Automatic AC Bridge for Resistance, Capacitance and Inductance Measurement

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Abstract

Impedance is an important quantity used to characterize electronic circuit components and also the material used to make them. It is also involved in different practical applications. The main aim of this paper is to introduce a ratio bridge which is fully automated system used to measure the electrical components that represent the impedance with high accuracy. The introduced ratio bridge consists of two voltage waveforms generators that are accurately synchronized, and a DMM as a null detector. An automated program has been designed to achieve a full automatic control of the bridge. The bridge construction and calibration procedures are introduced in this paper. The bridge has been used to measure AC resistance to resistance, capacitance to capacitance, and inductance to inductance standards at different frequencies for different waveforms at 1:1 ratio. The bridge performance is also evaluated. It is proved that it achieves an accuracy level reached to 10^{-5}. The uncertainty budget for the bridge measurements has been carried out and also introduced in this paper.

Keywords: Resistance measurement, Capacitance measurement, Inductance measurement, Automatic Ratio Bridge method, Uncertainty.

1. Introduction

Impedance is one of the most important physical quantities in science and engineering especially the electrical engineering. Electrical impedance is involved in different practical applications in industrial fields, which require an accurate measurement of its value [1]. It is used in many electrical, biomedical, chemical, and space technology applications. In electrical application, it is used in battery testing and solar cell characterizations. For biomedical applications it is used in tissue characterization. It is also used in conductivity measurements of chemical composite applications. In space technology applications it is important for atmospheric refractive index determination [2]. Accurate measurements of impedance are done in most of the national metrology institutes. There are many researches were carried out to measure impedance elements accurately as introduced in [3, 4]. Some bridges due to technical problems have limitations affect the measurements range, frequency and type of measurements [5].

In this paper a fully automated bridge has been constructed using two fully synchronized waveforms generators with an automated program specially designed to operate the system automatically at the National Institute of Standards (NIS), Egypt. This bridge has been used to measure AC resistance to resistance (R-R) standards at two different frequencies; 1000 Hz and 1592 Hz, using two different waveform shapes; sine wave and square wave. It has also been used to measure capacitance to capacitance (C-C) standards and inductance to inductance (L-L) standards at quadrature bridge frequency of 1592 Hz. All measurements are done in the same phase. The performance of the bridge is evaluated by using two known calibrated standards. One of them is used as a known standard and the other as unknown standard to compare the measurement results of the unknown standard that are measured by the bridge with its actual value obtained from its calibration certificate. The uncertainty sources associated with the bridge measurements have been also estimated.

2. Bridge Construction

The bridge set-up is shown in Fig. (1). It consists of two arbitrary NI electronic cards; NI card (1), and NI card (2) that are perfectly synchronized. A digital multi-meter (DMM) is also used to detect the minimum value of the voltage difference between the two known and unknown standards; X_1, and X_2respectively to monitor the balance point. The bridge is fully controlled automatically through an optic fiber cable for NI cards and, GPIB card and cable for DMM.

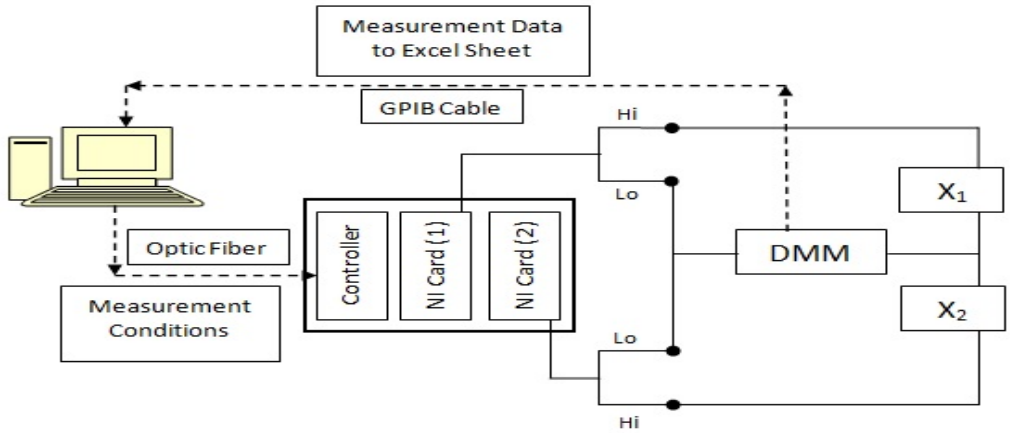

Fig (1) Fully automatic ratio bridge construction

At balance, the unknown standard value is obtained from equation:

$$\frac{V_1}{V_2} = \frac{X_1}{X_2} \qquad (1)$$

Where X_1 is the known standard value and X_2 is the unknown standard value. X_1 and X_2 can be R, X_C, or X_L.

3. Automatic Calibration Procedures

A fully automated ratio bridge system for accurate measurements has been constructed with an automated program to operate the NI electronic cards and DMM automatically. The bridge consists of four arms two of them contain the NI electronic cards which act as two sources of the bridge. The third arm contains a known standard that has a known calibrated value. In the fourth arm, the unknown standard is connected as shown in Fig. (1).

Output of one of the NI voltage sources has been kept at fixed voltage level. The variation of the voltage level has only been made by the other source. Consecutive changes are made on the voltage level to get the minimum voltage difference reading by the DMM which will consider being the balance condition. After getting the balance condition, the values of the voltages of the two NI electronic cards are calibrated using an 8.5 digit DMM. The unknown standard value is then calculated using equation (1).

The value of the variable voltage V_2 at the balance condition can be detected from the result data which will be corresponding to the min value of the DMM readings or by plotting the calibrated values of the variable voltages with the square of the average readings of the DMM, then by using the curve fitting method the V_2 can be calculated from the following equation:

$$V_{DMM} = \sqrt{aV_2^2 + bV_2 + C} \qquad (2)$$

$$V_{2min} = \frac{-b}{2a} \qquad (3)$$

Where a and b are the constants of the second order equation.

The minimum value of $V_2$is detected from the curve as shown in Fig. (4). Each reading of the DMM voltage is the average of 15 readings to calculate the repeatability of the measurements.

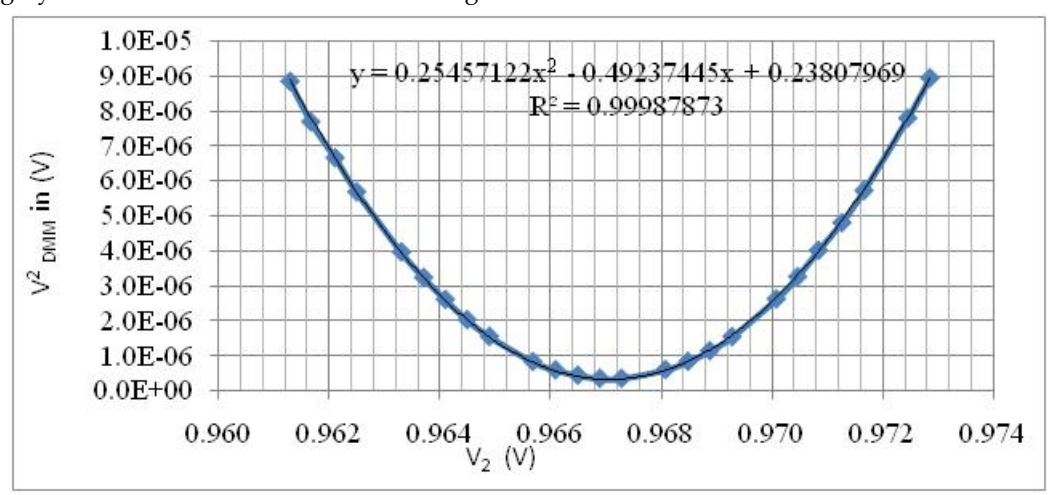

Fig (4) Example for curve fitting method to calculate V_{2min}

4. Calibration Results

The bridge has been used to measure resistance to resistance (R-R) standards, capacitance to capacitance (C-C) standards and inductance to inductance (L-L) standards at different waveforms and frequencies.

4.1 Resistance Standards Measurements (R-R)

Standard resistors of values 1 Ω, 100 Ω, and 10 kΩ are measured by using calibrated standards, at two frequencies 1000 Hz and 1592 Hz for two waveforms sine wave and square wave at ratio 1:1. Table 1 shows the obtained results at the different frequencies for sine waveform.

Table 1 Measurement results at different frequencies for sine waveform

Nominal Resistance Value	Freq., Hz	V_1, V	V_2, V	R_2 measured
1 Ω	1000	0.706782	0.706784	1.0000035 Ω
	1592	0.665583	0.665590	1.0000112Ω
100 Ω	1000	0.706856	0.706780	99.982642Ω
	1592	0.666091	0.666096	100.001082 Ω
10 kΩ	1000	0.706939	0.707630	9.997055 kΩ
	1592	0.665416	0.665549	10.001852 kΩ

Table 2 shows the obtained results at the different frequencies for square waveform.

Table 2 Measurement results at different frequencies for square waveform

Nominal Resistance Value	Freq., Hz	V_1, V	V_2, V	R_2 measured
1 Ω	1000	0.999632	0.999613	0.9999817 Ω
	1592	0.967186	0.966921	1.0000338 Ω
100 Ω	1000	0.999549	0.999420	99.987503 Ω
	1592	0.967066	0.967182	100.012306 Ω
10 kΩ	1000	0.999896	0.999576	9.996809 kΩ
	1592	0.966220	0.966400	10.001867 kΩ

4.2 Capacitance Standard (C-C) and Inductance Standard (L-L) Measurements

The unknown capacitance standard is measured by another known standard capacitance and the unknown inductance standard is measured by another known standard inductance. 1 μF capacitance standard and 10 H inductance standard are measured by using standards traceable to the NPL, at quadrature bridge frequency 1592 Hz for sin waveform. Table 3 shows the obtained results.

Table 3 Measurement results for sine waveform

Standard Nominal Value	Freq., Hz	V_1, Volt	V_2, Volt	Measured Value
1 μF	1592	0.665579	0.665571	1.00181 μF
10 H	1592	0.705921	0.705584	10.032 H

5. Bridge Evaluation

The bridge has been used to measure resistance, capacitance and inductance standards. The performance of the bridge has been evaluated by comparing the output results in each case with the calibrated value of the unknown standard to obtain the deviation in the bridge (Dev.).The repeatability of the measurements is done by repeating the measurements 15 times for each voltage step. Table 4 presents the evaluation of the bridge for resistance measurement of 1Ω standard resistor at 1592 Hz for sin waveform as an example.

Table 4 Bridge evaluation for 1Ω standard resistor measurement

Calibrated value of the standards			
R_1	1.0000007 Ω	R_2	1.0000004 Ω
Results of the bridge			
V_1	0.665677 V	V_2	0.665590 V
Applying eq.(1)			
R_2measured = 1.0000112 Ω			
Deviation in bridge, Dev.			
Dev. = R_2measured - R_2calibarted = 1.082×10^{-5}Ω			

The uncertainty components of the presented ratio bridge are estimated according to [6, 7]. Type (A) component which represents the repeatability of the measurements is normal distribution. All other components; Type (B) are rectangular probability distribution. The uncertainty components related to the two sources such as source synchronization, frequency stability are relatively small [8]. The expanded uncertainty calculation has been carried out for 95 % confidence level at a coverage factor k=2. The uncertainty components are listed in Table 5 for the 1Ω resistance standard measurement at 1592 Hz for sin waveform as an example.

Table 5 Uncertainty budget of the 1Ω resistance standard measurement

Source of Uncertainty	Type of uncertainty	Probability distribution	Divisor	Uncertainty contribution, ppm
Repeatability	Type A	Normal	1	4.0
DMM resolution	Type B	Rectangular	$\sqrt{3}$	0.1
Voltage Source Calibration V_1	Type B	Rectangular	2	4.2
Voltage Source Calibration V_2	Type B	Rectangular	2	4.2
Standard Resistor Calibration	Type B	Rectangular	2	0.8
Sources Synchronization	Type B	Rectangular	$\sqrt{3}$	0.3
Frequency Stability	Type B	Rectangular	$\sqrt{3}$	0.6
Combined uncertainty	7.2 ppm			
Expanded uncertainty (k=2)	14.5 ppm			

6. Conclusion

A fully automatic ratio bridge has been constructed using two synchronized sources and DMM through an automated program. It has been specially designed to control the operation of the bridge to save time and effort. The program allows performing many measurements at each voltage step to study the repeatability of the measurements. The bridge has been used to study resistance to resistance standards as well as capacitance to capacitance standards and inductance to inductance standards. The deviation of the bridge in the resistance and capacitance measurements are in the order of 10^{-5} while the deviation of the bridge in the inductance measurement is in the order of 10^{-3}. It proves that the bridge could be operated reliably at different frequencies using different waveforms for different quantities.

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