Electrical Characterization of a New Established Inductance Box Using an Automated Measurement System

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Abstract— **Inductance box is an instrument that generates a variety of inductance values, which are used to verify the accuracy and to calibrate inductance measurement devices. In this paper, characterization of a new fabricated inductance box has been investigated by using an automated system developed for inductance measurements. The new verified inductance box had been constructed by three inductance decades giving 4096 inductance steps using the all possible combinations. The output inductance steps of this inductance box have been measured for each decade at different frequencies over the range form 1 kHz to 10 kHz to study its frequency dependence as will be illustrated in this research. At different voltage values in the range form 0.6 V to 2 V, the output inductance values have been also measured to demonstrate the voltage dependence of the tested inductance box as will be presented in this work. All practical results of each decade at different frequencies and voltage levels have been carefully analyzed through accurate calculations and necessary representing figures as will be clearly described in this paper. Relative accuracy of this inductance box is in the range from 5×10^{-4} to 5×10^{-3} at 1 kHz and 1V. Its relative uncertainty due to the summation effect has been founded to be less than 6×10^{-5}. The relative expanded uncertainty for such automated systems is typically less than 0.025%.**

Index Terms— **automated measurement system, decade inductance, inductance measurement, fabricated inductance box, electrical characterization, voltage dependence, frequency dependence**

I. Introduction

Mainly inductance applications require accurate measurements of inductance using different inductance measuring instruments. So, they should be calibrated by inductance standards such as inductance boxes which can quickly and accurately provide standard inductance values for performing such calibrations. Inductance boxes are also commonly used for a system design process, as they can be easily inserted into a circuit to give any inductance value within a specified range to assist in identifying the optimal inductor value to be fixed in the final design for that circuit.

Generally, each inductance box is constructed by inductance decades that are normally formed internally by ten inductive elements to generate ten inductance values. In [1] and [2], the same number of the output inductance values is generated only by using four internal inductive elements. Moreover, fifteen output inductance values could be obtained and controlled automatically, also by using four internal inductive elements as described in [3].

Accordingly, a new inductance box was designed by four modules; inductance decades, micro-controller, keypad and LCD. There are three decades and each one of them has four inductive elements with corresponding four reed relays. The first decade has inductive elements values, 1 mH, 2 mH, 4 mH and 8 mH to give output inductance steps in the range from 1 mH to 15 mH with 1 mH/step. While the second decade has inductive elements values, 10 mH, 20 mH, 40 mH and 80 mH to give output inductance steps in the range from 10 mH to 150 mH with 10 mH/step. Finally, the third decade has inductive elements values, 100 mH, 200 mH, 400 mH and 800 mH to give output inductance steps in the range from 100 mH to 1500 mH with 100 mH/step. 4096 inductance steps values could be obtained by the all possible combinations of the steps of all decades, but 1666 of them are different from each others. The described inductance box could be automatically controlled by only one micro-controller.

In this paper, a fully accurate automated inductance measurement system has been used at the National Institute for Standards (NIS), Egypt to completely characterize the new patent inductance box through a specially prepared Lab VIEW program. Characterization of this new inductance box has been realized by investigating its accuracy, summation effect, frequency dependence and voltage dependence. All of these factors which verify and confirm the performance of this inductance box have been deeply and scientifically studied through huge number of repeated measurements for its output inductance steps. Hence, analyses of the obtained practical results have been carried out as will be explained in details trough this research.

II. Fully Automated System for Inductance Measurements

A fully automated system for accurate measurements of inductance has been assembled using the new fabricated inductance box, an Agilent E4980A LCR meter [4] and a computer; as shown in Fig. 1a.

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As illustrated in Fig. 1a and clearly in Fig. 1b, the inductance box serial port is connected to the computer USB port by USB to serial converter and the LCR meter is connected to the same computer by a USB cable to complete the closed loop control of that system.

The output terminals of the inductance box are connected to the input terminals of the Agilent E4980A LCR meter as depicted in Fig. 1b, which enables measurement of the output inductance steps as required. The whole system could be controlled automatically by a specially prepared Lab VIEW program. It could be used to select the required inductance steps to be measured with choosing the required measurement settings as frequency, voltage level, number of readings for each inductance step value and time delay between the generated steps. Then by press run button, all of these settings will be applied during the measurement process and the final results will be saved in a specified excel sheet.

III. Characterization of the Fabricated Inductance Box

To characterize the new inductance box some of its properties such as accuracy, summation effect, frequency dependence and voltage dependence should be investigated and analyzed. Each one of these characteristics is described and demonstrated in details. By using the Agilent E4980A LCR meter and Lab VIEW program; a large number of measurements have been taken and the previously mentioned parameters have been determined to verify the tested inductance box.

3.1. Level of Accuracy

The fifteen output inductance steps values of each one of the three decades inside the inductance box have been measured many times and the relative deviation for each step from its nominal value has been determined by the following equation;

$$\Delta_{step} = \frac{Actual\ Value - \text{Nominal Value}}{Actual\ Value} \qquad (1)$$

Averages of all results are analyzed and therefore the relative deviation has been founded in the range from 5×10^{-4} to 5×10^{-3} at 1 kHz and 1V.

3.2. Uncertainty Due to Summation Effect

The obtained relative deviation limits have been determined for individual steps, but there are 1666 different inductance values can be produced by this new inductance box, while the maximum number of the possible output inductance steps generated by all possible combinations is 4096 inductance steps. So, there are many repeated steps values that could be generated by different combinations. For example, the 111 mH could be obtained by using four different combinations as listed in the table 1.

Fig. 1a. Automated system for inductance measurements

Fig.1b. Connections of the fabricated inductance box

Fig.1. Fully automated system for accurate measurements of inductance.

Table 1

Different combinations for the same required inductance value.

Required inductance value	Setting of Decade A, (1 mH /Step)	Step of Decade B (10 mH /Step)	Step of Decade C (100 mH /Step)
111 mH	1	1	1
111 mH	11	10	0
111 mH	1	11	0
111 mH	11	0	1

So, there is an important figure should be determined for any inductance box which is the effect of summation. It can be determined by comparing measured inductance steps with equal nominal values but generated by different combinations as described in table 1, for only one case as an example. Many other different cases have been measured and all results have been studied and analyzed to estimate the uncertainty caused by the summation effect of the new inductance box. Therefore, the relative uncertainty due to the summation effect has been founded to be less than 6×10^{-5}.

3.3. Frequency Dependence of the Output Inductance Values

When a pure sine wave of voltage is applied across a pure inductor, then a pure cosine wave of current flows in the conductor. This cosine wave has the same shape as sine wave but, in the circuit described, lags the voltage that is applied a cross the inductor by 90° . In other words, the maximum value of current through the inductor occurs, when the changing of ac voltage across the inductor is passing through zero volts. The opposition to the flow of ac current in an ac circuit due to inductance is called inductive reactance, X_L. Both of the inductance and the frequency determine the magnitude of this reactance which can be expressed as:

$$X_L = 2\pi f L \tag{2}$$

Where: X_L is the inductive reactance in ohms, f is the frequency of the applied sine wave of voltage in hertz, L is the inductance in henneries, and $\pi = 3.1416$.

As predicted from Eq.2, the inductance L is inversely proportional to the frequency f when at the relatively low inductance values, or low frequencies according to the inductor type. Figure 2, proves exactly the described relationship of the inductance steps values with the variation of the applied frequency for the first decade. Hence the relative deviation of each step form its nominal value is calculated according to Eq. 1. It is very obvious that the actual inductance values decrease with increasing of the frequency.

When the value of the inductance increases as presented in the second decade and the frequency increases, for example, at 10 kHz, therefore, their relationship will be slightly changed at some points as represented in Fig.3. This is due to the effect of the impedance, which is defined by the following equation:

$$Z = \sqrt{R^2 + (X_L - X_C)^2} \tag{3}$$

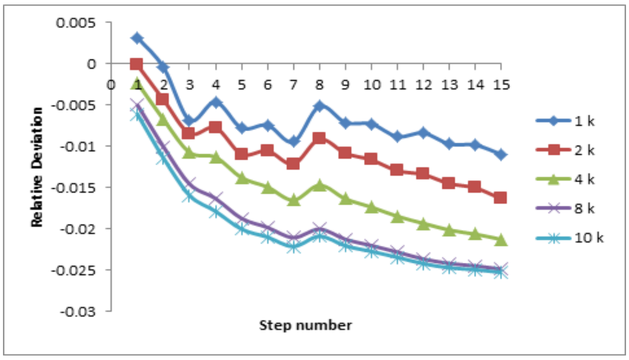

Fig.2. Relative deviation of the steps of the first decade at different frequencies.

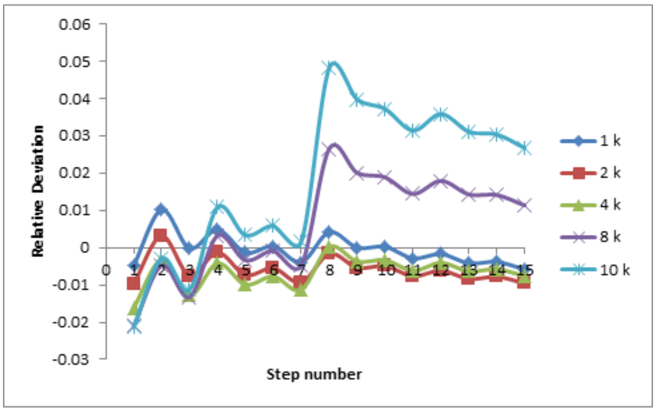

Fig.3. Relative deviation of the steps of the second decade at different frequencies

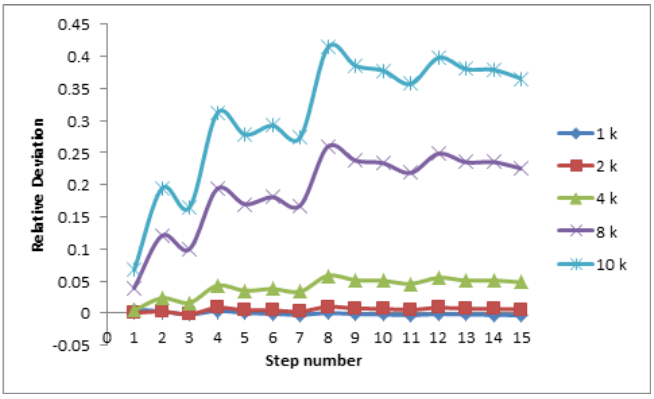

Fig.4. Relative deviation of the steps of the third decade at different frequencies

Figure 4, illustrates the relationship between the inductance steps and frequency variation, but at higher inductance values which are in the range from 100 mH to 1500 mH as previously mentioned.

At such higher inductance values; the effect of the impedance will be very clear especially at higher frequencies as 8 kHz and 10 kHz. So, at these conditions the electrical behavior of some inductors types as the used toroidal-core inductors is nearly reversed as cleared in Fig. 4, which is matched with the behavior of toroidal-core inductors. The interpretation of this phenomenon is given by [5] that says, "This can cause operational difficulties at higher frequencies, and because at these frequencies, the inductor is behaving more like a capacitor and less like an inductor".

3.4. Voltage Dependence of the Output Inductance Values

Inductance is the property of an electrical circuit that opposes any change in the magnitude of the current flowing in the circuit. Energy is stored in the magnetic field associated with a current flowing in the circuit. When the current changes, the flux will be changed then, a voltage is induced into the conductor by the magnetic field. In terms of inductance, the induced voltage can be expressed as given by [6]:

$$V_L = L\left(\frac{di}{dt}\right) \tag{4}$$

Accordingly, the relationship between the steps relative deviation and the voltage variation is shown in Figs.5, 6 and 7. When the testing voltage value increases the inductance value is also increases because the voltage is directly proportional to the inductance which practically proves Eq.4.

By comparing Figs. 5 and 6, it could be seen that for the second decade inductance which has higher inductance values; the difference between the voltage levels curves are decreased compared to the first decade.

More consistency could be realized for the third decade inductance curves, which emphasis that increasing the inductance range means decreasing the difference between the voltage levels curves as illustrated in Fig. 7.

At different voltage levels, the curves of the relative deviation of the inductance box steps are homogeneous and the values of the inductance steps are relatively stable which means that the voltage dependence of the verified inductance box is relatively small due to its improved performance.

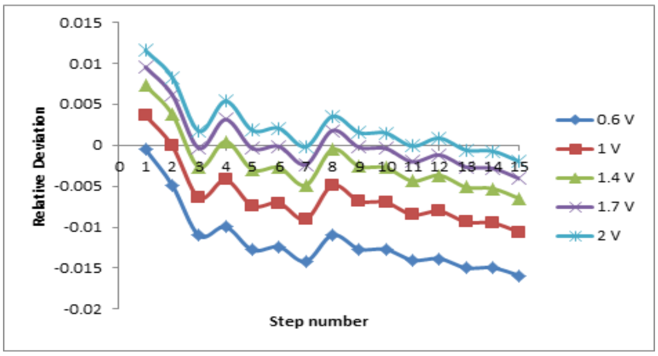

Fig.5. Relative deviation of the steps of the first decade at different voltage values

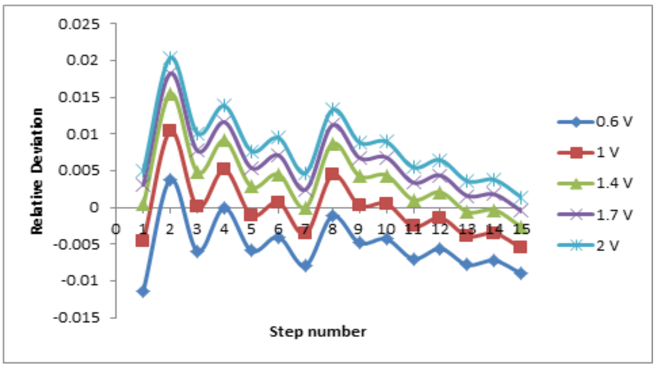

Fig.6. Relative deviation of the steps of the second decade at different voltage values.

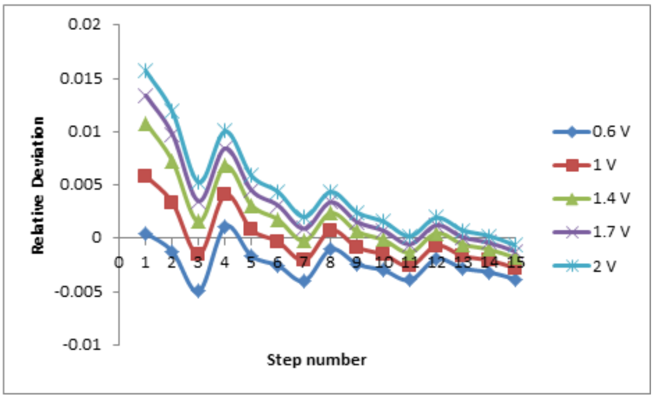

Fig.7. Relative deviation of the steps of the third decade at different voltage values

IV. Uncertainty Estimations

Uncertainty values of all inductance steps can be computed according to [7] and [8]. Therefore, The relative expanded uncertainty of such automated systems for inductance measurements is usually less than 0.025% at 95.54% confidence level with a coverage factor two, i.e.(k=2).

V. Conclusion

A fully automated system for inductance measurements has been assembled at the National Institute for Standards (NIS), Egypt by the fabricated inductance box, an Agilent E4980A LCR meter and a computer. Enormous number of measurements has been taken by the established automated system and therefore; characteristics of the verified inductance box could be realized. At 1 kHz and 1 V; the relative deviation of output inductance steps from their rated values is in the range from $\pm5\times10^{-4}$ to $\pm5\times10^{-3}$, while the relative uncertainty due to the summation effect is less than 6×10^{-5}. Frequency dependence of the steps of the tested inductance box is increasing with the increasing of the inductance values at high frequencies for the used toroidal-core inductors. On the other hand, the voltage dependence of the fabricated inductance box is relatively low and the relative deviation curves of its output steps become more homogeneous with the increasing of the inductance values at different voltage levels. The huge number of the output inductance steps enables the introduced inductance box to be used consistently for calibration of the inductance meters with relative expanded uncertainty less than 0.025%.

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