CONSIDERATIONS ON DIGITAL IMPEDANCE MEASUREMENTS

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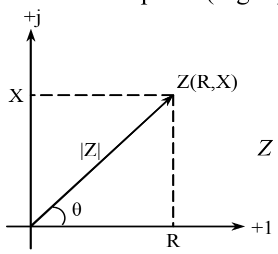
Abstract **– Impedance is the most important parameter used to characterize electronic circuits, components, and materials used to make components. This paper presents a synthesis of different methods of digital impedance measurements. There are also presented some examples of these measurements.**

Keywords: measurement, impedance, digital

1. INTRODUCTION

Impedance (Z) is generally defined as the total opposition a device or circuit offers to the flow of an alternating current (AC) at a given frequency, and is represented as a complex quantity which is graphically shown on a vector plane (Fig. 1).



$$Z = R + jX = |Z|\angle\theta$$

Fig. 1. Complex representation of impedance

Different impedance measurement techniques, such as oscillators, frequency domain techniques, and digital AC bridges, etc., have been developed in the last decades to satisfy the increasing requirements. Nowadays, all new methods of impedance measurement are digital. Even if the old analogical methods offer good accuracy and resolution, they are no more up to day and are transmuted in digital.

2. POSSIBILITIES OF DIGITAL IMPEDANCE MEASUREMENTS

The main methods of digital impedance measurement are: conversion methods, bridge methods, compensation methods, indirect and resonance methods. Here are described these methods.

2.1. Conversion methods

By conversion method the impedance is converted in an electric quantity: period of time, frequency, phase, voltage or current. The disadvantage of this method consists in fact that it is measured usually only the preponderant component of the unknown impedance or only one of the components of the unknown reactance.

In [1] is described a novel technique, which enables the measurement of two of the impedance sensor components. In this technique a simple first-order charge-balanced oscillator is used. The objective is to measure both components R_x and C_x of the unknown impedance, represented with a series model (fig. 2).

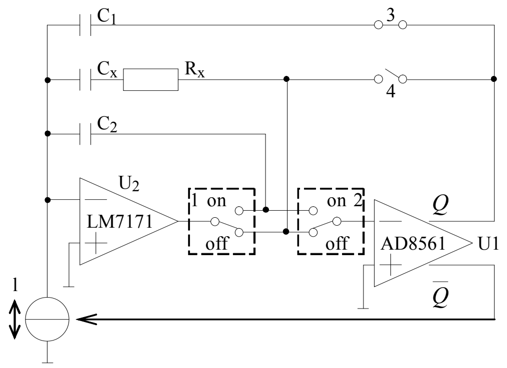


Fig. 2. Experimental circuit for R –C impedance measurement.

The output signal for both impedance components is a time period that can directly be supplied to a microcontroller input, without the need of an analog-to-digital converter (ADC). For calculating their values only one reference capacitor is needed. A continuous self-calibration multisignal measurement technique is used to improve the accuracy and to ensure that the interface circuit is independent of the unstable parameters of the active components. The experimental results prove that with this new technique, very high resolution for both components of the measured impedance can be achieved – better than 0.1 Ω for R_x and better than 0.1 pF for C_x.

In [2] it is presented one quite new realization of a low-cost and highly precise capacitance measurer (fig. 3). This method is based on capacitance to time domain conversion. In addition to the simplicity of its realization and simple calibration, the architecture of the measurer also provides for the elimination of the effects of supply voltage instability and temperature instability of reference voltages. A single stable resistor is all that is needed. The proposed method provides for input parasitic capacitance compensation. The achieved accuracy is the level required for the secondary die measurement.

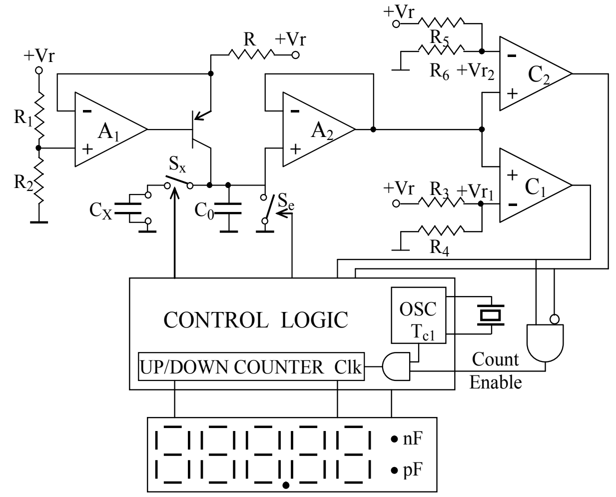


Fig. 3. Basic configuration of the capacitancemeter.

A novel device, able to convert inductance variations into digital words directly compatible with digital calculus systems is presented in [3]. The device was conceived as an application for inductive displacement sensors, but can be very well employed for other inductive or capacitive sensors designed to measure proximity, force, pressure, etc. The operating principle is based on maintaining constant the phase shift φ between the voltage $\underline{U}$ and the corresponding current $\underline{I}$ flowing through a series circuit which includes the sensor inductance L and resistor R, by adjusting the supply frequency (fig. 4). It was found that the inductance L is proportional to the voltage period T provided that φ and R_L be preserved constant.

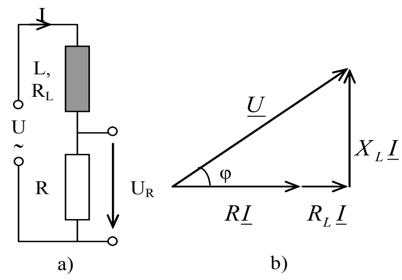


Fig. 4. a) Series L-R circuit, b) phasorial diagram.

Detection of a small resistance change is often needed in industrial and process control systems and medical instrumentation. In such systems, microprocessors are used exclusively for digital signal processing, and thus input data in a digital format is highly desired. A conventional way of detecting the resistance in the digital form is to use a relaxation oscillator whose frequency is determined by the resistance under measurement and a known capacitor. Though simple, this method suffers from nonlinearity. In addition, high sensitivity cannot be expected since the oscillation frequency is inversely proportional to the total resistance. The most sensitive means of detecting the resistance change is a Wheatstone bridge. Combining a Wheatstone bridge with a relaxation oscillator appears to be a promising approach to the high-sensitivity resistance-to-frequency (R-to-F) converter. The circuit described in [4] is a resistance-to-duty-ratio converter, and the feedback circuit, consisting of an integrator and a comparator, maintains the balance of the bridge by controlling the switched resistors incorporated in the arms of the bridge (fig. 5). The Wheatstone bridge is used merely to detect the resistance deviation from the offset value. Since no balance operation is involved, the circuit configuration is much simpler. The sensitivity is high enough, because of the differential integration involved, to be compared to that of the resistance-to-duty-ratio converter. The component requirement is minimum. Besides the simple configuration, it features a high resolution and an excellent linearity over the wide resistance range. Therefore, the described R-to-F converter will find wide applicability as the signal conditioner of platinum RTD's for temperature measurements, strain gauges for electronic balances, piezoresistors for pressure detection, and the other resistive sensors for instrumentation and measurements.

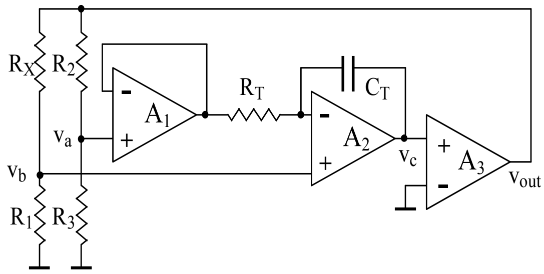


Fig. 5. A linear resistance-to-frequency converter: basic configuration.

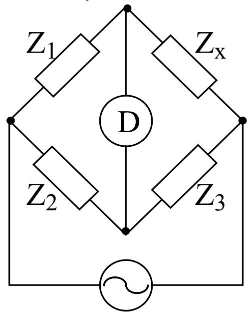
The principle of measuring method in [5] is also based on capacitance-to-frequency conversion. Here the unknown impedance is connected in the circuit of the relaxation oscillator. The errors introduced in this oscillator are also discussed. The oscillator circuit was simulated using the SPICE program, and gives the opportunity to study the behavior of the circuit under non-ideal conditions, and also to estimate the errors introduced in the measured capacitance and the frequency of oscillation.

The method of impedance-to-voltage conversion is in fact an improvement of classic ohmmeter principle. The accuracy is not so good, but there is an advantage of rapid measurement in a large domain of values and frequencies [6]. This method is the base for construction of ohmmeters, faradmeters and henrymeters which measure only one parameter of unknown impedance [7].

2.2. Bridge methods

Bridge method is one of zero methods for impedance measurement.

When no current flows through the detector (D), the value of the unknown impedance Z_x can be obtained by the relationship of the other bridge elements (fig. 6). Various types of bridge circuits, employing combinations of *L*, *C*, and *R* components as the bridge elements, are used for various applications.



$$\underline{Z}_x = \frac{\underline{Z}_1}{\underline{Z}_2}\underline{Z}_3$$

Fig. 6. Bridge method.

An impedance measuring prototype has been presented in [8]. It implements two measurement techniques: the first consists in solving the set of equation obtained from the relationships existing between i) the real and imaginary parts of the unknown impedance, and ii) the amplitude and the phase of two measured signals. The second technique consists of balancing an ac bridge whose reference arm is a virtual model of the real bridge. Experimental tests were carried out on a wide range of capacitive impedance values and on two standard inductances. The results indicate that the amplitude-phase technique provides medium accuracy (1 %) with the maximum measurement rate (1000 per second); the virtual bridge, at lower measurement rates (up to 80 per second), provides results comparable to those of the high precision (0.02%) reference instrument.

A digital impedance bridge composed of two digital sine-wave generators and inductive voltage dividers designed for precision comparison of different impedance standards is described in [9]. To increase the reliability of measurement and its accuracy, an unknown is compared to many reference standards and a special method of estimation is applied. The bridge enables one to measure impedance from 10 Ω up to 100 kΩ in the frequency range between 100 Hz and 1 kHz with a relative uncertainty smaller than 50 μΩ/Ω, which is mainly due to short term instability of the digital source and uncertainty of reference standards. Here is described an automated impedance bridge based on the application of a two-phase digital generator and a special statistical estimating procedure (fig. 7). Essential features of the bridge are: a simple configuration, adjustment of the voltage sources to be precisely equal to one another, a new measuring algorithm which uses a multi-standard comparison technique and a novel method of the impedance estimation. This system can fill a gap between commercially available automated instruments and high precision manually operated devices.

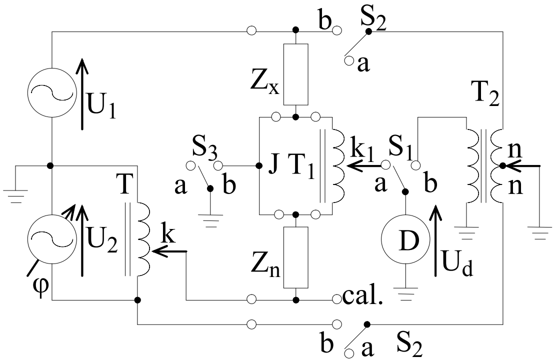


Fig. 7. Simplified diagram of the impedance bridge.

An impedance bridge that compares two-terminal standard inductors to characterized ac resistors in the frequency range of 10 Hz to 100 kHz is described in [10]. A dual-channel, digitally synthesized source and sampling digital multimeter are used to generate and measure relevant bridge signals. A linear interpolation algorithm is used to auto calibrate the bridge to a 1 nF gas dielectric capacitor. An intercomparison of the new bridge with existing measurement standards conducted in the low audio frequency range shows agreement of 50 to 200 parts in 10^6 for inductors for 1 mH to 10 H.

A virtual instrument based on a quasi-balanced bridge designed to measure the parameters of an inductor, a capacitor or a resistor is presented in [11].

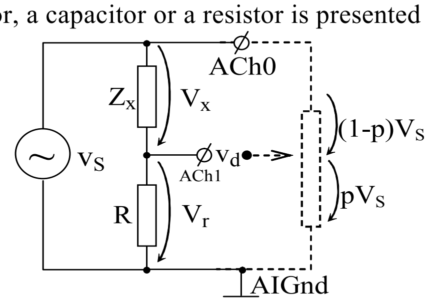


Fig. 8. The quasi-balanced bridge circuit

The unknown element, in series with a reference resistor, forms the real half of an ac bridge, while the software model of a resistive potentiometer shapes the virtual half (fig. 8). Actually, one acquires the supplying voltage and the voltage across the reference resistor respectively, after which these signals are digitally processed according to the quasi-balanced bridge algorithm. The use of only one fixed resistor as reference confers accuracy in measurement and the two independent quasi-balances obtained by modifying the same virtual potentiometer setting permit facile and fast automatic balancing.

2.3. Indirect methods

By this method the impedance components are calculated from the measured electrical quantities.

A novel method of measurement of component values of inductors and capacitors is described in [12]. The technique is independent of the voltage across or current through the unknown inductor or capacitor, as it involves only a set of phase measurements. The unknown capacitor/inductor is connected in series with a known standard resistance and this series circuit is excited by a source of required voltage and frequency (fig. 9). The resistive and reactive parts of the unknown component are calculated from the measured phase displacement between the three voltages: applied voltage, voltage across the inductor/capacitor and the voltage across standard resistance. The proposed scheme was verified both by simulation as well as by building a prototype. For the built prototype, with a one decade span in the measurement range, a commercially acceptable accuracy of ±2.0 % was achieved.

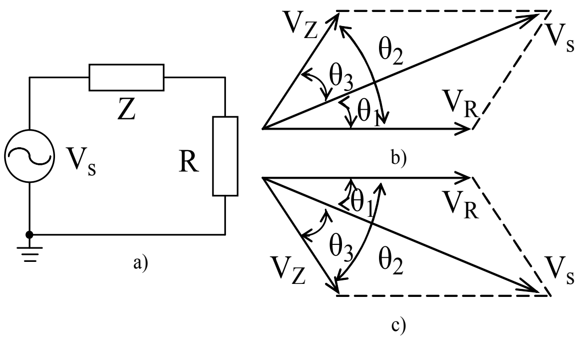


Fig. 9. a) Schematic; b) Phasor diagram for inductive impedance; c) Phasor diagram for capacitive impedance.

A waveform technique to measure complex impedance of dielectric films at high ac voltages by recording and analyzing the incident voltage and the resulting dissipation current waveforms using multichannel data acquisition (DAQ) instrumentation is presented in [13]. The voltage waveforms are Fourier transformed from the time domain to the frequency domain to obtain the fundamental and higher order harmonic responses as complex phasor quantities (fig. 10). The specimen impedance is determined by performing complex algebraic calculations. This procedure is capable of resolving the phase component between the specimen voltage and the specimen current and is thus suitable for determining the specimen complex impedance.

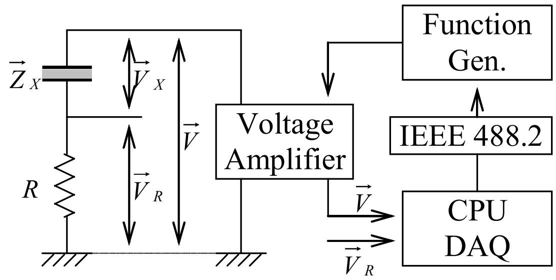


Fig. 10. Measurement diagram.

Two current-voltage methods for inductance measurement are presented in [14]. The thirst one is current-voltage method using vector voltmeters (fig. 11). It is based on evaluation of the module and phase angle of impedance (in the case of self-inductance) or transmittance (in the case of mutual inductance) using equations (1) and (2).

$$Z = \frac{v_2}{i} = R_r \frac{v_2}{v_1} = R_r \frac{V_{m2}\exp(j\varphi_2)}{V_{m1}\exp(j\varphi_1)} = \\ = R_r \frac{V_{m2}}{V_{m1}} \exp j(\varphi_2 - \varphi_1) = Z_m \exp(j\varphi_z) \quad (1)$$

$$T = \frac{v_s}{i_p} = R_r \frac{v_s}{v_{pr}} = R_r \frac{V_{ms}\exp(j\varphi_s)}{V_{mpr}\exp(j\varphi_{pr})} = \\ = R_r \frac{V_{ms}}{V_{mpr}} \exp j(\varphi_s - \varphi_{pr}) = T_m \exp(j\varphi_T) \quad (2)$$

where R_r = sampling resistor used for measurement of current; v_1 = voltage proportional to the current; v_2 = voltage across the measured impedance; v_{pr} = voltage proportional to primary current; v_s = voltage of the secondary winding of the circuit with mutual inductance.

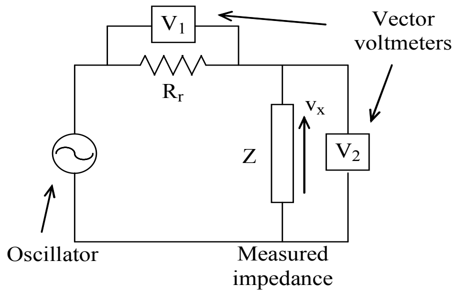


Fig. 11. Circuit diagram for current-voltage method.

The second current-voltage method [14] is a modernized version of the "three-voltmeter" method (fig. 12.). The method is based on the properties of an operational amplifier (OA), in which output voltage v_2 is proportional to input voltage v_1 and to the ratio of the reference resistance R_r to measured impedance Z. The phasor difference v_3 of voltages v_1 and v_2 can be obtained using the differential amplifier (DA). The three voltages (fig. 12.b) can be used for the module Z_m and phase φ calculation using relations:

$$v_2 = -iR_r = -\frac{R_r}{Z} v_1 \Rightarrow Z_m = \frac{V_1}{V_2} R_r \quad (3)$$

$$v_3 = v_1 - v_2 \Rightarrow \varphi = \arccos \frac{V_1^2 + V_2^2 - V_3^2}{2V_1V_2} \quad (4)$$

where V_1, V_2, V_3 are the results of rms voltage measurements in the circuit. The advantage of the method lies in limiting the influence of stray capacitances as a result of attaching one of the terminals of the measured impedance to a point of "virtual ground". However, to obtain small measurement errors, especially at high frequencies, amplifiers with very good dynamic properties must be used.

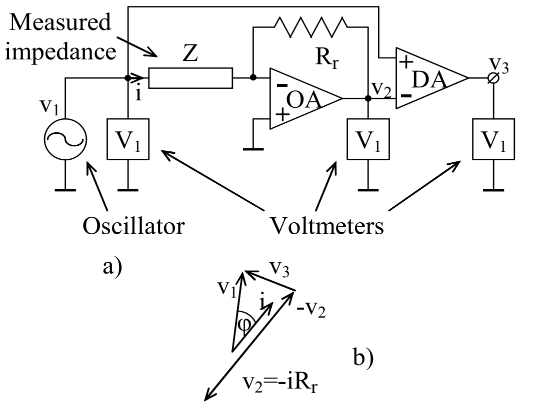


Fig. 12. Block diagram (a) and phasor diagram (b) of the „three-voltmeter" method.

Joint errors of inductance measurement, obtained by current and voltage methods, depend on the following factors: voltmeter errors, errors in calculating resistance R_r, system factors (residual and leakage inductances, resistances and capacitances), and the quality of approximation of the measured impedances by the equivalent circuit.

2.4. Compensation methods

Compensation method is also one of zero methods for impedance measurement.

In [15] a capacitance and loss conductance measuring circuit for the use in industrial transducers is presented. The circuit is based on self-balancing principle and it is immune to stray capacitance. The balancing process is controlled by a micro-controller. The capacitance and loss conductance are represented by the digital feedback signals or by the combination of the feedback signals with the forward path signals. Experimental results show that the circuit has high resolution (0.04 fF) and good linearity (0.999). The capacitance and loss conductance can be measured even when one component is much larger than the other. It is suitable for industrial transducer applications, especially when both capacitance and loss conductance need to be measured.

The automatic measuring arrangement described in [16] provides impedance measurement in the low frequency range with relative errors of only a few parts per million. A measuring arrangement with modular components is presented which, in contrast to existing measuring bridges, is of a modular structure. This permits, in principle, the measurement of any type of n-port. Due to the high reproducibility of the measurement results, this measuring arrangement appears to be well suited for high-precision impedance and network measurements in calibration laboratories. Fig. 13 shows the simplified structure of a typical digital impedance measuring bridge, the components of which are solely based on digital/analog circuit technique. The major elements of this bridge are a phase-sensitive digital null detector and signal generators providing highly reproducible sine-wave voltages by means of digital synthesis. A microprocessor evaluates the data traced by the null detector and afterwards readjusts the generators so as to minimize the error voltage of the bridge. With a given fixed working frequency, balance can be achieved by varying the phase and amplitude of one or both sources. If the reference impedance Z_{ref} and the two generator voltages U_1, and U_2, are known, the unknown impedance Z_x, can be calculated.

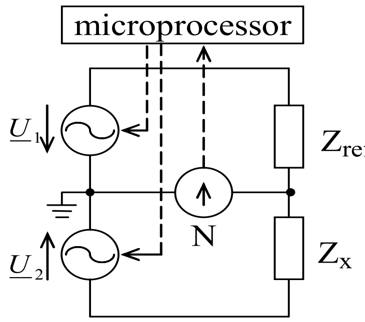


Fig. 13. Digital fixed-structured bridge.

2.5. Resonance methods

When a circuit is adjusted to resonance by adjusting a tuning capacitor C, the unknown impedance L_x and R_x values are obtained from the test frequency, C value, and Q value (fig. 14). Q is measured directly using a voltmeter placed across the tuning capacitor. Because the loss of the measurement circuit is very low, Q values as high as 1000 can be measured. Other than the direct connection shown here, series and parallel connections are available for a wide range of impedance measurements.

There are two main principles of this method:

- determination of ratio between resonance overvoltage and excitation voltage;
- amortisation time measuring for resonant circuit's oscillations.

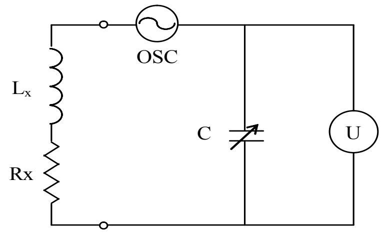


Fig. 14. Resonant method of impedance measurement.

The first one is the base for analogical quality factor measurement. The second principle is the base for digital quality factor measurement.
The Q-meters present a low accuracy, but have the advantage of operating at high frequencies.

3. CONCLUSIONS

This paper indicates the fact that a large variety of methods for digital impedance measurements exist and it is an open domain for future work. Some implementations for these methods are also presented.

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