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On-line Resistance Measurement of Substation Connectors Focused on Predictive Maintenance

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***Abstract*- To detect faults in their early stage in a substation, it is necessary to monitor, measure and analyze periodically the health condition of the electrical connectors, which are among the most critical devices in such installations. To do so, the electrical connector has to be combined with low-cost intelligent electronic devices (IED), including different sensor types and microcontrollers with wireless capabilities. Such an electrical connector is referred as SmartConnector. Using the data collected by the IED, it is possible to estimate accurately the current condition of the electrical connector in real-time, which in turn will determine the expected faults in the substation before a major failure occurrence. The electrical resistance plays a key role to determine the current health condition, and therefore to estimate the remaining lifetime of the electrical connector. The electrical resistance of a high-voltage substation connector is calculated in real-time using different methods proposed in this work, by using an analog-bipolar Hall effect sensor and an instrumentation amplifier. Experimental results, when compared with the standard 4-wire Kelvin method, show an error of less than 10%. Although the proposed methods have been validated for substation connectors, they can be applied to many other types of hardware with electrical contacts.**

I. INTRODUCTION

Substation connectors are critical elements in substations, since a failure can lead to very important outages with catastrophic consequences [1]. They are simple electromechanical devices [2], which provide a reliable connection between different conductors or bus bars with reduced voltage drop and power losses. The main purpose of such connectors is to transmit the electrical power between the two conductors or bus bars [3]. Substation connectors are usually made of aluminum, are of mechanical type, and they use bolts and nuts. The reliability and stability of the contact is an important issue, which is directly related to the value of the contact resistance. Therefore, it is necessary to know their condition in order to apply a predictive maintenance plan before the failure occurs. To this end, it is highly desirable to acquire on-line data to perform a fast diagnosis of the condition, and to determine which electrical connector will fail before the failure occurs, since the failure in one connector can lead to severe grid faults [4]. As soon as the electrical connector starts showing deterioration symptoms, some type of maintenance or replacement of the connector must be applied.

The contact resistance is possibly the main parameter affecting the condition of power connectors, thus greatly impacting their lifetime and efficiency [5]. Due to temperature cycling, the bolts tend to loose, thus increasing the resistance of the connector, although it has been reported that re-torqueing is not very useful [6], so it is better to directly replace the electrical connector before failure. It is well known that when the contact resistance starts increasing, the electrical and thermal behavior of the connector tends to deteriorate [7]. Hence, the electrical resistance of the connector is a good indicator of its condition.

In this work, different on-line low-cost methods to determine the electrical resistance of a high-voltage high-current substation connector are proposed. They are based on the measurement of the current and voltage drop across the connector by using an analog-bipolar Hall effect sensor, and an instrumentation amplifier, respectively.

Although this research is focused on substation connectors, the results can be applied to many other electrical devices, including contacts such as circuit breakers, electrical pantographs, or cable joints among others.

Section II describes the method to measure the direct current (DC) resistance of the connector to calibrate the proposed measurement system. In Section III different possibilities to perform an on-line measurement of the total resistance of the connectors are presented. Section IV details the on-line methodology proposed in this paper to measure the resistance of the connector. Section V summarized the experimental results carried out in this work, and finally, Section VI summarizes the conclusions of this paper.

II. DC RESISTANCE OF THE CONNECTOR

The contact resistance plays a key role in the efficiency, stable performance and long-term service of electrical connections [7]. Therefore, improved electrical connections require low and stable contact resistance, otherwise overheating and service life reduction are expected [8].

The standard method to measure the resistance of electrical connectors is the 4-wire or Kelvin method, as shown in Fig. 1. It is based on a 4-terminal ohmmeter with two separate circuits to acquire the voltage and current. A known stabilized DC current I_{DC} is applied and the voltage drop across the connector ΔV_{DC}, is measured to determine the electrical resistance of the connector as,

$$R_{DC} = \Delta V_{DC}/I_{DC} \tag{1}$$

However, this method has two main drawbacks. The first one is that it requires a stabilized DC current source, since the resistance cannot be directly measured by injecting an AC current. It is noted that when injecting an AC current, the

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impedance is measured instead of the resistance. The value of the impedance is usually much higher than that of the resistance of the connector, due to the reactance component. In addition, the reactance and thus, the impedance are greatly affected by the frequency of the injected AC current and the geometry of the experimental setup.

To calculate the electrical contact resistance (ECR), it is necessary to subtract the bulk resistance of the connector from the total resistance of the power connector, which has been measured with the 4-wires method [7],

$$R_{Contact} = R_{Measured} - R_{Bulk} \quad (2)$$

The bulk resistance of the power connector cannot be directly measured. It depends on the shape, size and resistivity of the materials of the connector. The bulk resistance R_{Bulk} can be calculated by means of finite element analysis (FEA).

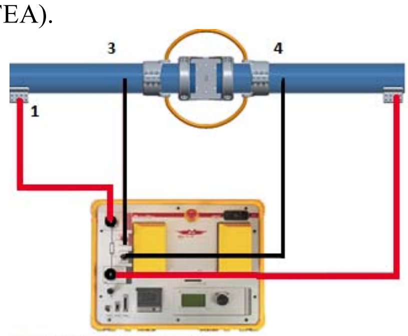

Fig. 1. Resistance measurement with the 4-wires method.

A. Effect of temperature on the resistance

It is well known that the temperature affects the resistance of the connector, since is made of aluminum. Therefore, the temperature must be measured simultaneously with the resistance of the connector. The measured DC resistance $R_{DC,T}$ at a given temperature T [ºC] is converted to the resistance $R_{DC,20°C}$ by applying [1],

$$R_{DC,20°C} = R_{DC,T} / [1 + \alpha(T - 20)] \quad (3)$$

α= 0.004 K^{-1} being the temperature coefficient of the aluminum.

III. On-Line Resistance Measurement

In this section different on-line methods to measure the total resistance of the connectors are presented. The electrical resistance of the connector plays a key role to determine the health condition of the connector and its evolution with time.

To perform an on-line measurement of the connector resistance, it is required to measure the voltage drop and the current flowing across the connector during normal operating conditions, that is, under 50 Hz AC supply. The expected current is in the range of some kA, and since the total resistance of the connector is in the range of some micro-ohms, the voltage drop across the connector is in the range of some mV. Since the resistance of the connector is in the order of the micro-ohms, an on-line low-cost measurement is a challenging problem.

To calculate the resistance in real-time, it is necessary to have additional information beforehand. In this case the additional information is the previously known resistance of the connector. Usually, when a connector is installed in substations, it is mandatory to measure its DC resistance R_{DC} immediately after the installation is complete, using a portable 4-wire micro-ohmmeter to verify that the installation has been done correctly. Therefore, in this work it is assumed that this data is available, which will be the reference or starting point.

A. Voltage drop measurement

The voltage drop across the connector can be measured by means of an instrumentation amplifier, since as already explained, the expected voltage drop is of some mV. Thus, it is necessary to minimize the effects of noise as the voltage to be measured is very low. The instrumentation amplifier has two inputs, which are connected to both sides of the connector to measure the voltage drop. The instrumentation amplifier subtracts one input signal from the other, thus rejecting the common-mode noise. The resulting signal is then amplified, which ideally is an amplified version of the drop voltage, whereas the remaining noise can be further minimized by means of post process filtering.

B. Current measurement

There are various current sensing technologies to measure the current in real-time, including shunt resistors, current transformers, Rogowski coils, Giant magneto resistive (GMR), Giant magneto impedance (GMI) or analog-bipolar Hall effect sensors [9], [10] among others. However, for high current applications, when balancing several features including sensor size, maintenance requirements, cost, and accuracy, the Hall effect sensor seems to be the most suitable choice [11]. However, there is a scarcity of works dealing with current sensing applications of such sensors for very high currents. In many low current applications, this sensor uses an open or closed loop configuration, which includes a magnetic core, thus making it unsuitable for the application analyzed in this work [11], [12]. Due to the large diameter of the bus bar, the required magnetic core is too bulky, expensive and difficult to install. It also generates unwanted vibrations. To avoid these disadvantages, and due to the high magnetic field around the bus bar, this work proposes measuring the current using a Hall effect sensor without the use of any magnetic core. The features summarized in Table I support this choice.

When the Hall effect sensor is placed perpendicularly to the magnetic field generated by the current carrying conductor or bus bar, the charge carriers experience the Lorentz force, thus resulting in an output voltage proportional to the magnitude of the magnetic field. Using this small size sensor, it is possible an on-line contactless measurement of high AC and DC currents.

The measured magnetic flux density B generated by the conductor or bus bar and the output voltage provided by the

Hall effect sensor $V_{HallSensor}$ (this value is obtained by removing the offset) are related as [11],

$$B_{Connector} = \frac{V_{HallSensor}}{k} \tag{4}$$

k [V/T] being the sensitivity constant. By applying the Biot–Savart law [11],

$$B = \frac{\mu_0 \cdot I_{Connector}}{\pi D} \tag{5}$$

And by placing the sensor on the outer surface of the bus bar, the current through the conductor can be calculated as,

$$I_{Connector} = \frac{B \cdot D}{4 \cdot 10^{-7}} \tag{6}$$

From (4) and (6) it results,

$$I_{Connector} = \frac{V_{HallSensor} \cdot D}{k \cdot 4 \cdot 10^{-7}} \tag{7}$$

The open loop configuration of the Hall effect sensor is selected considering that the bus bar is rigid, and the diameter of bus bar is already known.

The main cause of error for this sensor type is the sensitivity, since it is affected by air gap tolerances [12], bus bar dimensions and sensor orientation. The error can be reduced once the sensor is calibrated. This paper proposes an *in situ* calibration of the Hall effect sensor, thus minimizing the error caused by change of sensitivity. However, the fixation of the Hall effect sensor must be guaranteed and it must not move from its original place.

TABLE I

COMPARISON OF DIFFERENT CURRENT SENSING TECHNOLOGIES SPECIFICALLY FOR HIGH CURRENT APPLICATIONS.

Types	Cost	Size	DC capability	Install. difficulty	Linearity	Temp. (ºC)	Elect. Insulat.
Rogowski coil	Low	Big	No	Easy	Good	-20~100	Yes
Current transformer (CT)	High	Big	No	Difficult	Good	-50~150	Yes
Shunt resistance	Low	Big	Yes	Difficult	Poor	-55~125	No
GMR	Medium	Small	Yes	Easy	Fair	-40~150	Yes
GMI	Medium	Small	Yes	Easy	Fair	-40~150	Yes
Hall effect no core	Low	Small	Yes	Easy	Good	-40~125	Yes

C. *Impedance measurement in real-time*

An advantage of the 4-wire method is that it has two independent circuits. This property is exploited in the on-line measuring techniques explained below in which the current measuring circuit is completely insulated from the voltage measuring circuit.

However, as explained before, an on-line measurement of the current and the voltage drop across the connector under normal operating conditions (power frequency AC supply) does not provide a direct reading of the resistance of the connector since,

$$Z_{Measured} = \frac{\Delta V_{Connector}}{I_{Connector}} = \frac{k \cdot 4 \cdot 10^{-7} \cdot \Delta V_{Connector}}{V_{HallSensor} \cdot D} = \sqrt{R_{Connector}^2 + X_{Connector}^2} \tag{8}$$

Therefore, in AC applications, it is important to measure the phase shift between the current and the voltage drop across the connector in order to estimate the reactance. It can be done by calculating the real-time phase difference between the output voltage of the Hall effect sensor $V_{HallSensor}$ and the voltage drop across the connector $\Delta V_{Connector}$ [13]–[15].

IV. PROPOSED ON-LINE METHODS TO DETERMINE THE RESISTANCE OF THE CONNECTOR

In this section, three on-line methods to determine the current resistance of the connector are proposed, which are summarized in the flowchart of Fig. 2.

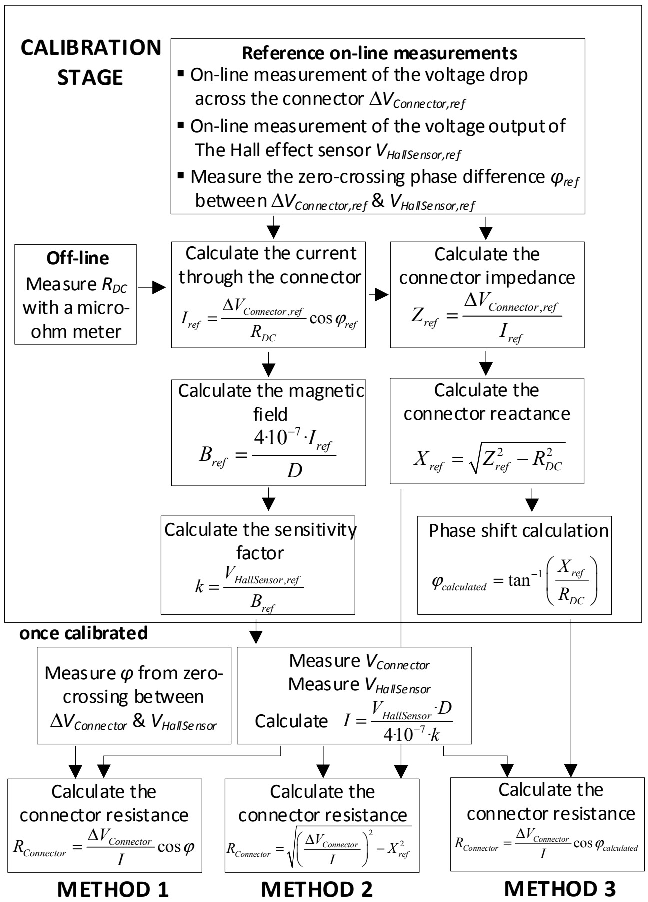

Fig. 2. Flowchart of the three proposed on-line methods to calculate the electrical resistance of the connector.

The flowchart in Fig. 2 shows two main stages, a calibration stage, which is carried out during the installation of the connector, and an after-calibration stage, which refers to the useful life of the connector under normal operating conditions. In the first stage, the sensitivity of the Hall effect sensor is calibrated during its installation, whereas in the after-calibration stage, the current value of the resistance of the connector is recalculated and updated based on on-line measurements.

In the calibration stage, the DC resistance R_{DC} of the connector is measured off-line, as detailed in Section II. It is also required to calculate the sensitivity of the Hall effect sensor, the reference impedance and reactance of the connector, Z_{ref} and X_{ref}, respectively, and the phase of the impedance, $\varphi_{calculated}$, which are highly influenced by the geometry of the installation.

A. Resistance measurement in real-time: Method 1

Method 1 (see Fig. 2) determines the resistance of the connector from its impedance as,

$$R_{Measured} = Z_{Measured} \cdot \cos\varphi \quad (9)$$

where the impedance of the connector is measured according to (8) and φ is the phase shift between the voltage drop $\Delta V_{Connector}$ and the output of the Hall effect sensor $V_{HallSensor}$.

In (9) we exploit the fact that the output voltage of the Hall effect sensor is related to the current through (7). So, the phase of the output voltage of Hall effect sensor should be the same as the phase of the current in the conductor or bus bar. This assumption was verified in the laboratory, by comparing the output voltage waveform of a calibrated Rogowski coil with the output voltage of the Hall effect sensor. It was found that there is no phase shift between them, as shown in Fig. 3, thus confirming this hypothesis.

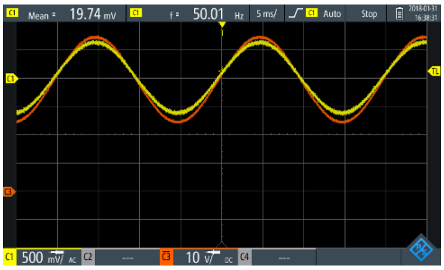

Fig. 3. Phase shift between the output voltages measured by a calibrated Rogowski and the analog-bipolar Hall effect sensor.

B. Resistance measurement in real-time: Method 2

Method 2 (see Fig. 2) calculates the resistance of the connector from its impedance and reactance as,

$$R_{Connector} = \sqrt{\left(\frac{\Delta V_{Connector}}{I}\right)^2 - X_{ref}^2} \quad (10)$$

where I is the present value of the electrical current, which is calculated as,

$$I = \frac{V_{HallSensor} \cdot D}{k \cdot 4 \cdot 10^{-7}} \quad (11)$$

and X_{ref} is the reference reactance of the connector obtained as,

$$X_{ref} = \sqrt{Z_{ref}^2 - R_{DC}^2} \quad (12)$$

where Z_{ref} is the reference impedance of the connector

$$Z_{ref} = \frac{\Delta V_{Connector,ref}}{I_{ref}} \quad (13)$$

It is noted that (12) does not take into account the possible changes in the resistance during the useful life of the connector since in this application $Z_{ref} >> R_{DC}$ (typically $Z_{ref} \approx 10 \cdot R_{DC}$), and therefore the effect of small changes in the resistance of the connector in the evaluation of X_{ref} is very reduced.

C. Resistance measurement in real-time: Method 3

According to Fig. 2, Method 3 calculates the resistance of the connector from its impedance and reactance as,

$$R_{Connector} = \frac{\Delta V_{Connector}}{I} \cos\varphi_{calculated} \quad (14)$$

$\varphi_{calculated}$ being the phase of the impedance, which is defined as,

$$\varphi_{calculated} = \tan^{-1}\left(\frac{X_{ref}}{R_{DC}}\right) \quad (15)$$

where X_{ref} is calculated as in (12) and R_{DC} is the DC resistance of the connector, which is measured off-line with the 4-wire method.

It is noted that (15) assumes a constant resistance, although it is known that it evolves along time. However, since in this application $X_{ref} >> R_{DC}$ (typically $X_{ref} \approx 10 \cdot R_{DC}$), $\varphi_{calculated}$ is little influenced by small changes of the resistance of the connector, which is corroborated in Fig. 4.

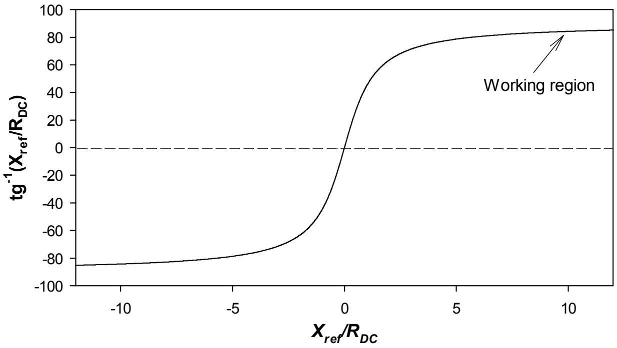

Fig. 4. Graph of the $\tan^{-1}(X_{ref}/R_{DC})$ to illustrate the little change of $\varphi_{calculated}$ in (14).

V. EXPERIMENTAL

In this section, the analyzed connector, the experimental setup and the obtained results are presented and discussed.

As stated, to apply a predictive maintenance plan, on-line data is required. Since the better indicator of the electro-thermal performance of the connector is the electrical resistance, this parameter must be evaluated in real-time. However, this is a challenging problem, since the electrical resistance of substation connectors is in the order of the micro-ohms. In addition, they are usually placed outdoors, in high-voltage and high-current environments, where any human intervention must be minimized or avoided.

A. The analyzed connector and the complete loop

Fig. 5a shows the connector analyzed in this work and the bus bar carrying current. It is an expansion mechanical connector of bolted type. To test the connector, a loop is required, which includes the parts shown in Table II.

The installation of the electrical connector was done following the standard procedure, consisting in applying grease to the contacts after brushing. A tightening torque of 150 Nm was applied to the bolts of the connector. Along with the main electrical connector, a mechanical connector for the support was also used, as depicted in Fig. 5c.

To complete the loop, a return rectangular bus bar was used, along with flexible cables to connect the bus bars with the output of the high-current transformer. To this end, 6 long rectangular copper bars, 20 copper cables and 2 flexible copper connectors were used as shown in Fig. 5c.

By means of the high-current transformer, an AC current was injected to the test loop, which was in the range 0-8000 A_{rms}.

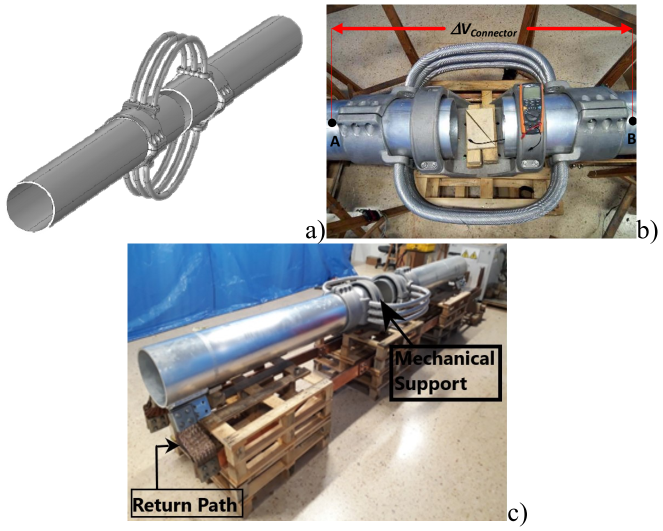

Fig. 5. Substation connector under test. a) 3D geometry of the bus bar connector analyzed in this work. b) Detail of the connector. c) The complete loop.

TABLE II

PARTS OF TEST LOOP OF THE CONNECTOR

Parts	Material	Units	Size
Bolted Expansion Coupler Connector	A356.0 alloy	1	Length = 1.27m Inner Diameter = 300 mm
Cylindrical Bus bar conductor	Aluminum	2	Length = 2000 mm Thickness = 12 mm Outer diameter = 300 mm
Mechanical Connector	Aluminum	1	Length = 592 mm Inner diameter = 300 mm
Bolts	Steel	12 8 50	M16 x 70 M16 x 65 M12 x 70
Welded type rminal	A356.0	4	Length = 200 mm Breadth = 100 mm Thickness = 20 mm
Rectangular bus bar (return)	Electrolytic Copper	4	Length = 2000 mm Thickness = 10 mm
Trench connector	Electrolytic Copper	4	Length = 460 mm Thickness = 20 mm
Flexible cables with terminals	Electrolytic Copper	8 12	Length = 1260 mm Diameter = 40 mm Length = 600 mm Diameter = 30 mm

B. Experimental Setup

During laboratory tests, an NI USB-6000 (USB Multifunction DAQ) from National Instruments was used for on-line data acquisition, along with the SignalExpress 2015 software, to monitor and record such data, although the final version will include a microcontroller with integrated ADC converter and Bluetooth wireless communications.

To measure the voltage drop across the power connector, two aluminum 24 AWG wires were connected between points A and B (see Fig. 5b) and the input channel 1 and the ground terminals of the USB-6000 device, respectively. By this way the voltage drop of the connector was measured using the inbuilt instrumentation amplifier of the data acquisition device.

A DRV5033VA analog-bipolar Hall effect sensor from Texas Instruments was used to measure the current flowing through the testing loop. It offers a sensitivity in the range of (–140 mV/mT to -45 mV/mT). It was placed on the top of the bus bar, facing the direction of the magnetic field lines. The output voltage of the Hall effect sensor was acquired by the USB-6000 device.

Simultaneously, an Omega TC-08 thermocouple data logger was used to acquire the temperature of the connector and the bus bar using T-type thermocouples.

On-line voltage and current measurements performed by using the above devices, allow determining the resistance of the connector by applying the three methods detailed in Section IV. Those results are compared with the results from the standard 4-wire method presented in Section V.C.

C. DC Resistance measurement

The DC reference resistance of the connector was measured by applying the standard 4-wire or Kelvin method as detailed in Section II. A Micro-Centurion II digital micro-ohm meter from Raytech (max. current 200 A_{DC}, accuracy ±0.01μΩ) was used for this purpose.

By applying this method, the total resistance between points A and B in Fig. 5a was R_{DC} = 9.94 μΩ, after being corrected to 20ºC. This value is taken as a reference, in order to assess the accuracy of the three methods proposed in this work.

It is well known that the DC and AC resistance can be different, due to the skin and proximity effects [16]. However, due to the specific geometry analyzed in this work, such effects, although not null, are almost negligible [17][18].

D. Experimental results

The experimental setup shown in Fig. 5 was tested by applying heating and cooling cycles to determine the resistance of the connector. During the heating stage, a constant AC current of 8000 A_{rms} was applied. After every heating-cooling cycle, the entire setup was disconnected from the high current transformer and a DC current of 200A was injected from the micro-ohmmeter to measure the DC resistance of the connector $R_{DC,cycle\_i}$, which was taken as the reference value in each cycle. Next, after each cycle, 14 current levels, which were increased in steps of 0.5 kA from 0.5 kA up to 7 kA, where applied to the connector to perform an on-line measurement of its resistance by applying the three proposed methods. Fig. 6 shows the 14 readings obtained during each mentioned cycle. It shows a small dispersion of the results. It is attributed to the change of the sensitivity of the Hall effect sensor, which is the responsible of the error of the measurements.

Table III summarizes the results attained in each thermal cycle. It represents the mean errors of the 14 readings at each cycle, when compared with the values obtained from the 4-wire micro-ohmmeter measurement at the same cycle.

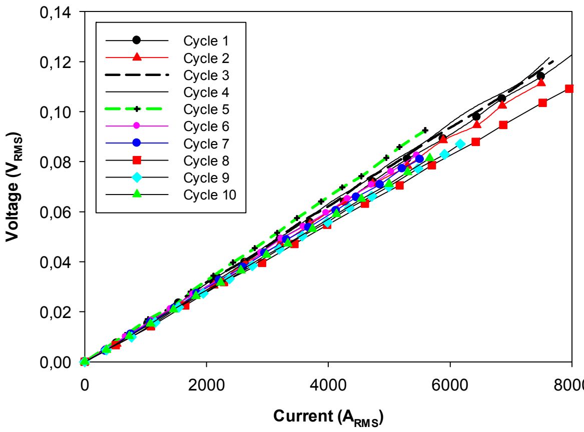

Fig. 6. Measured voltage $\Delta V_{Connector}$ between the terminals A and B of the analyzed connector (see Fig. 5b) versus the calculated current as in (7).

TABLE III
RESISTANCE ERROR OF THE THREE PROPOSED METHODS

	Resistance error (%)		
Cycle	**Method 1**	**Method 2**	**Method 3**
1	3.97	3.52	1.21
2	10.79	9.95	3.11
3	4.26	4.73	2.80
4	8.99	4.80	1.77
5	4.76	13.19	5.43
6	7.58	5.74	1.85
7	4.96	13.50	4.75
8	12.41	29.65	10.59
9	14.99	23.89	7.94
10	9.36	18.50	6.08
Average value	8.2 ± 3.8	12.7 ± 8.9	4.6 ± 3.0

Results presented in Table III show that the three analyzed methods provide mean errors between 4.6 and 12.7 %. Method 3 is the one producing more accurate results, its accuracy being enough for the application analyzed in this work. Error sources are mainly due from inaccuracies of the sensors. The Hall effect sensor must be calibrated, and its sensitivity can be altered by air gap tolerances, differences in bus bar dimensions or improper sensor orientation. The noise also has an impact in the final accuracy since it affects the reading of the voltage drop $\Delta V_{Connector}$ and the zero-crossing phase difference between and $V_{HallSensor}$ and $\Delta V_{Connector}$.

VI. CONCLUSION

The predictive maintenance of power devices, including substation connectors, is currently a trending topic, since in this moment, health condition models are not available, and they can help to increase the reliability of the substations and the power grid itself. To this end, an on-line measurement of the electrical resistance of the connector is required. Since the idea is to measure the medium-term evolution of the electrical resistance, such measurement does not require high accuracy. However, a direct measurement of the connector resistance under real operating conditions when supplied at power grid frequency is a challenging problem, due to the reactance term of the inductance, which is often much higher than the resistance term. In this work three on-line methods to measure the resistance based on low-cost electronics have been proposed. It has been proved that it is possible to measure the resistance of power connectors with accuracy in the order 5-10% by means of low-cost sensors, which is enough for this application.

This work will be further extended to include a wireless communications system, and other types of sensors to apply a predictive maintenance strategy.

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