Proceedings of the 7th World Congress on Electrical Engineering and Computer Systems and Sciences (EECSS'21)
~~Prague, Czech Republic~~ Virtual Conference – July, 2021
Paper No. EEE 117
DOI: 10.11159/eee21.117

Design of Low Impedance Standard Defined In a Four-Terminal-Pair Configuration

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Abstract - Electrical low resistive impedance are widely used as resistance standards in metrology laboratories. The aim is to measure a high level of alternative and direct currents (AC and DC) with high accuracy, or to use it as resistive loads suitable for calibrating instruments (such as impedance meters). The use of a low resistive impedance as a standard requires knowledge of its magnitude deviation from DC and its phase angle as a function of frequency. In this paper, we present a design of a low impedance (current shunt) for current measurements at 2 A up to 5 kHz. The structure of the current shunt is defined in a four terminal-pair (with BNC connectors). The relative deviation from DC is less than 0.23 % in magnitude for a current of 2 A up to 5 kHz.

***Keywords*: Current shunts, current measurement, alternative current (ac), ac–direct current (dc), calibration, low impedance, four-terminal-pair configuration, uncertainty.**

1. Introduction

In industry, the main methods for measuring the capacity of batteries is based on a conventional approach by integrating the current of a charging (or discharging) process or by measuring voltage curves of the battery under defined conditions. In recent years, the current methods do not meet the requirements for quality assessment of second-use batteries, as they are either too slow or too inaccurate for economically viable reprocessing of Li-ion batteries. Therefore, several research projects are being set up to develop adequate measurement methods.

The work detailed in this paper has been carried out in the framework of the European metrology project *LiBforSecUse* [1]. This latter aims to provide a metrological approach to characterize Lithium-ion batteries that have completed their first industrial life in electric vehicles and can be used for a second application, for example as an energy storage system [1]. The measurement procedure studied in this project is based on impedance. The impedance-meters used to measure the impedance and then the capacity of the batteries are preliminary calibrated using the SOL method (Short - Open - Load). The SOL calibration requires the use of three main standards: a short circuit, an open circuit and a suitable load [2], it also requires knowing their precise electrical equivalent models.

A new passive resistive measurement standard based on current shunt geometry of a few milli-ohm is developed. The current shunt has been designed for electrical currents below 2 A and frequencies up to 5 kHz. The structure is defined in a four-terminal-pair configuration with BNC connectors suitable for direct connection to industrial impedance meters: for example, BT4560 impedance meters. The targeted uncertainties are less than 1%.

Generally, a current shunt is characterized by the parameters: ac-dc difference (δ), angle phase shift (ϕ), drift, temperature coefficient (TC) and power coefficient (PC). The variation in frequency of the current shunt impedance is characterized by the first two parameters (δ and ϕ). The variation in frequency of the impedance magnitude compared to the dc value (ac-dc difference δ) is given by [3]:

$$\delta = \frac{|Z_{shunt}| - R_{DC}}{R_{DC}} \tag{1}$$

With Z_{shunt} being the impedance magnitude of the current shunt and R_{DC} being its dc resistance value.

The phase angle ϕ of the current shunt is calculated as a function of the real part and imaginary part of its impedance, it is given by:

$$\phi = arctan\left(\frac{\Re[Z_{shunt}]}{\Im[Z_{shunt}]}\right) \tag{2}$$

where $\Im[Z_{shunt}]$ is the imaginary part of the shunt impedance, and $\Re[Z_{shunt}]$ is the real part of the shunt impedance.

In this paper, we present the development and metrological characterisation of low a impedance measurement standard traceable to the SI.

2. Presentation of the current shunt structure

The proposed current shunt is based on a calculable structure defined in a two-terminal-pair configuration using a resistive disk made of a resistive alloy placed on an insulating substrate and on a coaxial line made of an inner conductor and an outer conductor (shielding) [3]. The material of the resistive disk is typically *Evanohm* (copper alloy), and the resistive layer is placed on an insulating *Shapal* substrate. The inner conductor is connected electrically to the inner and outer conductors. The resistance of the shunt is then defined by the resistive disk. This latter is perpendicularly arranged to the inner conductor of the shunt. This part of the structure defined in two-terminal-pair is illustrated in Fig. 1.a. Two N-Type connectors are welded to the inner conductor at both sides of the coaxial line: the first connector is used for injecting the input current and the other for measuring the output voltage. These connectors are placed in the same axis as the inner conductor of the coaxial line.

The current shunt has a coaxial configuration (currents circulating in the inner and outer conductors are equal in magnitude and of opposite directions) that ensures immunity against external electromagnetic fields. The return current I_1 flowing in the outer conductor in the opposite direction and with an amplitude equal to the forward current circulating in the inner conductor (see Fig. 1.b). The current I_1 flows radially through the resistive disk. The geometry of the resistive disk and the distribution of the current allows reducing strongly its self-inductance: a few aH (attohenry). The electrical output voltage U_2 is generally measured by a calibrated voltmeter at the output of the shunt between the central connector and the shield (see Fig. 1.b). The voltage U_2 is the voltage measured across the resistive disk. Finally, the transfer impedance Z_{21} of the impedance matrix [Z] defines the impedance of the current shunt Z_{Shunt}.

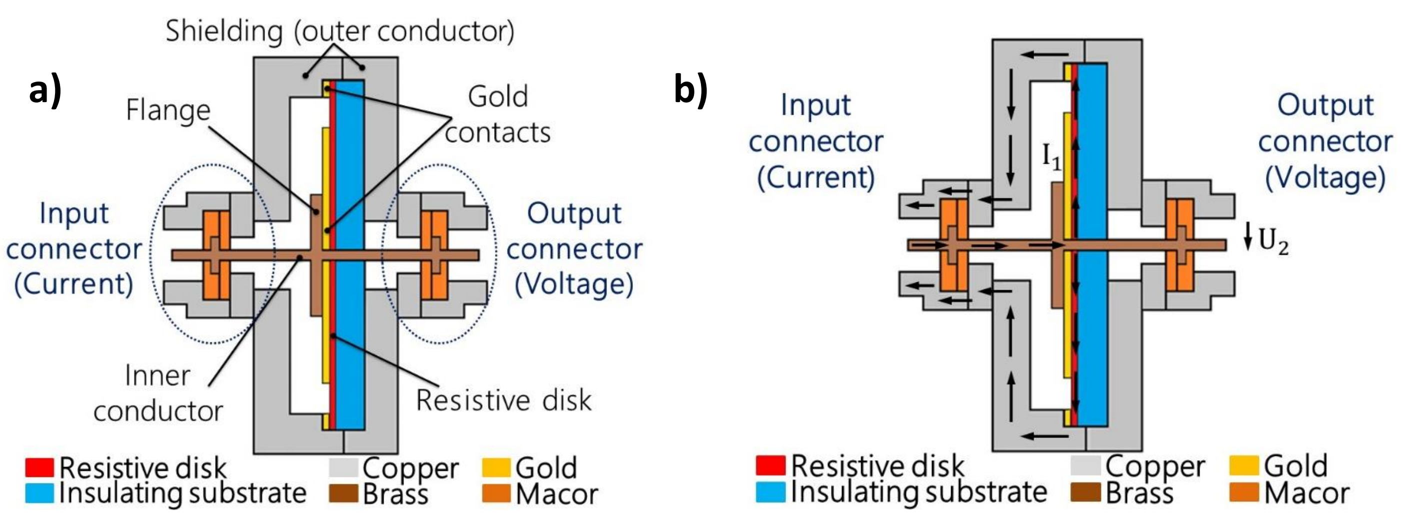

Fig. 1: a. Structure of the current shunt defined in two terminal-pair. b. Structure of the current shunt defined in two terminal-pair including input current and output voltage.

The geometrical dimensions of the resistive disk are defined to obtain the desired resistance value for the current shunt [3]. The internal and external radii of the disc are determined by a gold deposit constituting the contact electrodes on the disk. The choice of the alloy was made according to the electrical, thermal and mechanical characteristics of the materials. A nickel-chromium alloy called *Evanohm* was selected among other possible alloys. The DC resistance of the resistive disk is equal to 17.5 mΩ at 23 °C.

An adapter box has been fabricated to convert the two terminal-pair coaxial device (with N-type connectors) in four terminal-pair (with BNC connectors). The BNC connectors are electrically insulated from the metallic box. This structure is suitable for the calibration of the RLC-meter. The adapter box has been manufactured so that the “high” and "low" connections of the inner and outer circuits are mutually at right angles to eliminate mutual inductance between them [4]. The principle of the adapter box is shown in Fig. 3.a. The BNC connectors of the voltage are placed near the output of the current shunt (2TP structure with N-type connectors) in order to minimize the influence of cables and connectors on the voltage measurement. The Fig. 3.b. shows the final structure of the current shunt defined in four terminal-pair (with BNC connectors).

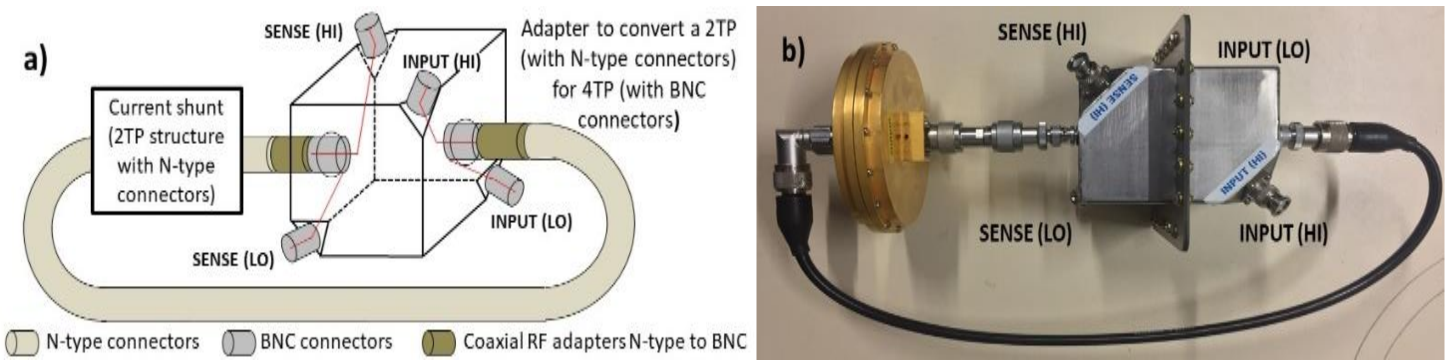

Fig. 3: a. Current shunt with the adapter box to convert a coaxial two terminal-pair device (with N-type connectors) in terminal-pair configuration (with BNC connectors). b. Final structure of the current shunt defined in four terminal-pair (with BNC connectors).

3. Metrological characterisation of the current shunt impedance

3.1. Frequency variation

The AC-DC difference and phase angle are measured for the current shunt developed at 2 A for the frequencies: 53 Hz, 1 kHz, 2 kHz, 3 kHz, 4 kHz and 5 kHz. The measurement system used is a phase angle measurement system for sinusoidal voltage (10 mV to 1 000 V) with frequency range from 20 Hz to 20 kHz. Its principle is based on a sampling method with a least squares sine fit algorithm [5]. This measurement system has been adapted for AC resistors comparisons. The automated reference setup ensures uncertainties less than 250 μΩ/Ω and 5 mrad respectively on the amplitude and phase of the AC resistors between 10 mΩ and 1 MΩ for a frequency range up to 20 kHz.

The developed current shunt has been characterized using this bench. Two repeatable characterization measurements were carried out with a delay of 6 months between the two measurements. The AC-DC difference and the phase angle at 2 A up to 5 kHz are respectively less than: 1.4 ± 0.5 mΩ/Ω (k = 2) and 1.1 ± 0.9 mrad (k = 2). The Fig. 4. shows the AC-DC difference and phase angle at 2 A of the developed current shunt.

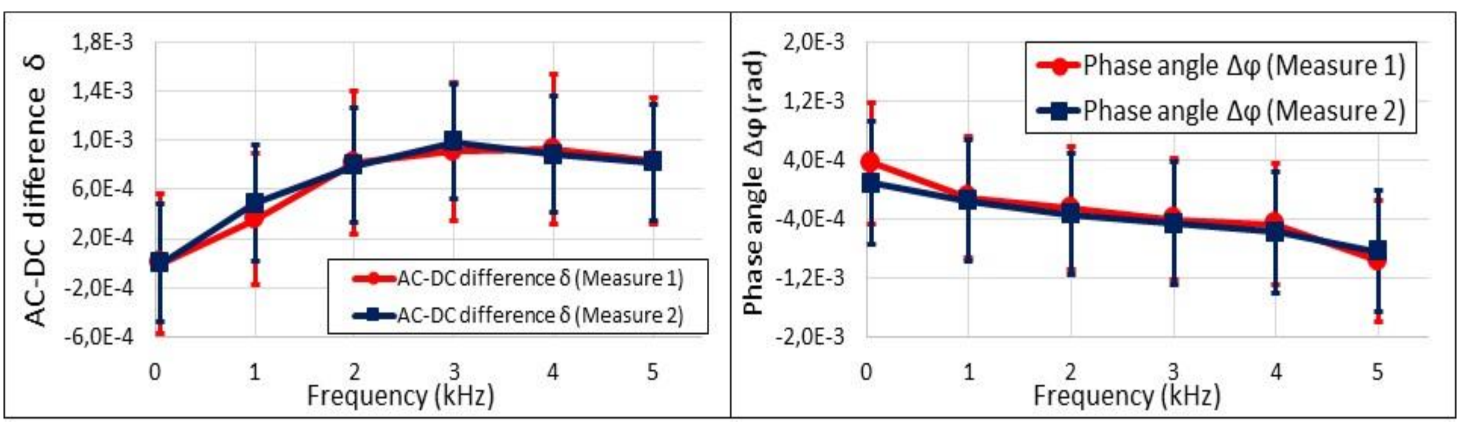

Fig. 4: AC-DC difference and phase angle at 2 A of the developed current shunt.

3.2. Drift

The drift of the current shunt (DC resistance stability as a function of time) is an important parameter to be This is obtained by measuring, at a constant temperature, the DC resistance of the current shunt as a function of time. drift of the developed current shunt was measured with the measuring bench used at LNE (Laboratoire National de Métrologie et d'Essais) to calibrate the DC resistances. The drift has been measured over few days during 6 months to an estimation of the long term stability. It is defined by:

$$\text{Drift} = \frac{\beta_1}{\beta_0} \quad (3)$$

where β_0 and β_1 are, respectively, the intercept and the slope of the linear regression of the current shunt DC resistance as a function of time.

The measured drift value is less than 1.5 (mΩ/Ω)/day (5.3x10^{-2} year^{-1}). This important value is mainly caused by the quality and the sputter deposition parameters (not optimized) of the deposited Evanohm layer [3]. Therefore, before using the current shunt, it is necessary to calibrate its DC resistance and to wait for a heating time of the current shunt at the nominal electric current of approximately 15h. The DC resistance values are measured with an expanded uncertainty (k = 2) of ± 2 μΩ.

4. Conclusion

The current shunt developed is characterized by its coaxial geometry. Its calculable design was made to obtain a low impedance variation (less than 1%) up to 5 kHz. It is mainly composed of a resistive disk placed in a coaxial line whose end is connected to two N-type connectors: the first one to inject the current and the second one to measure the voltage. The structure is completed by an adapter box to convert the two terminal-pair coaxial device (with N-type connectors) to measure four terminal-pair (with BNC connectors). The value of the DC resistance of the current shunt has been defined at 17.5 mΩ for a current less than 2 A. The absolute values measured for of transposition deviation and phase angle are less than 1.4 mΩ/Ω and 1.1 mrad respectively for currents below 2 A and frequencies up to 5 kHz. These values obtained permit a current shunt impedance variation less than 0.23 % (for a target set at 1%). The sputter deposition parameters will be optimized to minimize the drift, temperature coefficient TC and the non-homogeneity of the deposited thin film.

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