Metrologia
Fortaleza - CE 2017

Medição de resistência elétrica muito baixa em corrente alternada

Measurement of very low electrical resistances in alternating current

Márcio Antônio Sens

Eletrobras Cepel

E-mail: sens@cepel.br

Abstract: The cross-sections of electric cables for power transmission lines have become increasingly large. In Brazil cables up to 2500 kCM (1267 mm²) are used in the transmission from the Amazon Region to the Southeast Region. In these sections certainly, the Skin Effect becomes also significant and must be verified the electrical resistance in ac current. Since the samples are usually 5 to 10 meters, the expected electrical resistance is of the order of few tens of micro-ohms. The paper will show that the steel core may have some contribution to the resistance at high currents, of the order of 2 to 3 kA.

Keywords: Skin Effect; ac resistance; measurement; aluminum; cable.

1 INTRODUCTION

Concerns about the differences between the electric resistance in direct current and the electric resistance in alternating current for wires and electric conductive cables of large transverse sections, at the frequency of 60 Hz, are not new. Much theoretical speculation and numerical simulations have been made and disseminated since Lord Kelvin in 1887. Records of effective measures of such effects, however, few are found [1], [2]. The ac resistance measurements, in fact, constitute great technical difficulties.

In order to evaluate the resistance to alternating current of electrical conductor wires and cables of large transverse sections, in samples of up to 20 meters or in small samples of superconducting cables, the following are required:

- Application and measurement of currents at high levels, exceeding 1000 A at 60 Hz;
- Measurement of low voltage levels, less than 10 volts or less than 1 volt;
- The test object at stable temperature, in the air or under liquid nitrogen.

For an electrical cable distant enough from other metals, in a closed loop, with negligible parallel capacitance and magnetic coupling with other neighboring circuits also negligible, it can be considered to have only one inductance with an equivalent series electrical resistance. The measurement principle adopted here was that of Rs and Xs.

In order to obtain these equivalent parameters, it is sufficient to measure the voltage and current during the current application period. By mathematical processing we obtain the apparent power - S (VA), the power dissipated in heat - P (W) and the reactive power - Q (var), and with these, by dividing the respective power by the quadratic current we obtain the impedance - Z, the resistance - Rac and the reactance - Xs, respectively.

2 EXPERIMENTAL TESTING SYSTEM

In the experiments dealt with in this paper, single-phase 166 kVA current sources were used, with continuous adjustments of up to 5000 A, at 60 Hz. For accurate measurement of high current levels, three current transformers - CTs are available, a multi-ratio CT of 100 to 6000 A-5 A (± 50 ppm), another of a multi-ratio, from 100 to 12000 A-5 A (± 50 ppm) and a single ratio CT of 1000-1 A (± 2 ppm). All CTs are provided with tertiary compensation windings, to be in parallel with the respective secondary windings.

For accurate measurement of the electric currents, the current transformers - CTs were connected to triaxial shunts of class ± 0.03 %, through 4 wire probe connections at the power analyzer.

For the measurement of low voltage levels, the sample segment under test was connected directly to a low voltage module of 1.58 V or, in case of overload, to an inductive voltage divider of 10-1 V, with the use of coaxial cable or twisted pair of measurement cables.

Now the most important and relevant subject of the present paper — with high currents, there is still a way to keep the object under the temperature of the surrounding medium, for repeated and increasing applications of currents on the same sample, every five minutes of test.

This difficulty was overcome by the use of a fast measuring system, synchronized with a fast current drive system, never exceeding 70 ms (1 to 4 cycles of 60 Hz). Thus, the sample does not receive enough energy for the significant temperature rise during the test duration and can remain at (23 ± 2) °C or at (77 ± 1) K. The tests can be repeated, because the surface power in the sample will be less than 1 μW / mm².

The test circuit described in Figure 1, where the thickest line represents the aluminum cable under test, in length generally in the order of 10 to 15 meters, but with potential draws of distances from one to 5 meters. A longer cable length than the segment under evaluation becomes necessary for the sample to pass through the high current power supply.

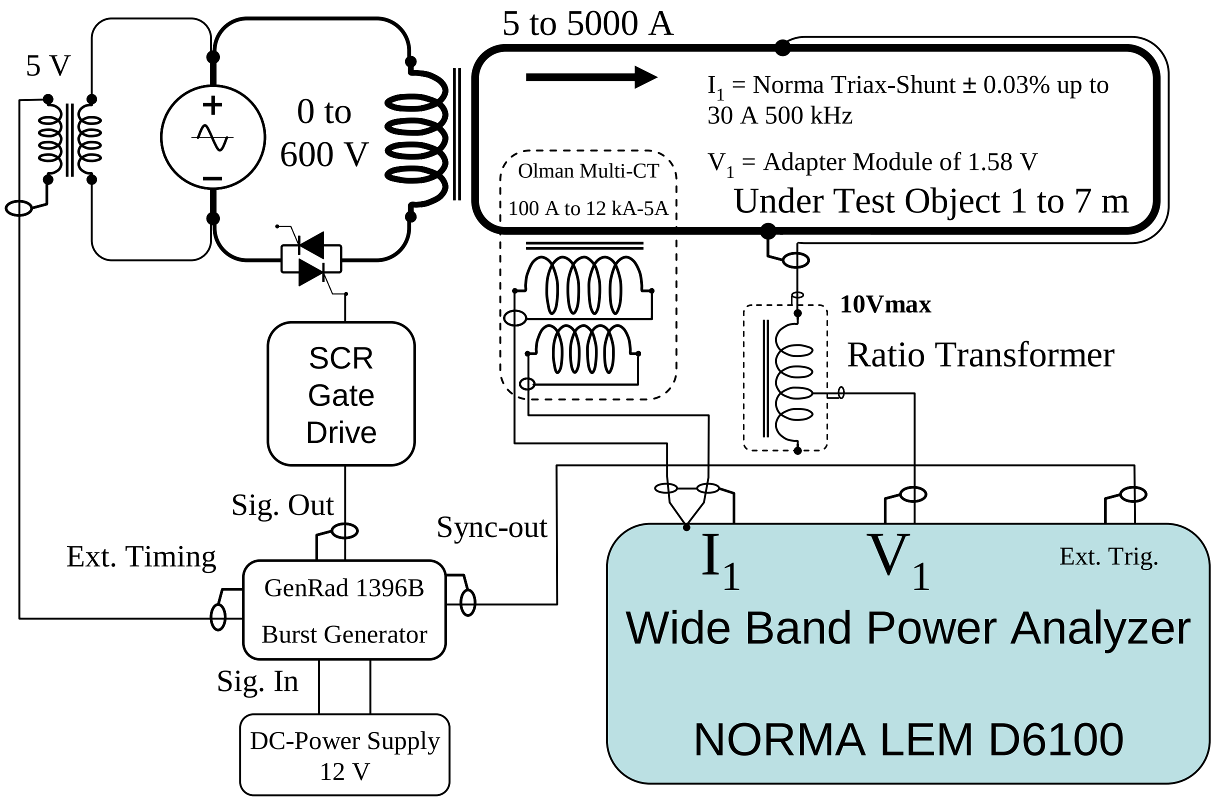

Figure 1 - Schematic diagram of experimental testing system.

After the proper connections and adjustments, the test is initiated by the Burst Generator, pre-set for current application with duration of one, two, three or maximum four cycles of 60 Hz, in single mode. With the start of the current, through the SCR Gate Drive, simultaneously a trigger pulse is applied to the Power Analyzer LEM D6100 to initiate the measurement. After one second, the measurement test is finished.

2.1 *Alternating current resistance of samples of aluminum cables for electric power transmission*

Although in the last 20 years many tests were contracted by Brazilian industries to measure the electrical resistance to alternating current of electric cables for electric power transmission, and some even for rural electrification in steel cables, the results constitute laboratory confidentiality and can not be published.

However, as an internal research to clarify doubts about the electrical resistance of the ACSR cables (aluminum with steel core for reinforcement in the mechanical strength of rupture) with three layers of aluminum wires, to check if the electrical resistance at the frequency of 60 Hz could vary with the intensity of the applied current, for values well above the rated currents, by the inductive effects on the steel core [5] or by other effects, two similar cable samples were used for experimental laboratory investigations. A sample of five meters of cable Rail – 954 kCM, for 970 A, used, withdrawn from the operation and another one of cable Duck-605 kCM, for 770 A, new, was selected to be tested. The 60 Hz electrical resistance of both samples was measured at very high current levels, above rated values, up to 290 %.

Laboratory currents were used at 60 Hz frequency, greater than 2 kA for Duck cable and more than 3 kA for the Rail cable. Sample temperatures were maintained within the tolerances of the laboratory environment even at high currents of (23 ± 2) ºC, using low thermal energy for the measurements, lasting only four cycles (4/60 s) for each reading, with an interval of at least five minutes between measurements or reapplications of measure currents.

3 EXPERIMENTAL RESULTS

The results of the variations of the resistances with the current applied to the Rail cable as well as the dissipated power are shown in Figure 2. The electric resistance in 60 Hz of this cable is 73 μΩ / m, according to the manufacturer [4].

The results of the variations of the electrical resistances with the applied current for the Duck cable, and the dissipated power are shown in Figure 3. The variations of resistance and the power dissipated in direct current were used as references. The 60 Hz resistance of this cable is 112 μΩ / m, according to the manufacturer [4].

The results shown in Figure 2 confirm that the ac resistance of the Rail cable increased about 14 % with respect to its dc resistance, for an applied 60 Hz current equal to 290 % of the rated current of the cable.

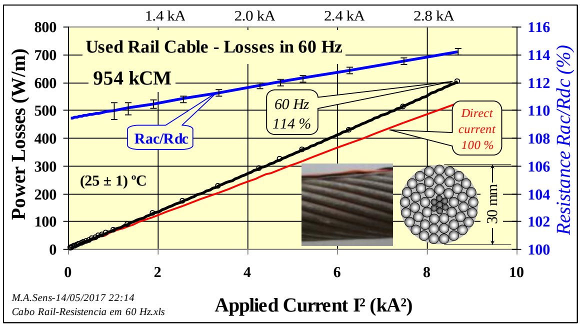

Figure 2 – AC resistance for Rail cable – Used.

In contrast, as shown in Figure 3, the ac resistance of the new cable Duck increased only 4 % with respect to its dc resistance, for the same condition, that is, for 290 % of the rated current.

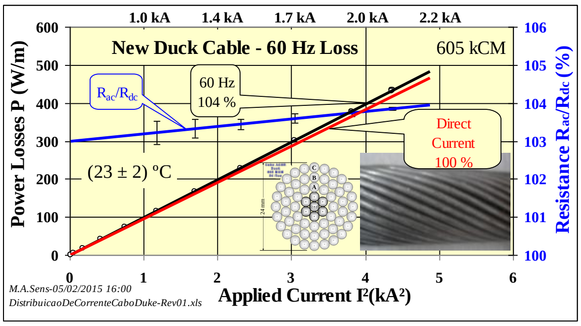

Figure 3 - AC resistance for Duck cable – New.

The differing behavior between samples of new and used ACSR cable can be observed, by the Figure 2, and Figure 3. The surface layer of aluminum oxide is of high electric resistivity. The oxidized surface layers of the cables are not the same, but one cable is older in service than the other, as shown inside of the pictures.

A third cable sample was also assessed, but at different temperatures, where the heating of the sample was obtained by long time measurement current itself. This is the Grosbeak heat-resistant cable, which is a two-layered aluminum wires. It was tested at temperatures up to 180 °C on currents up to 1000 A, at 60 Hz, as Figure 4.

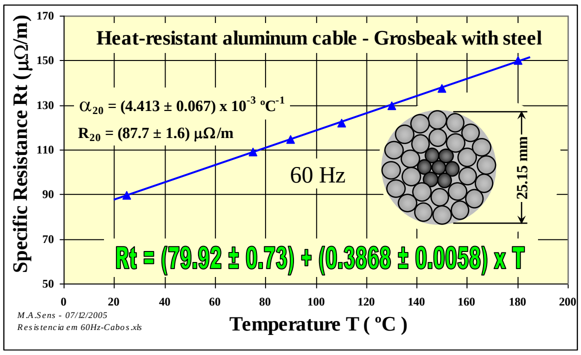

Figure 4 - AC resistance for Grosbeak cable.

Using the data obtained experimentally, the coefficient of variation of the resistance with the temperature, with the respective uncertainties, was calculated as also indicated in Figure 4.

3.1 *Validation of results*

Four standard resistors of current rated of 15 to 600 A, with rated resistances of 100 μΩ to 100 mΩ, were evaluated in DC and AC by the techniques described here, in currents up to 1100 A for all units, even for that one of 15 A. The results indicated a linear correlation of the power with the quadratic current, between 35 and 1100 A, greater than or equal to 0,9999995.

4 CONCLUSIONS

It was concluded from the results presented here that the test system meets the expectations of finding differences between the electric resistance in alternating and continuous current and that in alternating current, in fact, the resistance is greater, according to all the literature dealing with skin effect. However, the trials revealed an unexpected result. The results showed that new and used cables have distinct behavior under high currents. This differing behavior between samples of ACSR cables new and used is certainly due to the surface aging of the aluminum of the cable during the use. Depending on the environmental conditions, the surface of the aluminum degrades more or less. Moreover, this layer of aluminum oxide is of high resistivity and hard material. With the oxidized surface layer, the circulation of electric current between layers and between adjacent wire conductors is reduced, forcing the current through the turns of the cable's aluminum wires. The turns way, on the other hand, are longer than the cable itself and, therefore, have greater electrical resistance than the compacted cable. Possibly, the greatest increase of the electric resistance to alternating current in the aged cables can still be attributed to the magnetic flux density in the steel core, because it is a cable with odd layers. But for new cables, the finding of this hypothesis is still a challenge for other experimental investigations, such as those carried out at Ontario Hydro, Canada [3].

5 REFERENCES

[1] G. SCHRÖDER, J. Kaumanns, R. Plath, "Advanced measurement of ac resistance on skin-effect reduced large conductor power cables", Jicable ´11, Paper A 8.2.

[2] Gero SCHRÖDER; Dominik HÄRING; Andreas WEINLEIN and Axel BOSSMANN "AC resistance measurements on skin-effect reduced large conductor power cables with standard equipment", on 9th Jicable'15 - Versailles 21-25 June, 2015.

[3] J. S. Barrett and O. Nigol - Ontario Hydro-CA; C.J. Fehervari and R. D. Findlay – kCMaster University-Ontario-CA – "A New Model of AC Resistance in ACSR Conductor", IEEE Transaction on Power Systems, Vol. PWRD-1 N. 2, April 1986.

[4] Nexans, Catálogo de Produtos, disponibilizado em http://www.nexans.com.br/eservice/Brazil-pt_BR/pdf-family_-74539/Cabos_de_Alum_nio_Nu_CA_Serie_kCMIL_.pdf, acesso em 26/02/2017.

[5] Sens, Márcio Antônio and Ueti, Edson, "Envelhecimento de cabos condutores para transmissão de energia elétrica" at XXIV SNPTEE - National Seminar On Production And Transmission Of Electrical Energy, October 22 – 25/17, Curitiba - PR – Brazil.

M.A.Sens- 03/09/2017
XII Semetro-2017-Very Low Ac Resistance Measurement-Rev04-Ressubmissao.doc