Precise Bridge for Impedance Measurement Based on Programmable Waveform Generators

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Abstract

An automated bridge using programmable waveform generators has been introduced in this paper with a fully controlled automated system using LabVIEW program. The bridge operation depends on ratio measurement technique. The system consists of two programmable waveform generators that are perfectly synchronized through their internal T-clock, two impedances, and digital multi-meter (DMM) with LabVIEW program that has been prepared to have full control on the measurement conditions. The bridge has been used to measure different quantities such as resistance to capacitance and capacitance to inductance standards at the quadrature frequency, 1592 Hz. The bridge has been evaluated and accomplishes an accuracy of 10^{-4} for the resistance to capacitance measurement and accuracy of 10^{-3} for capacitance to inductance measurements. The uncertainty components for the performed measurements have been evaluated and introduced in the paper.

Keywords: Resistance to capacitance ratio, Capacitance to inductance ratio, Impedance measurement, Automatic ratio bridge method, LabVIEW program, Uncertainty.

1. Introduction

Impedance calibrations with different level of accuracy are carried out using different systems. Calibration of impedance with the highest level of accuracy can be done using a quadrature bridge such as introduced in [1, 2] to calibrate the capacitance in terms of resistance. Another system that has high accuracy level is the coaxial ac bridge [3, 4]. Also resonance bridge and Maxwell-Wien bridge as introduced [5, 6] are used to link inductance to capacitance with high accuracy. All the above bridges although they have high accuracy level but they have some disadvantages such as they are time consuming, and not easy to operate or to get balance. Commercial impedance analyzers are also used to calibrate impedance at frequencies from few hertz to megahertz but they are not at the same level of accuracy as the bridges. Different laboratories have developed digitally bridges to overcome the gap between the accuracy of the ac bridges and commercial impedance analyzer such as introduced in [7-10].

In this paper, a fully automated system has been constructed based on two programmable waveform generators that are perfectly synchronized, two impedances, DMM, and a computer with a LabVIEW program. It is specially prepared to control the operation of the two waveform generators and to record the output data from the DMM in an excel sheet. The bridge has many advantages such as it has high level of accuracy relative to the impedance analyzers, and the bridge is effortlessly constructed and simply to operate because it is fully automated. The system has been evaluated at 1592 Hz which is the quadrature bridge frequency and at 1:1 impedance ratio. The bridge asymmetry has been evaluated in case of resistance to capacitance ratio measurement as an example. The uncertainty budget of the system has been introduced.

2. Description of the System Construction

The introduced automated system consists mainly of a four arms AC bridge, and a DMM. The two arms of AC bridge consist of two perfectly synchronized waveform generators that work as two identical sources for the bridge. The other two arms contains two impedances. The system also contains the DMM which issued as null detector. Fig (1) shows the system construction used for the comparison of two impedances.

The bridge is fully automated and controlled using LabVIEW program. The program has been specially prepared to operate the waveform generators, control the bridge operation and to record the results in excel sheet. Variations of both amplitude and phase angle of one of the waveform generators are made until the balance condition is observed by the DMM. The balance equation is:

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$$\frac{|V_1|\angle\emptyset_1}{|V_2|\angle\emptyset_2} = \frac{|Z_1|\angle\theta_1}{|Z_2|\angle\theta_2} \quad (1)$$

Where: V_1 and V_2 are the output applied voltages from the waveform generators. Z_1, and Z_2: known and unknown standard impedances respectively

After determining the balance point, the value of one of the unknown impedance is then calculated in terms of the other one which is the known standard impedance.

3. Balancing Procedure of the Bridge Using the Automated Program

A LabVIEW program is particularly designed to setup the calibration conditions and to control the bridge operation. At first, the program controls the output signals which come from the waveform generators. After that, the LabVIEW program record the output measurement readings from the DMM and save them in an excel sheet. Synchronization of the generators has been obtained by their internal T-clock to make sure that the starting time for both signals is exactly the same and the phase shift is as entered in the program.

The program controls many measurement factors such as the value of the output voltage level, type of wave signal, frequency, and phase angle. It also controls the delay at the start of the operation, number of readings for each measurement, and the delay time between each measurement. Fig (2) represents the setup tap in the front panel of the designed LabVIEW program, where the input conditions to the system are controlled. The file path of the excel sheet is also recorded in this interface.

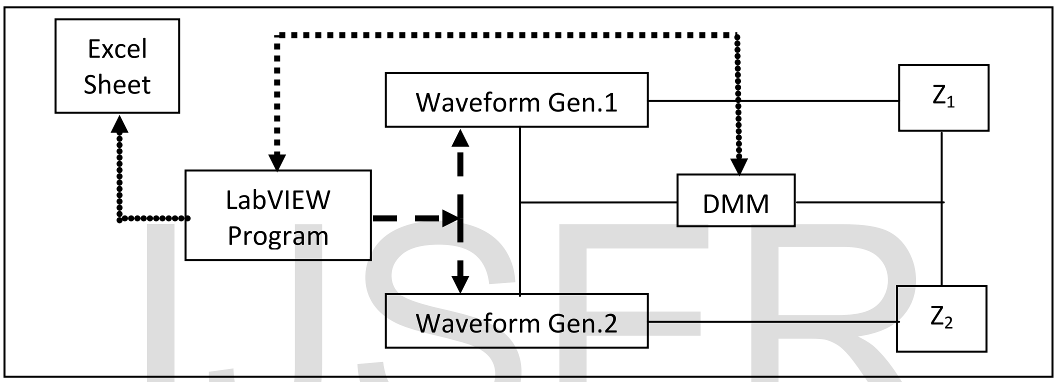

Fig (1) Block diagram of the system construction

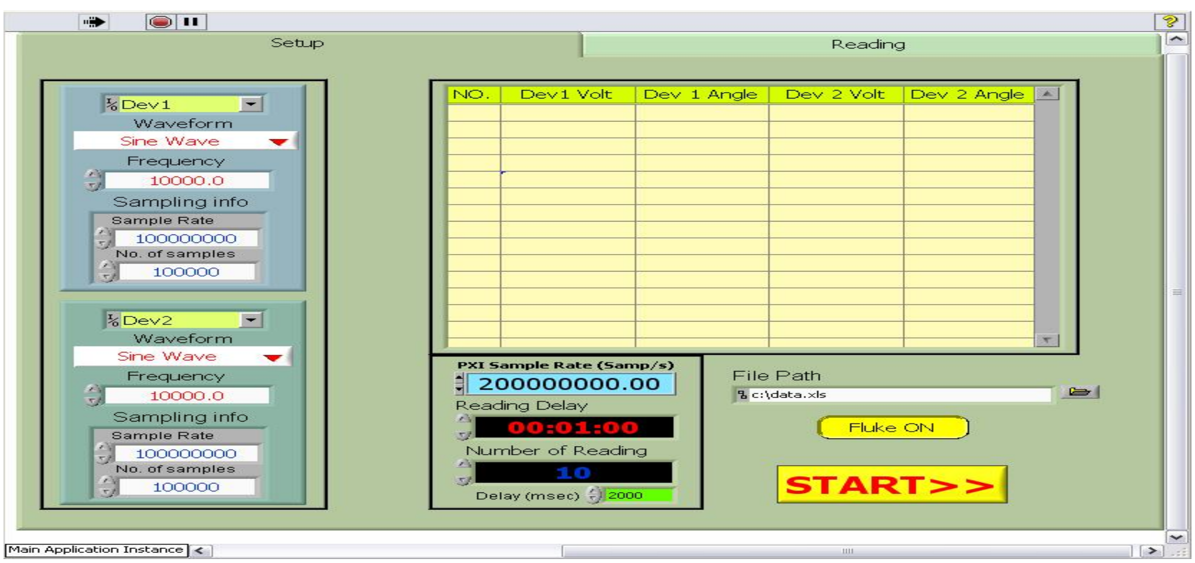

Fig. (2) Main interface of LabVIEW program

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The reading tap in the front panel of the LabVIEW program is represented in Fig (3). It finally shows the measurement step number, the voltage level and phase angle of each source at each measurement step. It also shows the output readings of the DMM and the average of readings of each measurement step. To get the bridge balance, two main adjustments have to be carried out. The first adjustment is performed on the voltage level of one of the waveform generators, and the second adjustment is made for its phase angle. The second waveform generator must have a fixed voltage level and fixed phase angle.

Consecutive changes through the LabVIEW program are made on the voltage level and the phase angle to get the minimum voltage difference reading by the DMM. The program records the output results from the DMM to an excel sheet. The value of the variable voltage and phase angle at the balancing condition can be detected from the results data which will be corresponding to the minimum value of the DMM readings. After determining the balance point, the values of the voltages of the two waveform generators are calibrated using a 8.5 digit DMM. Then the unknown impedance is then calculated using equation (1).

4. Calibration Results and Bridge Evaluation

The bridge is used to calibrate unknown impedance by calibrated standard impedance. The bridge performance has been confirmed by comparing the output ratio of the voltages from the waveform generators with the calibrated values of the standards used in the system at the balancing point. The deviation of the bridge readings are calculated using equation (2):

$$\mathrm{Dev.} = \frac{V_1}{V_2} - \frac{Z_1}{Z_2} \quad (2)$$

Where V_1 is the calibrated value of the applied voltage signal on the standard impedance Z_1 which is considered as the unknown standard impedance, and V_2 is the calibrated value of applied voltage signal on the known standard impedance Z_2.

The bridge system has been used to measure capacitance to resistance (C-R) ratio and capacitance to inductance (C-L) ratio at frequency of 1592 Hz.

4.1 Capacitance to Resistance Ratio Measurement

A standard air capacitor of 10 nF is measured referring to a 10 kΩ resistor at 1592 Hz using sine wave. The phase shift between the waveform generators are set to be 90^0 for the measurements.

From equation (2), the deviation of the bridge can be computed using the following equation:

$$\mathrm{Dev.} = \frac{V_{X_C}}{V_R} - \frac{X_C}{R} \quad (3\text{-a})$$

Where V_{X_C} is the calibrated applied voltage on the standard capacitance that has impedance of value X_c, which is the impedance of the capacitance at 1592 Hz that is obtained by the following equation:

$$X_C = \frac{1}{2\pi FC} \quad (3\text{-b})$$

V_R is the calibrated applied voltage on the standard resistance, R.

The measurement results are listed in Table (1).

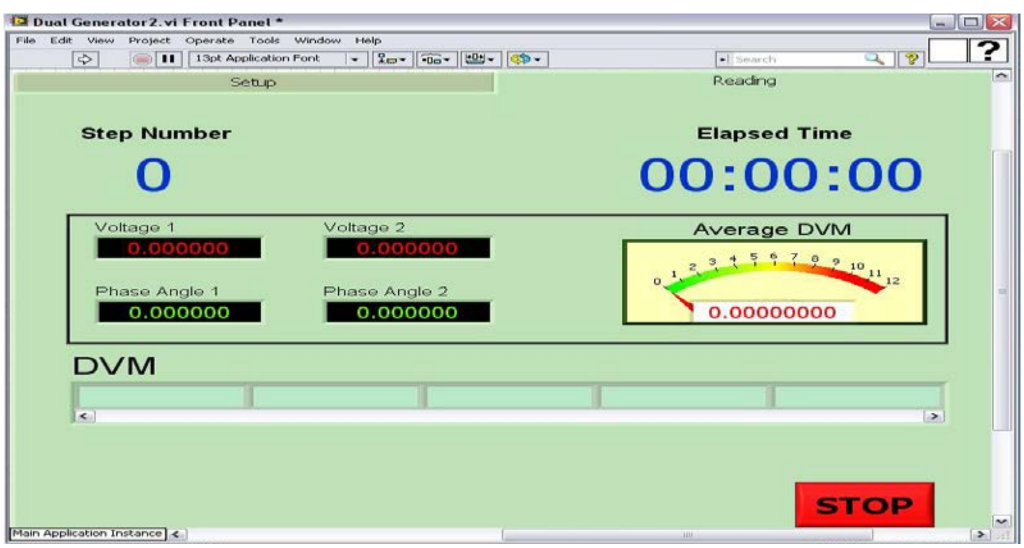

Fig. (3) Output interface of the LabVIEW program

Table 1 Measurement results of capacitance, 10 nF to resistance, 10 kΩ ratio at 1592 Hz

nominal value of the standards, 10 kΩ, and 10 nF	
X_C = 10.009101 Ω	R = 10.00001089 Ω
X_C/R = 1.00091	$r = V_{Xc}/V_R$ = 1.00141
Dev. = $(V_{Xc}/V_R) - (X_C/R) = 5.03 \times 10^{-4}$	

4.2 Inductance to Capacitance Ratio Measurement

Standard inductors of 1 mH and 10 mH are measured by comparing to 10 µF and 1 µF standard air capacitors respectively. The measurements have been done using sin wave at frequency of 1592 Hz with phase shift of 180°. Table (2) and Table (3) show the results of the measurements in both cases.

From equation (2), the deviation of the bridge can be computed using the following equation:

$$\text{Dev.} = \frac{V_{X_C}}{V_{X_L}} - \frac{X_C}{X_L} \quad (4\text{-a})$$

Where V_{Xc} and V_{XL} are the calibrated applied voltages on the standard capacitance X_C and standard Inductance X_L respectively. X_L is the impedance of the inductance at 1592 Hz which is obtained by the following equation:

$$X_L = 2\pi FL \quad (4\text{-b})$$

Table 2 Measurement results of inductance, 1 mH to capacitance, 10 µF at 1592 Hz

nominal value of the standards, 10 µF, and 1 mH	
X_C = 9.99717 Ω	X_L = 10.00028 Ω
X_C/X_L = 0.999434	$r = V_{Xc}/V_{XL}$ = 1.001522
Dev. = $(V_{Xc}/V_{XL}) - (X_C/X_L) = 2.09 \times 10^{-3}$	

Table 3 Measurement results of inductance, 10mH to capacitance, 1 µF at 1592 Hz

nominal value of the standards, 10 µF, and 1 mH	
X_C = 99.9717 Ω	X_L = 100.0028 Ω
X_C/X_L = 0.999434	$r = V_{Xc}/V_{XL}$ = 1.001114
Dev. = $(V_{(Xc)}/V_{(XL)}) - (X_C/X_L) = 2.11 \times 10^{-3}$	

4.3 Bridge Asymmetry

The bridge system asymmetry has been also studied to evaluate the bridge performance. The bridge system asymmetry has been calculated in the case of capacitance to resistance standards (C-R) measurement, as an example. The bridge asymmetry can be calculated by the following equation [10]:

$$\text{Bridge asymmetry} = \left(\frac{r_1 + r_2}{2}\right) - 1 \quad (5)$$

Where r_1 is the ratio between the voltages at the first position and r_2 is the ratio between the voltages by replacing the position of each standard with the other.

In case of (C-R) measurement, at first, the ratio (V_{Xc}/V_R) is measured, and then the ratio (V_R/V_{Xc}) is measured by replacing the position of the waveform generator cards with each other. The bridge asymmetry is listed in Table (4).

Table 4 Bridge asymmetry in the case of capacitance, 10 nF to resistance, 10 kΩ ratio at 1592 Hz

nominal value of the standards, 10 kΩ, and 10 nF		
C = 9.98808 nF	X_C = 10.009101 Ω	R = 10.00001089 Ω
$r_1 = V_{Xc}/V_R$ = 1.00141	$r_2 = V_R/V_{Xc}$ = 0.99860	
Bridge asymmetry, Eq. (7)	= 6.48 ppm	

5. Uncertainty Budget

The uncertainty sources of the system are estimated, and the calculations have been carried out according to the guide to the expression of uncertainty in measurement (GUM) [11]. The components of the uncertainty budget are divided into two types; Type (A)which is referring to the repeatability of the readings and it has a normal distribution. The other type is Type (B) which represents all the other components in the system and it may have a normal or rectangular distribution. The expanded uncertainty calculation has been done at 95 % confidence level with coverage factor k=2. The uncertainty components are listed in Table 5.

6. Conclusion

Bridge system for impedance measurements based on programmable waveform generators has been introduced. It can be constructed in electrical metrology laboratories, and fully controlled automatically by special designed LabVIEW program. The introduced bridge system is used to calibrate standard capacitance by standard resistance and standard inductance by standard capacitance at quadrature bridge frequency, 1592 Hz. The bridge deviation in both cases has been calculated, and it is found to be in the range of 10^{-4} in the case of capacitance to resistance measurement. While in the case of inductance to capacitance measurements it is found to be in the range of 10^{-3}.The bridge asymmetry has been also studied and calculated in the case of capacitance to resistance measurement as an example and it is within the range of 7 ppm on the average.

Table 5 Uncertainty budget of capacitance to resistance measurements at 1592 Hz

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Source of Uncertainty	Type of uncertainty	Probability distribution	Divisor	Uncertainty contribution, ppm
Repeatability	Type A	Normal	1	3.0
Voltage Source Calibration V_1	Type B	Normal	2	2.5
Voltage Source Calibration V_2	Type B	Normal	2	2.5
Standard Resistor Calibration	Type B	Normal	2	0.02
DMM resolution	Type B	Rectangular	$\sqrt{3}$	0.1
Sources Synchronization	Type B	Rectangular	$\sqrt{3}$	0.3
Frequency Stability	Type B	Rectangular	$\sqrt{3}$	0.6
Bridge asymmetry, average	Type B	Rectangular	$\sqrt{3}$	3.8
Combined uncertainty	6.1 ppm			
Expanded uncertainty (k=2)	12.2 ppm			

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