

The first measurement determines the impendence of the 1 nF capacitor using the capacitance bridge at 1 kHz, $C_{1nF\ AH}$. The capacitor measured is a four-terminal-pair device and the capacitance bridge uses two ports so the interface provides an appropriate connection switch.

The second measurement is made using the LCR meter, $Z_{1nF\ LCR}$. The interface switches the capacitor ports to the LCR meter. The LCR meter has four ports: high and low current ports and high and low voltage ports. The goal of this calibration process is to calibrate the 10 nF capacitor by using a known 1 nF capacitor. The reason for this action will be explained later.

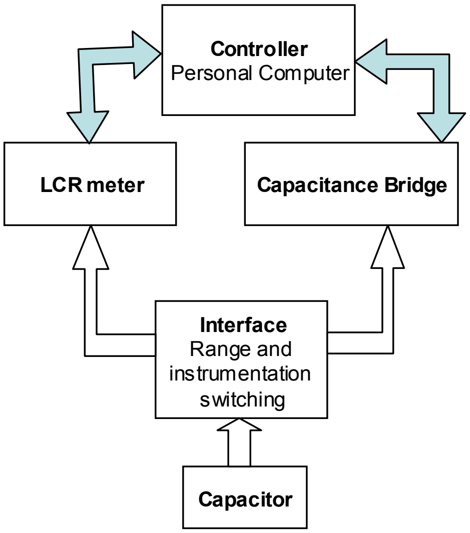


Figure1. Capacitance Scaling Measurement System.

The 10 nF capacitor has one-tenth the impedance of the 1 nF capacitor. If the voltage across the voltage ports on the LCR meter is ten times less while measuring the 1 nF capacitor, the LCR meter will act as if it is measuring a 10 nF capacitor. This property is enabled using an inductive voltage divider with a 10:1 ratio connected to reduce the voltage across the LCR meter voltage ports. The interface provides the appropriate switch.

The third measurement characterizes the 10 nF capacitor using the LCR meter, $Z_{10nF\ LCR}$. The interface switches the inductive voltage divider out of the voltage port loop.

The calibrated impedance for the 10nF capacitor, Z_{10nF} is calculated using the above-described measurements and the calibrated inductive voltage divider ratio, IVD_ratio (this calibration procedure will be explained later):

$$Z\_10nF = IVD\_ratio \frac{\mathrm{Z\_1nF\_LCR}}{\mathrm{Z\_10nF\_LCR}} \mathrm{C\_1nF\_AH}.$$

Why do we need to do the calibration in this rather complex manner?

There are several measuring methods that are available for calibrating 1 nF capacitors. They include calibration using a vector network analyzer and a capacitance bridge. This method covers a very wide frequency range (up to 10 MHz) and is complex to perform. Its accuracy is on the order of 100 parts in 10^{-6}. A multi-frequency automatic capacitance bridge may be used to measure a 1 nF capacitor up to 20 kHz with an uncertainty on the order of 10 parts in 10^{-6}. In the field of metrology, it is important to independently verify results. Since the proposed capacitance scaling method derives the values from a known standard that is traceable to the U.S. representation of the farad, it is considered a valid and reliable measurement procedure. Another important property of the described method is that it uses the ratio of measurements to establish the result. The LCR meter is an instrument that produces repeatable results with good linearity but has systematic errors on the order of 100 parts in 10^{-6}. Since the impedances measured using the LCR meter are used in a ratio format, the overall uncertainty is not very high. A software program has been developed that simulates the errors of the instrumentation in this calibration process. The results of the simulation suggest that the random component of the errors is on the order of 30 parts in 10^{-6}, even though the uncertainty of the LCR meter is much higher. This software program is available upon request from the authors.

The procedure that establishes the IVD ratio uses the same set up given in Figure 1. The frequency range of the scaling capacitor method is from 120Hz to 100 kHz. Standard capacitors of values 100 pF and 1000pF are used to calibrate the inductive voltage divider. These capacitors have air as the dielectric and that guarantees a flat frequency dependence. All of the calibrations performed on this type of capacitor support this assumption.

There are four measurements necessary to calibrate an inductive voltage divider. First, the 100 pF capacitor is measured using the capacitance bridge, producing $C_{100pF\ AH}$. The next measurement is of the impedance of the 100 pF capacitor using the LCR meter with inductive voltage divider in the circuit, giving $Z_{100pF\ LCR}$. Next, the 1000 pF is measured using the LCR meter, producing $Z_{1000pF\ LCR}$. Lastly, the capacitance bridge measures the 1000 pF, giving $C_{1000pF\ AH}$. The IVD ratio is then calculated using:

$$IVD\_ratio = \frac{\mathrm{Z\_100\,pF\_LCR}}{\mathrm{Z\_1000pF\_LCR}} \frac{C\_1000pF\_AH}{\mathrm{C\_100pF\_AH}}$$

The next capacitor, 100nF, is measured by using the result of the 10 nF, Z_{10nF}, and making the same two sets of measurements mentioned above. The 10 nF capacitor is measured using the LCR meter, giving $Z_{10nF\ LCR}$, and then the 100 nF capacitor is measured using the LCR meter, giving $Z_{100nF\ LCR}$. The result is obtained using:

$$Z\_100nF = IVD\_ratio \frac{\mathrm{Z\_10nF\_LCR}}{\mathrm{Z\_100nF\_LCR}} \mathrm{Z\_10nF}.$$

This same process is repeated to characterize all of the other capacitors in the set. It is important to mention that all of the errors are accumulated during this bootstrap process.

This concludes the theoretical presentation of the capacitance scaling method. Practically, there are several modifications that have to be implemented. Those will be introduced during software program presentation.

Practical Implementation of the Capacitance Scaling Method using Graphical Control Software

A control software program was written with an extensive set of on-line instructions in order to make the calibration process user-friendly. The program will be presented step by step.

The first step is the inductive voltage divider calibration. It is recommended that this calibration be performed before each calibration of a capacitor set, in order to minimize the measurements errors.

The program creates one file to store the measurements and another file where the report summarizing the calibration results will be stored. All of the file names are unique and include the capacitor value and the date and time of calibration. Extra care is introduced in order to keep the serial numbers of the calibrated devices in order. This is done in order to organize the measurements in unique storage and report files.

When we discussed the calibration method, we did not mentioned that it is not possible to cover the frequency range from 100 Hz to 100 kHz with one single transformer. The system is implemented using two transformers: a low-frequency operating from 100 Hz to 10 kHz, and a high-frequency transformer operating from 10 kHz to 100 kHz. The software program prompts the user to switch from the low- to high-frequency range by throwing switches on the interface.

The user is guided through the calibration process with prompts on the computer screen. The procedure pauses until the user responds to the prompt.

All of the instrumentation control is performed via software. The sequencing of the measurements taken, the specific values for the voltages applied, and the appropriate frequencies are all prescribed and controlled without user intervention. Also, data averaging and formatting is performed and means and standard deviations recorded for further analysis.

The second step is the actual capacitor calibration. The program requires selection of a file with IVD ratio information. Also when the capacitor to be calibrated is not 10 nF, the procedure requires the selection of the impedance value of the capacitor ten times less. Example: when a 10 μF capacitor is calibrated, its calibration is tied to 1 μF standard and the result is simply taken from the report file and the LCR measurements are performed as prompted.

There is one additional detail associated with this procedure. For the higher values of the capacitors at the higher frequencies, the offset is measured. This step is not a significant contributor to the overall calibration procedure and will not be discussed in detail here. The software prompts the user to throw switches on the interface at appropriate times. It also incorporates the offset corrections in the calculation of the impedance.

It is difficult to show the software implementation in a figure since it is a rather complex and cumbersome printout. Every effort will be made to present the program at the time of the conference. The next set of figures will show LAbView diagrams and a front panel. The Figure 21 shows the input output manipulations, working with strings and data variables. The Figure 3 shows the calculation of impedance and the Figure 4 shows the front panel that communicates input data with a user. All of those examples are in support the fact that the LabView is user and programmer friendly software suitable for instrumentation control.

Conclusions

The calibration procedures for electrical, or any other, units are often complex since there are many different conditions that must be met. In this paper, we made an attempt to present a capacitor calibration, step by step, in a straightforward way. There is substantial educational value in relating general descriptions of measurement procedures described in a journal paper to practical realization using instrumentation and control software available in the laboratory. Both students and researchers can benefit from this type of exercise.

References:

[1] T. Aoki and K. Yokoi, " Capacitance Scaling System", IEEE Transactions on Instrumentation and Measurement, Vol. 46, No. 2 April 1997, pp. 474-476.

[2] "Capacitance Scaling System Calibration Procedure" Agilent Technologies Japan, Ltd., May 2002 (Rev. 1).

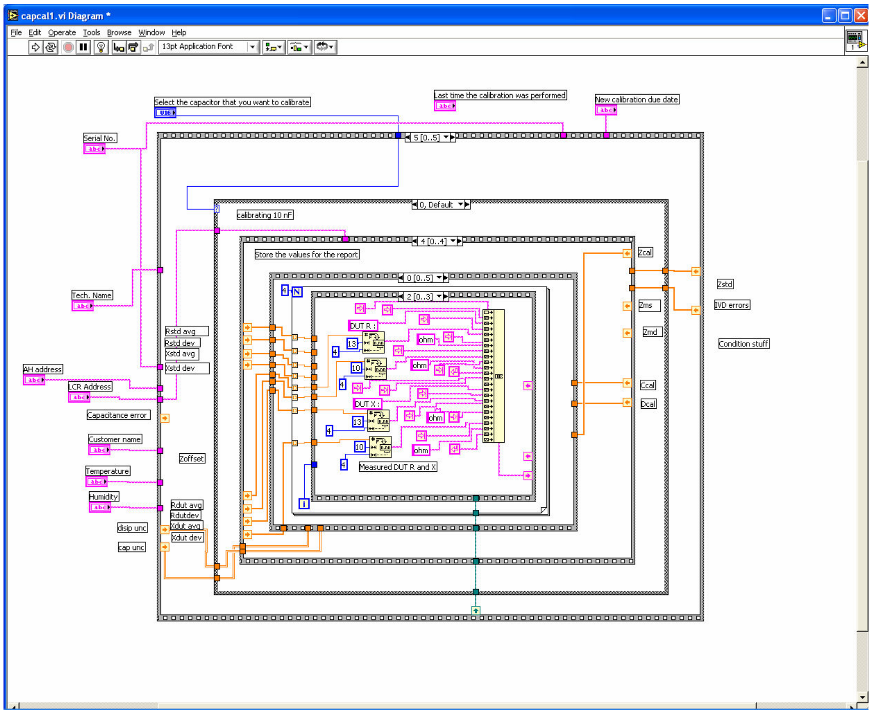


Figure 2. Input output routine.

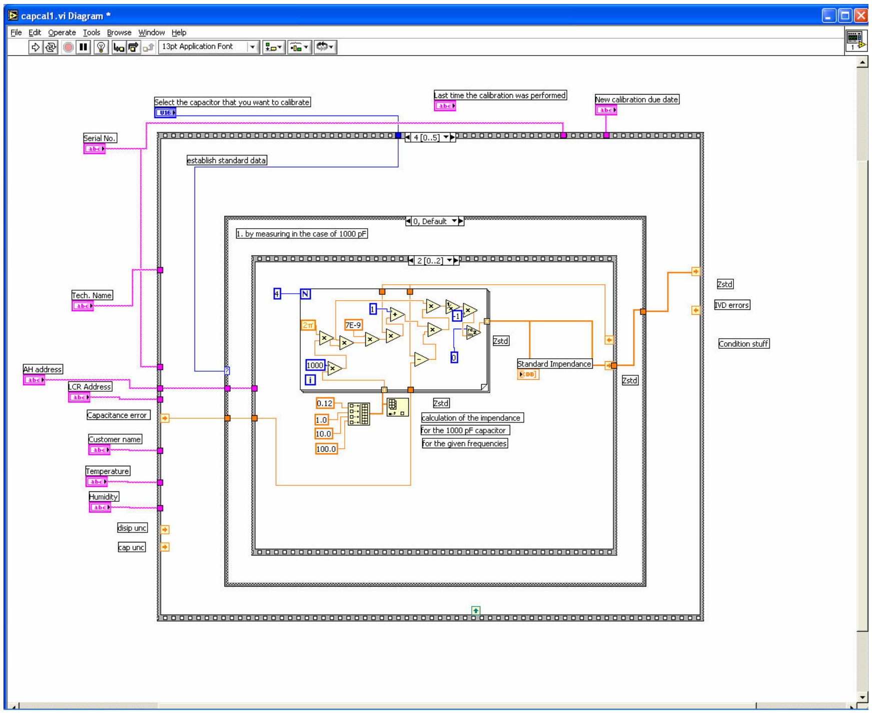
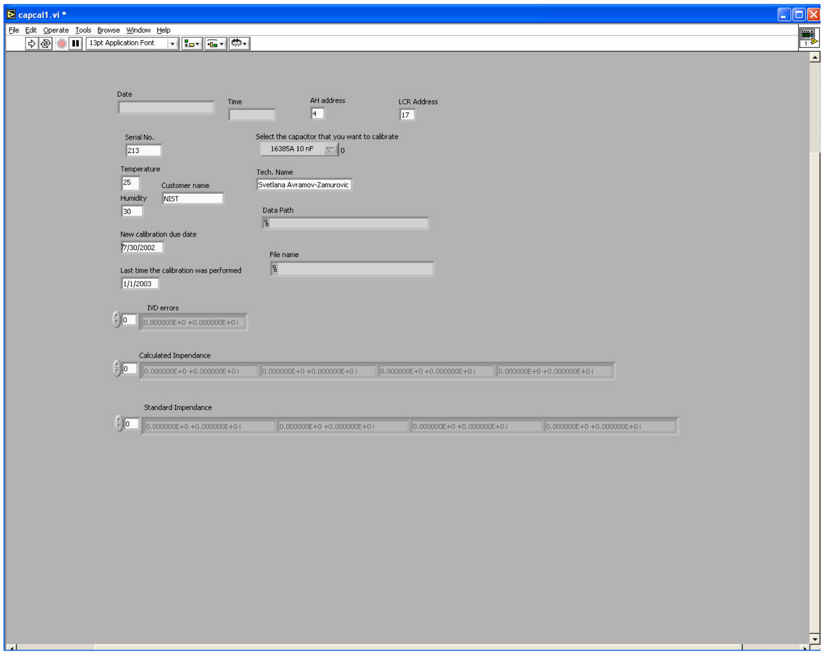


Figure 3. Impendence calculations.



Date

Time

AH address: 4

LCR Address: 17

Serial No.: 213

Select the capacitor that you want to calibrate: 16385A 10 nF 0

Temperature: 25

Customer name: NIST

Humidity: 30

Tech. Name: Svetlana Avramov-Zamurovic

Data Path

New calibration due date: 7/30/2002

File name

Last time the calibration was performed: 1/1/2003

IVD errors: 0 | 0.000000E+0 +0.000000E+0 i

Calculated Impendance: 0 | 0.000000E+0 +0.000000E+0 i | 0.000000E+0 +0.000000E+0 i | 0.000000E+0 +0.000000E+0 i | 0.000000E+0 +0.000000E+0 i

Standard Impendance: 0 | 0.000000E+0 +0.000000E+0 i | 0.000000E+0 +0.000000E+0 i | 0.000000E+0 +0.000000E+0 i | 0.000000E+0 +0.000000E+0 i

Figure 4. Front panel.