Automatic compensation system for impedance measurement

Automatic Compensation System for Impedance Measurement

Alessio Carullo, Marco Parvis, *Senior Member, IEEE*, Alberto Vallan, and Luca Callegaro

***Abstract*—This paper deals with the realization of the four-pair terminal definition of impedance standards. A simple, though reliable, system is described that allows an automatic compensation of the voltage at the low potential port of impedance standards to be obtained. Such a system employs a commercial data acquisition board and a signal generator with adjustable-phase capability, which acts as the phase reference for the generator that feeds the impedance standard. A standard PC controls the whole system and implements the demodulation and the control algorithms. Preliminary tests have been performed in the frequency range of 50 Hz to 20 kHz with different kinds of impedance standards (resistive, inductive and capacitive), obtaining a residual voltage at the low potential port of less than 5 μV.**

***Index Terms*—Compensation, impedance measurement, intelligent systems, standard.**

I. Introduction

IMPEDANCE measurement techniques which are employed in metrology laboratories typically rely on manually-adjusted or auto-balancing bridge networks [1]–[4], vector-voltmeter systems, or resonant circuits [5]. Other techniques have been recently proposed that are based on the measurement of rms voltages [6], [7] or which employ digital signal processors and digital instruments [8]–[10].

Whatever the implemented technique is, suitably shielded standards and current-equalized measuring circuits have to be employed in order to minimize the effects of external magnetic and electrical fields [11], thus ensuring a good repeatability of the obtained results. A universally accepted way to realize reliable impedance standards that do not interact with external electrical systems, at least in the frequency range from dc to a few megahertz, consists of defining the impedances as four-terminal pair networks [12]. Fig. 1 shows the realization of a four-terminal pair impedance, which is an electrical network with separate current and potential coaxial connectors on both the high and low sides. The figure also highlights the defining conditions, such as

- the current $\mathbf{I_H}$ that leaves the high potential port $\mathrm{P_H}$ has to be zero;
- the voltage $\mathbf{V_L}$ between the inner and outer conductors at the low potential port $\mathrm{P_L}$ has to be zero, as well as the current that leaves the same port;
- the current $\mathbf{I}$ that leaves the center conductor of the low current port $\mathrm{C_L}$ has to be the same of the current that returns through the outer conductor.

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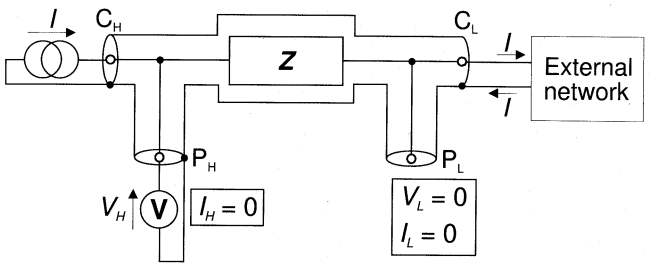

Fig. 1. Realization of an impedance standard as a four-terminal pair network.

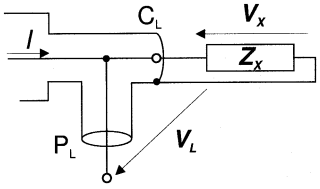

Fig. 2. Equivalent circuit at the low current port $\mathrm{C_L}$.

In the defining conditions and hereafter, bold letters express complex quantities. If these conditions are met, the four-terminal pair impedance is defined as

$$\mathbf{Z_F} = \frac{\mathbf{V_H}}{\mathbf{I}} \tag{1}$$

where $\mathbf{V_H}$ is the voltage measured at the port $\mathrm{P_H}$ and $\mathbf{I}$ is the current that flows through the impedance $\mathbf{Z}$ and the shield. One should note that the impedance $\mathbf{Z_F}$ is the sum of the inner impedance $\mathbf{Z}$ and of the shield impedance. When all the required conditions are met, the external network connected to the port $\mathrm{C_L}$ does not affect the impedance $\mathbf{Z_F}$.

When a four-terminal pair impedance is measured, it is important to give confidence about the compliance to the required defining conditions. Among these, the condition $\mathbf{V_L} = \mathbf{0}$ is the most critical to be met, as $\mathbf{V_L}$ depends on the impedance $\mathbf{Z_X}$ of the circuit connected to the port $\mathrm{C_L}$. Fig. 2 shows an equivalent circuit, where $\mathbf{Z_X}$, which also takes cable and contact impedances into account, can be considered in series with the impedance $\mathbf{Z_F}$. In this case, the effect of $\mathbf{Z_X}$ on the measured amplitude impedance is, in the worst case, $(|\mathbf{Z_X}|)/(|\mathbf{Z_F}|)$. This effect becomes significant if $\mathbf{Z_X}$ has an amplitude that is of the same order of the amplitude uncertainty of $\mathbf{Z_F}$, hence also contact and cable impedances could affect an impedance standard whose uncertainty is of some tens of milliohm. In order to reduce such an effect, a suitable technique has to be implemented to minimize the voltage $\mathbf{V_L}$. In practice, active techniques are employed which are based on the injection of a compensation

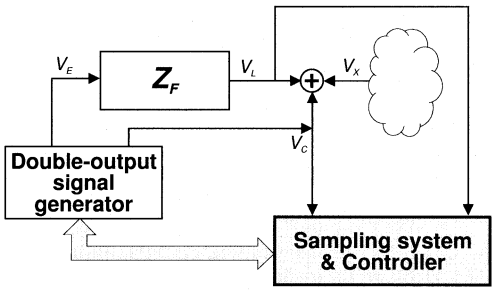

Fig. 3. Principle scheme of the proposed compensation system.

signal into the circuit. Such a compensation signal can be generated by means of inductive voltage dividers or, more conveniently, by analogue or digital generators which are synchronized to the generator that feeds the measuring circuit [13], [14].

When a partial compensation of $\mathbf{V_L}$ is performed, the effect of $\mathbf{Z_X}$ on $\mathbf{Z_F}$ decreases of the same order of the ratio $(|\mathbf{V_{Lr}}|)/(|\mathbf{V_L}|)$, where $\mathbf{V_{Lr}}$ is the residual value of $\mathbf{V_L}$ due to the non ideal compensation.

II. Compensation Technique

The principle scheme of the proposed compensation system is shown in Fig. 3, where the effect of the voltage $\mathbf{V_X}$ due to the spurious impedance $\mathbf{Z_X}$ on the voltage $\mathbf{V_L}$ is highlighted. A programmable double-output generator provides two isofrequential signals: the exciting voltage $\mathbf{V_E}$, which feeds the unknown impedance, and the compensation voltage $\mathbf{V_C}$, which is injected into the measuring circuit. A sampling system acquires the voltage $\mathbf{V_C}$ and the voltage $\mathbf{V_L}$ to be nullified. The acquired samples are then employed to implement a control algorithm, which is designed for computing amplitude and phase of the voltage $\mathbf{V_C}$ that minimize the voltage $\mathbf{V_L}$.

A. Compensation System Prototype

A prototype of the compensation system has been arranged according to the basic scheme shown in Fig. 3. Such a compensation system, whose architecture is shown in Fig. 4, employs a commercial digital generator (Agilent Technologies mod. 33 120A) to provide the compensation voltage $\mathbf{V_C}$. A multifunction calibrator (MFC: Fluke mod. 5720A) feeds the unknown impedance with a known current. The MFC is locked to the compensation generator and both the generator and the calibrator communicates with a PC through a standard IEEE-488 interface.

The compensation signal $\mathbf{V_C}$ is injected into the measuring circuit by means of a feedthrough transformer, whose voltage ratio $\mathbf{K}$ has a nominal amplitude of 0.01 and a nominal phase of 0°.

The voltage $\mathbf{V_L}$ is amplified by means of a variable gain amplifier, which is made up of an instrumentation amplifier connected in cascade to a programmable gain amplifier (PGA). The instrumentation amplifier has a fixed gain, which is 100, and its expected referred to input (RTI) noise is of about 1 μV_{rms}. The gain of the PGA can be set to the values 1, 10, 100, or 1000.

The output voltage $\mathbf{V_m}$ of the variable gain amplifier and the compensation voltage $\mathbf{V_C}$ are acquired through a DAQ board with a resolution of 12 bit and a sampling frequency of 50 kHz if two signals are acquired. A program that runs on the PC where the DAQ board is installed manages the acquisition process, sets the digital generator, the multifunction calibrator, and the PGA gain by means of the digital outputs of the DAQ board.

The acquired samples are processed in order to demodulate $\mathbf{V_m}$ with respect to $\mathbf{V_C}$, i.e., to provide the in-phase (V_{mP}) and in-quadrature (V_{mQ}) components of $v_m(t_k)$ with respect to $v_C(t_k)$, where the symbol t_k represents the variable discrete time. Amplitude and phase of the complex quantity $\mathbf{V_m}$ are then obtained by means of V_{mP} and V_{mQ}. The phase of $\mathbf{V_C}$, which is a setting parameter of the digital generator, is eventually added to the phase of $\mathbf{V_m}$ in order to express both $\mathbf{V_m}$ and $\mathbf{V_C}$ with respect to the same fixed reference system. One should note that an alternative solution could be the demodulation of $\mathbf{V_m}$ with respect to $\mathbf{V_E}$, but this technique would require the phase between $\mathbf{V_E}$ and $\mathbf{V_C}$ to be known.

A simple integrative control is then implemented in order to obtain the setting of the programmable generator that allows the minimization of $\mathbf{V_L}$ to be obtained. Such a control is based on

$$\mathbf{V_C}[i+1] = \mathbf{V_C}[i] - \frac{\mathbf{V_m}[i]}{\mathbf{A}\cdot\mathbf{K}} \tag{2}$$

where $\mathbf{A}$ is the complex gain of the device that amplifies the voltage $\mathbf{V_L}$ and i is the iteration step.

Amplitude and phase of the quantity $\mathbf{A}\cdot\mathbf{K}$ are estimated during a preliminary phase, which requires the exciting current $\mathbf{I}$ to be turned off and the feedthrough transformer to be excited by the compensation generator. In these conditions, the amplifier output $\mathbf{V_m}$ is acquired, so that the characterization of the chain transformer-amplifier is obtained. As this characterization requires a very short time, it can be performed at every measuring frequency.

Fig. 5 shows the user interface of the acquisition and compensation program, which has been developed in Visual Basic™ language. The preliminary-characterization phase is performed by means of the FdT estimation section of the user interface, which contains a text box, where the amplitude of the voltage $\mathbf{V_C}$ is typed, and a button, which turns the MFC off, sets the compensation generator and starts the acquisition of $\mathbf{V_m}$ and $\mathbf{V_C}$.

Once such a preliminary characterization has been performed, the user sets current and frequency of the multifunction calibrator by means of the test parameters section of the program interface and starts the acquisition process. The demodulation and control algorithm computes amplitude and phase used to set $\mathbf{V_C}$, which are shown in the control parameters section. The residual section of the user interface gives the residual amplitude of the voltage $\mathbf{V_L}$ (in μV_{rms}) and of its fundamental component (in μV_{pp}), which are referred to the input (RTI) of the variable gain amplifier. The graphical area at the bottom of the user interface shows the waveforms of the compensation signal $\mathbf{V_C}$ (dark trace) and of the residual voltage $\mathbf{V_L}$.

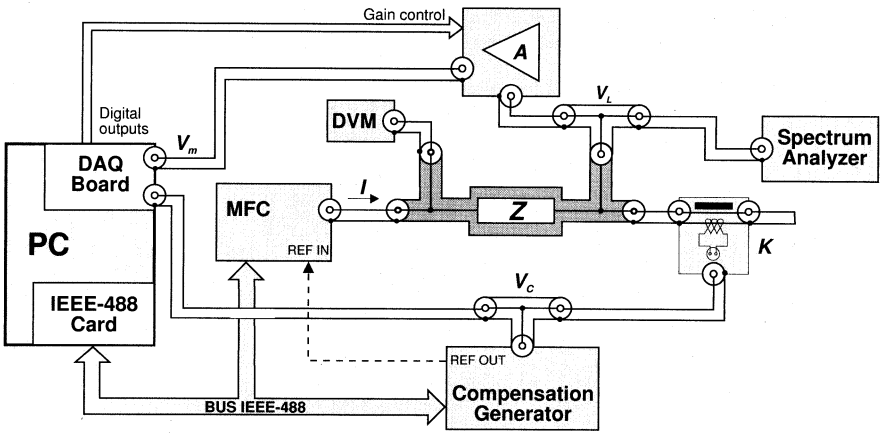

Fig. 4. Block scheme of the experimental setup.

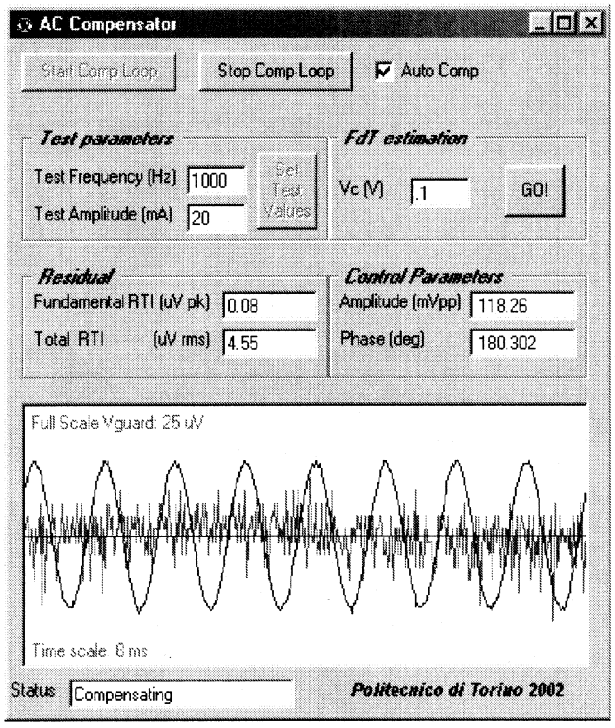

Fig. 5. User interface of the acquisition and compensation program.

III. Experimental Results

The effectiveness of the proposed compensation system has been tested by measuring the amplitude of different four-terminal pair impedances, whose values are known with an uncertainty that is less than the expected uncertainty. The system of Fig. 4 has been used, which allows a simple volt-ammeter method to be implemented, while a spectrum analyzer (SA) measures the residual value of V_L in order to validate the values measured by the acquisition program. A picture of the arranged bench is shown in Fig. 6.

The DAQ board capabilities allow 16 000 samples of each voltage signal $\mathbf{V_L}$ and $\mathbf{V_C}$ to be acquired at a maximum sampling frequency of 50 kHz. The test frequency spans from few hertz to a maximum value of 20 kHz, where almost 6000 signal periods are acquired. As the test frequency decreases, the sampling frequency is reduced in order to acquire at least 10 periods of the signals $\mathbf{V_L}$ and $\mathbf{V_C}$.

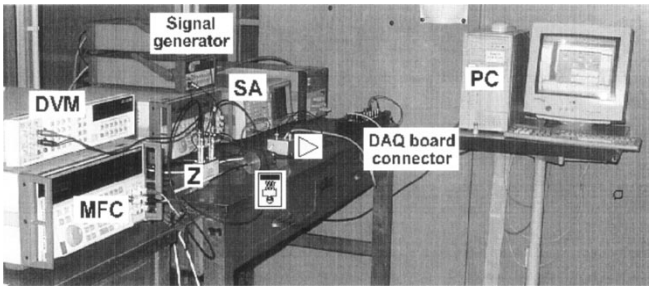

Fig. 6. Experimental bench.

As an example, the results obtained by feeding an ohmic-inductive impedance $\mathbf{Z}$ with a current $\mathbf{I}$ of 10 $\mathrm{mA_{rms}}$ at 1 kHz ($|\mathbf{Z}| \approx 50\ \Omega$) are discussed. When the automatic compensation system is disabled, the amplitude of the voltage $\mathbf{V_L}$ is of about 3 $\mathrm{mV_{rms}}$. This means that the spurious impedance $\mathbf{Z_X}$ has an amplitude of about 0.3 Ω and its effect on the unknown impedance is, in the worst case, of 0.6%. By enabling the compensation system, the amplitude of $\mathbf{V_L}$ decreases to a value of less than 5 $\mu\mathrm{V_{rms}}$ in a time interval of less than 5 s, thus reducing the effect of $\mathbf{Z_X}$ on $\mathbf{Z_F}$ down to 10 ppm (part per million) in the worst case.

The measurements of the voltage $\mathbf{V_L}$ carried out by means of the spectrum analyzer are in good agreement with the ones obtained by the acquisition program. Furthermore, the spectrum analyzer shows that the spectrum of the residual signal $\mathbf{V_L}$ is mainly distributed at high frequencies, as it also appears in the graphical area of the user interface shown in Fig. 5. Hence the residual signal is mainly due to the wide-band electronic noise of the system: in the previous example, the residual fundamental component of $\mathbf{V_L}$ has an amplitude of about 300 $\mathrm{nV_{pp}}$ according to the spectrum-analyzer. If a narrow-band measuring technique is employed, as that described in [10], only the fundamental component of $\mathbf{V_L}$ affects the measurement uncertainty of a four-terminal pair impedance, hence the effect of $\mathbf{Z_X}$ on $\mathbf{Z_F}$ is made negligible.

The results that refer to the amplitude of three standard impedances measured at 1 kHz by means of the simple volt-ammeter method are shown in Fig. 7. The estimated uncertainty,

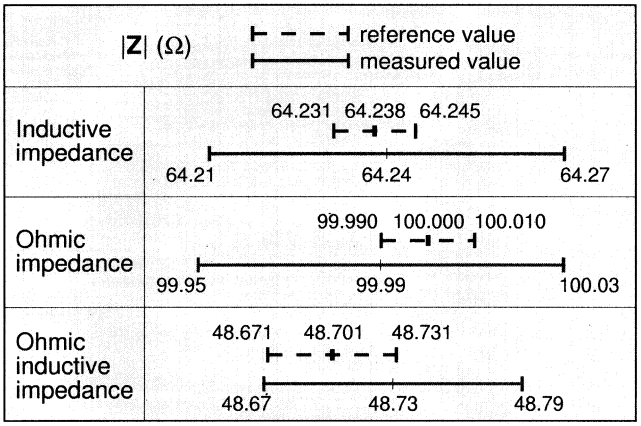

Fig. 7. Measured amplitude of three standard impedances.

which is mainly due to the uncertainty contributions of the MFC and of the digital voltmeter, shows the compatibility between reference and measured values. A reduction of the measurement uncertainty will be obtained by implementing a narrow-band measuring technique based on a comparison method [10], which allows amplitude and phase of the unknown impedance to be estimated.

IV. Conclusion

The system the authors have described in this paper implements a control strategy that reduces the voltage $\mathbf{V_L}$ at the low potential port of a four-terminal pair impedance by injecting into the circuit a compensation signal. A value of $\mathbf{V_L}$ close to zero is required in order to minimize the effect of spurious impedances, for example due to cables, contacts or external networks, on the measurement of impedance standards defined as four-terminal pair networks.

The prototype the authors have arranged does not require the use of dedicated devices, as its basic elements are a general-purpose data acquisition board and a commercial digital generator. The system also embeds a variable gain amplifier, which has been arranged with standard components, and a feedthrough transformer that allows the compensation signal to be injected into the measuring circuit. A program that runs on the PC where the DAQ board is installed manages the acquisition process and implements the control algorithm.

Experimental tests have shown the effectiveness of the proposed compensation system and have highlighted its limits, i.e., the maximum testing frequency, which is of 20 kHz, and the minimum residual value of the voltage $\mathbf{V_L}$. The frequency limitation is strictly related to the maximum sampling frequency of the employed DAQ board, hence the use of another board with enhanced sampling capabilities would allow one to easily extend such a limitation. The residual value of $\mathbf{V_L}$ is instead due to the wide-band noise of the voltage amplifier. The authors are now arranging a low-noise prototype of variable gain amplifier in order to further reduce such a residual voltage.

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