Turkish Journal of Electrical Engineering & Computer Sciences

http://journals.tubitak.gov.tr/elektrik/

Research Article

Turk J Elec Eng & Comp Sci
(2017) 25: 4142 – 4148
© TÜBİTAK
doi:10.3906/elk-1611-39

Automated module for characterization of reference standards of capacitance by impedance-matrix method

Satish SINGH*, **Thomas JOHN**
LF, HF Impedance and DC Metrology, CSIR-National Physical Laboratory, New Delhi, India

Received: 04.11.2016 • **Accepted/Published Online:** 03.04.2017 • **Final Version:** 05.10.2017

Abstract: An automated module has been developed, implemented, and validated for the characterization of four-terminal-pair capacitance standards using an impedance-matrix method. These air-dielectric capacitance standards are being used as reference or transfer standards of capacitance at high frequency across national metrology institutes worldwide. In the reported work, an automated characterization module performs the acquisition of reference capacitance and residual capacitive parameters from an ultraprecision capacitance bridge. It also acquires single-port reactances of the capacitance standard from an impedance analyzer at frequencies ranging from 40 MHz to 100 MHz. The acquired capacitive and reactance parameters are stored structurally in arrays from where they are further analyzed according to the impedance-matrix method. The frequency characteristics of four-terminal-pair capacitance standards are thereafter estimated up to 10 MHz and are presented through a user-friendly interface. An automated module provides a reliable, precise, and efficient way to control the frequency characterization of reference standards of capacitance. The reported work emphasizes the importance of automated modules to control complex procedures, which are involved in the advancement of metrology.

Key words: Automation, capacitance standards, impedance, measurement, extrapolation

1. Introduction

CSIR-NPL is the National Metrology Institute (NMI) of India and it assists industries, regional calibration laboratories, and R & D organizations/institutes across India by providing metrological and apex level calibration services. Measurement automation is certainly a core component of any NMI for the advancement of calibration and measurement techniques [1]. It should be flexible, user friendly, reliable, efficient, and accurate along with reduced workload. Measurement automation has several applications in laboratories for reliable and efficient measurement and instrument control [2–8]. Four-terminal-pair (4TP) capacitance standards are used as working standards up to 30 MHz in leading NMIs around the world. The evaluation and characterization of the 4TP capacitance standard is essential from the metrological point of view. The evaluation of capacitance standards using the s-parameter method [9–11] is very complex and it requires measurement of two-port s-parameters with a vector network analyzer and a lot of computation is required to determine the uncertainty in measurement. The impedance-matrix ([Z]) method proposed by Suzuki [12–14] is an alternate technique to characterize the same and it is relatively simple to implement. The present work describes the design approach for an automated module developed for the characterization of 4TP standards of capacitance of values 1000 pF

---

*Correspondence: singhsp3@nplindia.org

and 100 pF up to 10 MHz using the [Z] method. The various features and functions of the developed module are highlighted in detail in this paper.

2. Overview of impedance matrix method

In the impedance [Z] method, the frequency characteristics of the capacitance standard are estimated by determining 4TP impedance (Z_{4TP}) of the standard, which in turn is determined using (1).

$$Z_{4TP}=\sqrt{\frac{z_{22}}{z_{11}-z_{11s3}}((z_{11}-z_{11s2})(z_{44}-z_{44s3})-(z_{11}-z_{11s3})(z_{44}-z_{44s2}))} \tag{1}$$

In (1), each $z_{11},z_{22},z_{44},z_{11s2},z_{11s3},z_{44s2},z_{44s3}$ represents single-port impedance (R+jX) of [Z] and is measured at one of the ports of the 4TP capacitance standard. For instance, z_{11} is measured at port 1 of 4TP standard when the remaining ports (2, 3, and 4) are left open. z_{11s2} is the impedance measured at port 1 of the standard with its port 2 shorted to ground. In the present work, the real component (R) of impedance is not taken into consideration for the determination of frequency characteristics of capacitance standards. Hence, the imaginary component (reactance parameter: $X_{11},X_{22},X_{11s3},X_{11s2},X_{44},X_{44s2},X_{44s3}$) of each corresponding impedance: $z_{11},z_{22},z_{44},z_{11s2},z_{11s3},z_{44s2},z_{44s3}$ of each capacitance standard is acquired from an RF impedance analyzer (Agilent E4991A) at a set of frequencies ranging between 40 MHz and 100 MHz by using a fully integrated characterization module. In addition, reference capacitance and residual capacitive parameters of each 4TP standard are acquired from a capacitance bridge (AH 2700A) at 1 kHz. The acquired reactance and capacitive parameters are stored structurally in arrays from where they are further analyzed according to the characterization procedure summarized in Figure 1 to estimate the frequency characteristics of each capacitance standard up to 10 MHz.

3. Automated characterization module

The automated module for the characterization of the capacitance standard has been developed using LabVIEW using the IEEE 488.2 (GPIB) interface. LabVIEW is a graphical programming language that enables matching between real hardware and virtual components to create a system [2]. The strength of LabVIEW is in instrumentation and data acquisition, making it well suited for metrology laboratories [4]. It also implements graphical dataflow similar to a flowchart diagram [8]. In the present paper, the automated characterization module is intended for the characterization of 4TP capacitance standards using the [Z] method up to 10 MHz. This section of the paper highlights various features and functions of the module, which is categorized into following four primary tabs.

3.1. Initialization and configuration

This tab of the automated characterization module has been developed to initialize and configure the capacitance bridge and impedance analyzer using the following two subtabs:

AH2700 capacitance bridge: It is used to initialize the ultraprecision capacitance bridge connected to the capacitance standard using Bayonet Neill–Concelman (BNC) cables. The various functions of the capacitance bridge such as the measurement frequency, average exponent, and maximum voltage have been configured through a user-friendly interface. The user is also given an option to input number of measurements that can be repeated after a specified interval of time. In the reported paper, three-terminal capacitive

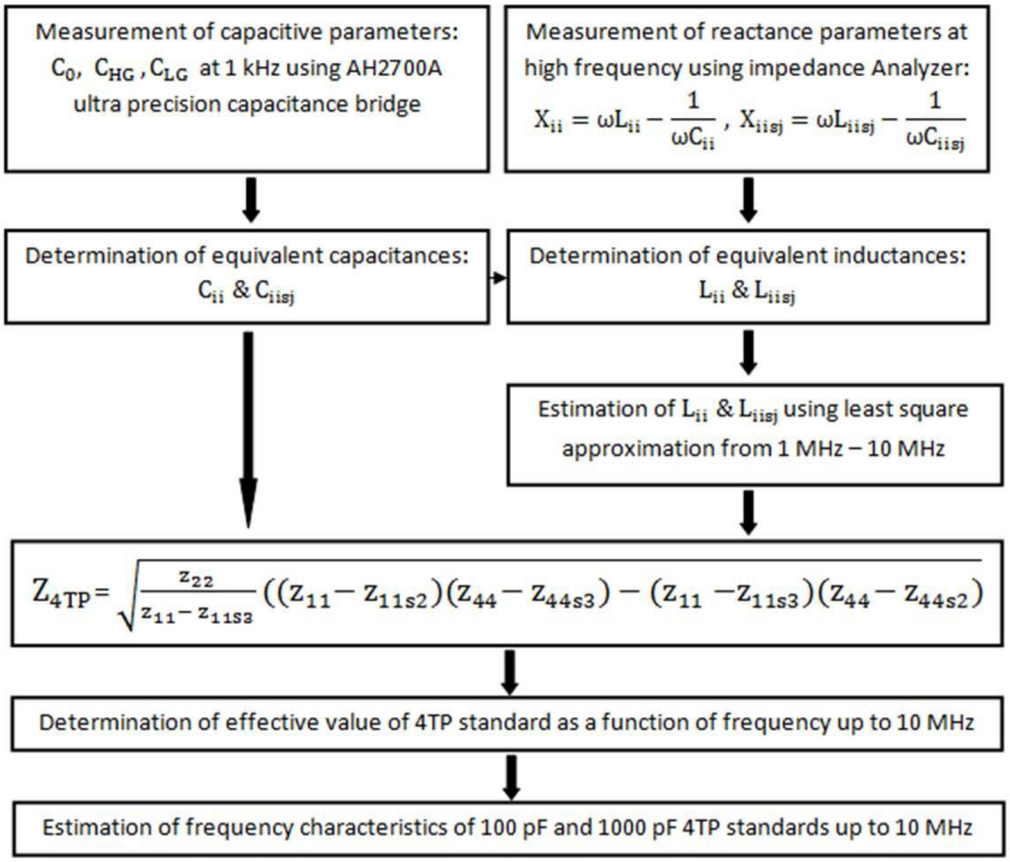


Figure 1. Characterization procedure.

parameters (reference capacitance (C_0) high-to-ground guard capacitance(C_{HG}), and low-to-ground guard capacitance(C_{LG}))of a simple electrical equivalent circuit model of the 4TP capacitance standard shown in Figure 2 are acquired from the capacitance bridge and are stored structurally in arrays for the estimation of frequency characteristics of the 4TP standard up to 10 MHz.

E4991A RF impedance analyzer: After completion of measurement of the three capacitive parameters of the capacitance standard, an automated characterization module prompts the user to connect the capacitance standard to the RF impedance analyzer using an APC7-BNC (f) adapter. The user is also allowed to select the impedance parameter from the pull-down menu provided through the interface as shown in Figure 3. The user has to input start, stop, and step frequency for the measurement of various reactance parameters. The user is given an option to either perform an open, short, load (OSL) calibration at the measurement port of the impedance analyzer prior to measurements using a BNC type calibration kit or can use the "RECALL STATE" feature through the front panel to recall the previous calibration state. In the reported paper, the reactance parameter X_{22} has been measured at a set of frequencies ranging from 60 MHz to 100 MHz with a step size of 2 MHz and all other reactance parameters other than X_{22} are measured in a frequency range varying from 40 MHz to 60 MHz with a step size of 1 MHz. The impedance analyzer used is calibrated for impedance using ultraprecision coaxial airlines, which are being maintained as primary standard for low values of impedance standards at high frequency at NPLI [15]. Figure 4 summarizes the hierarchy of operations performed by the characterization module for the OSL calibration and measurement of various reactance parameters.

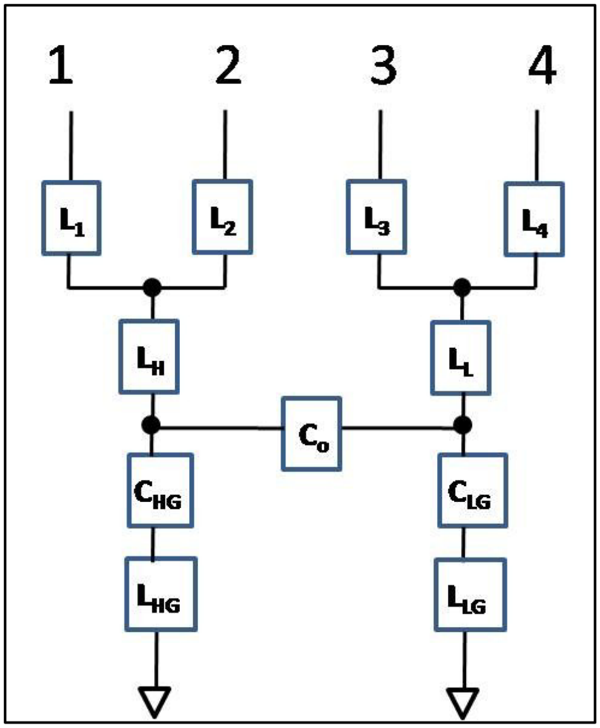
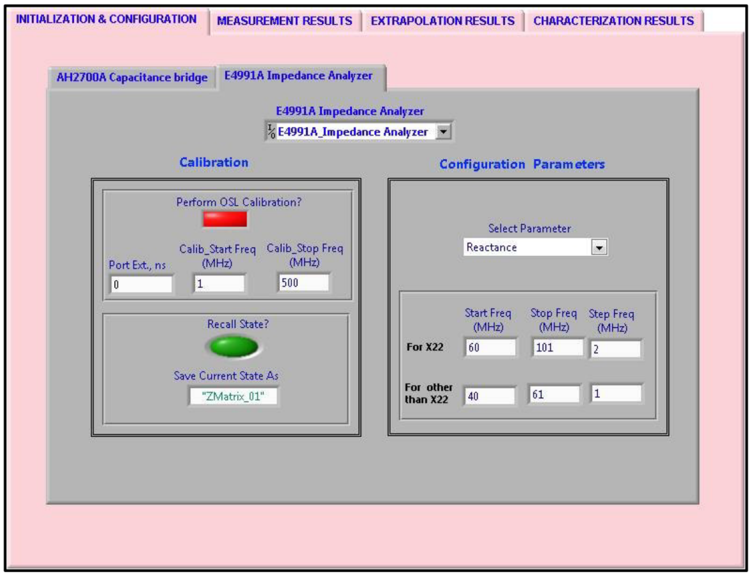


Figure 2. Electrical equivalent circuit model of 4TP capacitance standard.



E4991A Impedance Analyzer: E4991A_Impedance Analyzer

Port Ext., ns: 0

Calib_Start Freq (MHz): 1

Calib_Stop Freq (MHz): 500

Save Current State As: "ZMatrix_01"

Select Parameter: Reactance

	Start Freq (MHz)	Stop Freq (MHz)	Step Freq (MHz)
For X22	60	101	2
For other than X22	40	61	1

Figure 3. Initialization and configuration tab.

3.2. Measurement results

This tab is used to present measurement results using following two subtabs:

Capacitive parameters: The characterization module presents the average value of capacitive parameters $(C_0, C_{HG}C_{LG})$ acquired from the capacitance bridge. The variation in the measured data can also be observed graphically through the front panel interface, which makes the review and analysis of measurements

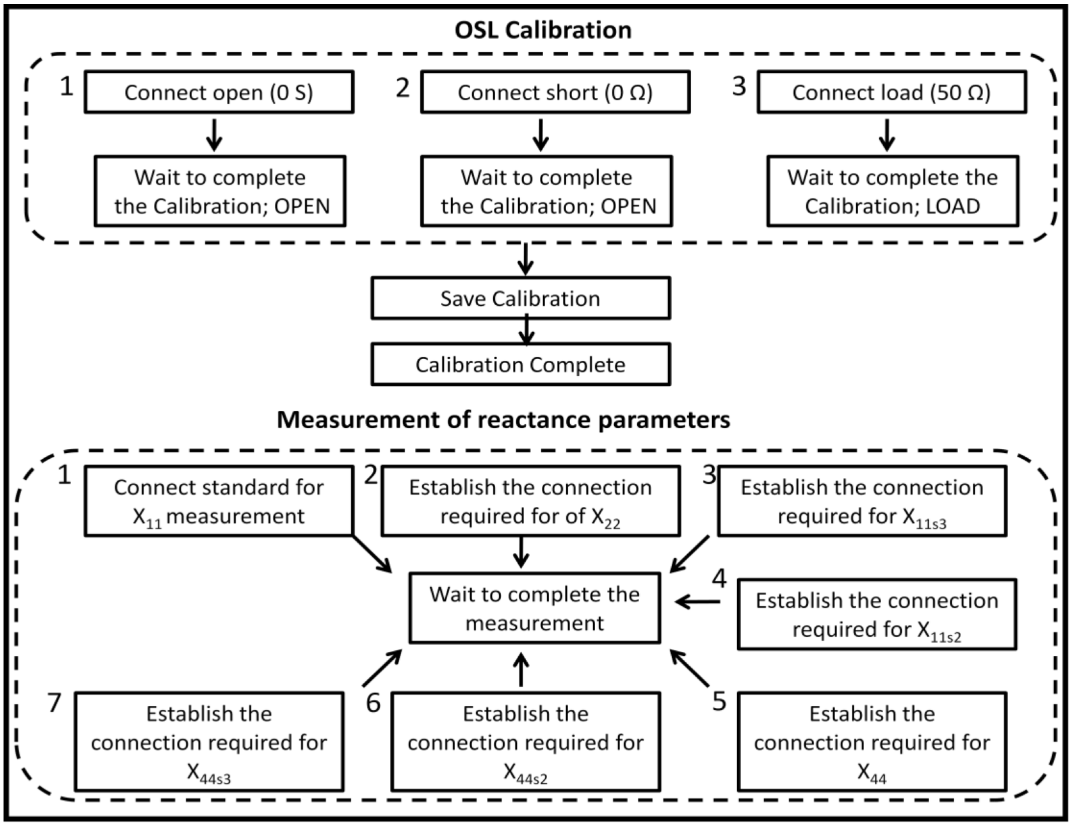


Figure 4. Hierarchy of operations in OSL calibration and reactance measurements.

efficient. The characterization module also determines equivalent capacitances of each single-port impedance according to network equations (2–4) derived using EECM:

$$C_{11}{=}C_{22}{=}C_{33}{=}\ C_{44}{=}\ C_{HG}//(C_0{+}C_{LG}) \tag{2}$$

$$C_{11s3}{=}C_{44s2}{=}C_{HG}//C_0 \tag{3}$$

$$C_{11s2}{=}C_{44s3}{\cong}\ 0 \tag{4}$$

Single-port reactances: This subtab presents the measured reactance parameters at different frequencies to the user each in the form of an array. Each array represents the reactance component or parameter comprising equivalent capacitance (C_{ii} and C_{iisj}) and equivalent inductance (L_{ii} and L_{iisj}) and can be defined in generalized form by (5) and (6):

$$X_{ii}{=}\ \omega L_{ii}{-}\frac{1}{\omega C_{ii}} \tag{5}$$

$$X_{iisj}{=}\ \omega L_{iisj}{-}\frac{1}{\omega C_{iisj}} \tag{6}$$

The automated module also computes equivalent inductances (L_{ii} and L_{iisj}) as a function of corresponding measured frequency, by performing mathematical calculations on (5) and (6).

3.3. Extrapolation results

The automated characterization module employs an extrapolation technique on obtained equivalent inductances (at high frequencies) to extrapolate them to low frequencies ranging from 10 MHz down to 1 kHz. To employ the extrapolation technique, the module implements least squares data approximation [13] on each equivalent inductance by fitting it on a straight line as a function of square of frequency. Thus L_{ii} and L_{iisj} can be expressed by a generalized equation given by (7):

$$L_{ii}=L_{iisj}=L_1 f^2+L_2, \tag{7}$$

where L_1 and L_2 represents the slope and intercept of the straight line, respectively, and are determined using the formula node function of LabVIEW.

3.4. Characterization results

The characterization module computes the effective value of capacitance using (1) at specified set of frequency ranging from 1 kHz to 10 MHz. The frequency characteristics of the 4TP capacitance standard up to 10 MHz are also estimated by determining capacitance deviation from the reference capacitance to the typical capacitance values determined at frequencies above 1 kHz. To validate the automated characterization module, the values of capacitance standards (100 pF and 1000 pF) up to 10 MHz computed through the automated characterization module are compared with the evaluated values obtained by s-parameter method [11] and also with the values obtained by measuring each 4TP standard using an Agilent 4285A LCR meter. The Table illustrates the comparison results for 1000 pF and 100 pF capacitance standards along with associated expanded uncertainty in measurement (u_e) up to 10 MHz.

Table. Comparison of measurement results (pF).

Freq., MHz	Capacitance from s-parameter method [11]		Computed capacitance using automated module		Measured capacitance using LCR meter	
	1000 pF	100 pF	1000 pF	100 pF	1000 pF ± U_e	100 pF ± U_e
1	1001.18	100.00	1000.13	99.55	1000.85 ± 1.00	100.04 ± 0.50
2	1001.95	100.02	1000.90	99.57	1001.58 ± 1.00	100.04 ± 0.50
4	1005.00	100.06	1004.02	99.63	1004.64 ± 1.00	100.04 ± 0.50
6	1010.15	100.14	1009.26	99.73	1009.77 ± 2.00	100.08 ± 0.50
8	1017.44	100.25	1016.67	99.78	1016.92 ± 3.50	100.13 ± 0.50
10	1026.97	100.39	1026.38	99.99	1026.16 ± 6.00	100.19 ± 0.50

4. Conclusion

An automated characterization module provides an efficient and reliable way to implement complex characterization of four-terminal-pair capacitance standards using the [Z] method up to 10 MHz. The automated module configures and controls the impedance analyzer and capacitance bridge for the acquisition of single-port reactance and capacitive parameters of capacitance standards respectively as per the electrical equivalent circuit model. These acquired parameters are further analyzed according to the characterization procedure to estimate the frequency characteristics of capacitance standards. The computed capacitance using automated characterization module has been validated by comparing with the s-parameter method and with the values obtained by direct measurement using a precision LCR meter. The results are found to be in good agreement with each other. The automated module will be further modified to incorporate the extended feature of the evaluation of expanded uncertainty in the measurement of each capacitance standard. The reported work emphasizes the importance of automated modules to control complex procedures, involved in the advancement of metrology. Measurement automation enables NMIs to manage high level research activities and measurement traceability in metrology.

Acknowledgments

The authors are grateful to Dr DK Aswal, Director CSIR-NPL, for the permission to publish the work and Dr VN Ojha Head, Time & Frequency and Electrical & Electronic Metrology Division, for constant encouragement. The authors are also thankful to the Council of Scientific and Industrial Research (CSIR), India, for funding PSC0111 project, under which this work has been performed.

References

[1] Batagelj V, Bojkovski J, Drnovsek J. Software integration in national measurement-standards laboratories. Sci Meas Technol IET 2008; 2: 100-106.

[2] Azaklar S, Korkmaz H. A remotely accessible and configurable electronics laboratory implementation by using LabVIEW. Comput Appl Eng Educ 2010; 18: 709-720.

[3] Kim DJ, Fisk Z. A LabVIEW based template for user created experiment automation. Rev Sci Instrum 2012; 83: 123705.

[4] Zulkifli MZ, Harun SW, Thambiratnam K, Ahmad H. Self-calibrating automated characterization system for depressed cladding EDFA applications using LabVIEW software with GPIB. IEEE T Instrum Meas 2008; 57: 2677-2681.

[5] Weng Z, Zhou R. Design and Simulation of Temperature Measurement Circuit Based on LabVIEW and Multisim. In: 2011 Second International Conference on Mechanic Automation and Control Engineering. 2011. 5689-5692.

[6] Babita B, Sharma DK, Satish S, Ansari MA, Saxena AK. A versatile automation program using LabVIEW for low dc current measurement. JSIR 2014; 73: 91-94.

[7] Gu J, Jin L, Qin S, Wang X, Xu Z. Researching on the automatic impedance measurement system. 2005 Int Conf Electr Mach Syst 2005; 3.

[8] Elliott C, Vijayakumar V, Zink W, Hansen R. National Instruments LabVIEW: A Programming Environment for Laboratory Automation and Measurement. JALA - J Assoc Lab Autom 2007; 12: 17-24.

[9] Callegaro L, Durbiano F. Four-terminal-pair impedances and scattering parameters. Meas Sci Technol 2003; 14: 523-529.

[10] Özkan T, Gülmez G, Turhan E, Gülmez Y. Four-terminal-pair capacitance characterization at frequencies up to 30 MHz using resonance frequencies. Meas Sci Technol 2007; 18: 3496-3500.

[11] Satish S, Babita B, Khurana B, Kumar S, Saxena AK. Evaluation of four-terminal-pair capacitance standards using electrical equivalent circuit model. Measurement 2015; 73: 121-126.

[12] Suzuki K. A new universal calibration method for four-terminal-pair admittance standards. IEEE T Instrum Meas 1991; 40: 420-422.

[13] Avramov-Zamurovic S, Koffman AD, Oldham NM, Waltrip BC. The sensitivity of a method to predict a capacitor's frequency characteristic. IEEE T Instrum Meas 2000; 49: 398-404.

[14] Satish S, Kumar S, Babita B, John T, Saxena AK. Evaluation of air dielectric four-terminal-pair capacitance standards using resonance frequency of impedance elements. Measurement 2017; 100: 176-182.

[15] Satish S, Kumar S, Babita B, John T, Saxena AK. Realization of coaxial reference air-lines as high frequency capacitance standard at CSIR-NPL. Measurement 2016; 92: 166-171.