SILVER CERTIFICATE AWARD

Electrical linear resistance versus weight measurement of conductors: what benefits can we expect?

Measuring the linear electrical resistance of conductors rather than weight calculation/measurements described in ASTM standards offer manufacturers advantages, one of which is eliminating the need to cut the conductor.

By Boris Dardel and Vincent Arbet-Engels

ASTM Standards allow for both linear mass and resistance measurements for the qualification of conductor design. Although weighting seems to be the easiest way and is a method commonly used to determine the conductor area and its corresponding resistance based on material conductivity, advantages of the direct resistance measurement approach allow for fine tuning of the design and consequently significant material cost savings. Moreover, possibility to measure directly on-the-line without cutting the conductor brings a further cost/time benefit.

This paper compares two different approaches in measurement of the linear resistance. It reviews various standards, then describes the on-the-line principle, and continues by comparing the two methods based on their respective precision. The last part highlights the importance of the precision of the measurement in the design of the cables.

Standardization

Prescriptions of IEC 60228 “Conductors of insulated cables” are based on a) the number/dimension of wires, that defines the flexibility of the conductor, and b) the linear electrical resistance that defines its size (cross-section). This last parameter is the main component of the cable design in term of ampacity.

On the contrary, ASTM standards B8-11 (respectively B231/B231M-12) “Standard Specification for Concentric Lay-Stranded Copper (respectively Aluminum) conductors” require qualifying the design both in terms of area and linear resistance. Area is either extracted from wire dimensions or calculated from measured conductor weight according to ATSM B263/B263M-14. Linear resistance is derived from calculated area and resistivity of the material, the latter being measured according to ASTM B 193-02.

Nevertheless, accuracy of the measurement is subject to errors in the determination of the sample length and mass measurements, lay length uncertainties and material density and resistivity considerations. Fig. 2 shows typical weight/resistance measurements distribution for 240-mm aluminum-stranded conductors.

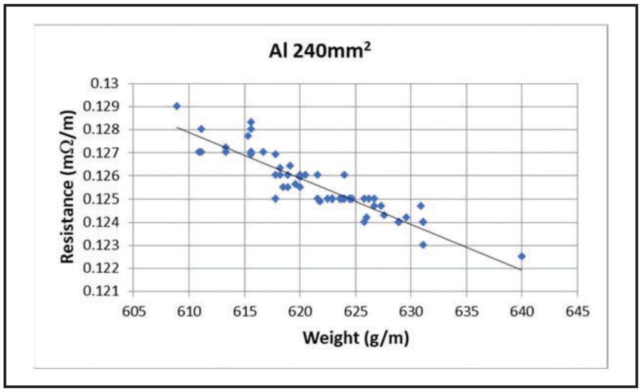

Fig. 1. Typical resistance vs weight distribution.

Fig. 2. On-the-Line measurement device.

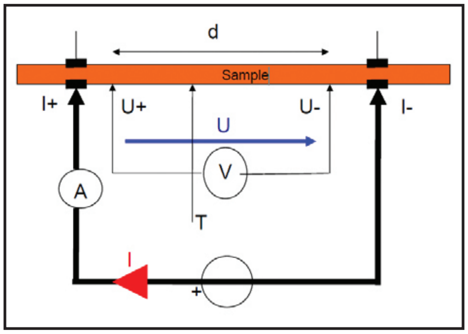

Fig. 3. Resistance measurement principle.

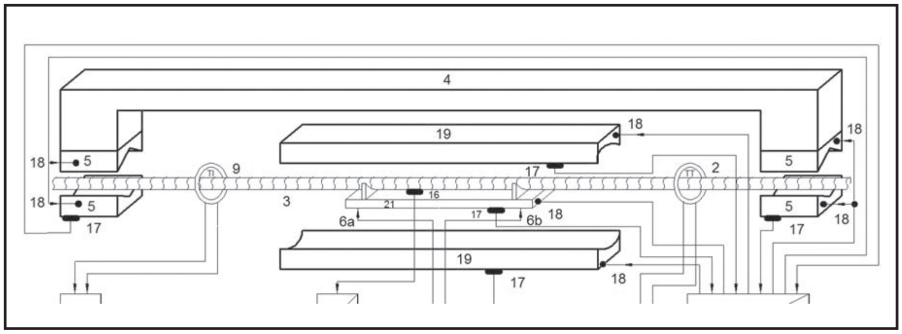

Fig. 4. Schematic of system.

It is worth noting that for covered or insulated wires and cables, the sole direct measurement of DC electrical linear resistance is considered sufficient to cover also area requirements. This can be performed by fully integrated systems with known accuracy that incorporates all these parameters in one single measurement, such as in Fig. 2. Moreover, on-the-line measurement without cutting the conductor is readily feasible as described in the following paragraph.

On-the-line measurement: principle

Resistance measurements are based on Ohm's law:

$$R = \frac{U}{I}$$

Where: R = Resistance;
U = Voltage drop;
I = Injected current

A known current is injected in the conductor and the voltage drop is measured as shown in Fig. 3. As the conductor is electrically connected to the production machinery, it is necessary to control and regulate the current flowing through the measured portion of the conductor in order to avoid any perturbations due to parasitic currents flowing back into the production line. To do so, a circulation loop is built by firmly connecting the conductor with clamps (components #5 on Fig. 4). The current is injected into the conductor at very low frequency by induction, with the help of a coil placed on one side of the loop (#2 on Fig. 4). A second coil is placed on the other side (#9 on Fig. 4) for current sensing.

Fig. 5. On-the-line device from AESA.

Voltage drop is measured by two knives applied on the conductor at a calibrated distance of 1 m apart (#6 on Fig. 4). The measured value is then scaled to get the real DC resistance, thanks to synchronous rectifiers.

When measuring directly on the production line, the cable is compact and under quite high longitudinal mechanical tension. This definitively helps to reduce the contact resistances between wires and allow for better current distribution throughout the complete cross-section. Moreover, the use of hydraulic jaws ensures the reproducibility of the high clamping forces needed to connect large aluminum cords.

As material resistivity depends on temperature, the temperature of the sample must be stable and recorded during the measurement per the following formula:

$$\rho = \rho_0[1 + \alpha(T - T_0)]$$

where ρ = *Resistivity*
T = *Measurement temperature*
T_0 = *20°C = Reference temperature*
α = *Temperature coefficient of the resistivity*
0.393% for Copper and 0.403% for Aluminum

The temperature of the on-the-line conductor is usually higher than the ambient temperature due to friction and deformation heating inherent to the cabling manufacturing process. Therefore the device is equipped with a heating system (#18 on Fig. 4) controlled by temperature sensors (#16 and #17 on Fig. 4) that allows bringing the equipment to the conductor temperature. Measurement automatically starts after complete thermal stabilization (within few minutes depending on temperature and conductor size).

System operation and performance

The device is mounted on trolley for easy placement on-the-line. See Fig. 5. Height and inclination are quickly adjusted to fit the line configuration. The line must be stopped before the system is put in place. The jaws can be mechanically or hydraulically activated. See Fig. 6. Jaws can be adapted to cable design to avoid deformation due to clamping. Moreover, for aluminum conductors, where oxide layer creates large contact resistance between wires, so-called compaction "voltage" rings are supplied to improve homogeneity of current through the cross-section. See Fig. 7.

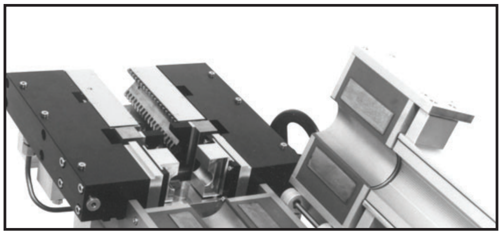

Fig. 6. Close-up of hydraulic jaw.

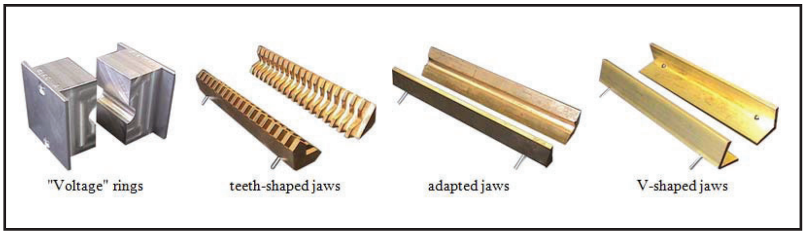

Fig. 7. Sets of specific hydraulic jaws.

Measurement precision is 0.1% for conductors up to 1000 mm^2 for copper and 300 mm^2 for aluminum, respectively. For larger conductors (up to 1800 mm^2 for copper and 1200 mm^2 for aluminum), precision is 0.2%. When using the heating system, these values may slightly increase, depending on the selected stabilization parameters.

Comparison between weight and resistance methods

Determination of conductor area using weighting method according to ASTM standards (B263/B263M) is based on the following formula:

$$A = \frac{1}{K}\frac{W}{L \times f}$$

where *A* = *Conductor area*
K = *Correction factor for the wires overlengths due to stranding*

$$K = 1 + \frac{k}{100}$$

with k = Increment of mass or electrical resistance
W = *Mass of the sample*
L = *Length of the sample*
f = *Mass factor of the material (density)*
8.890g/cm³ for Copper and 2.705g/cm³ for Aluminum 1350 at 20°C

Uncertainty can then be expected to be as follows:
ΔK = 0.16% (deviation of the lay length of 0.01 x diameter of the layer)
ΔW = 0.1% (as prescribed in the standard)
ΔL = 0.13% (square distribution of +/- 1/32 inch over 2 feet)
Δf = Negligible

→ ΔA = 0.23%

Determination of linear resistance from area calculation according to ASTM standards is based on the following formula:

$$R = \frac{K \times \rho}{A} = K^2 \frac{L \times f \times \rho}{W}$$

where: R = Linear resistance
ρ = Resistivity of the material
0.017241Ω mm^2/m for 100% IACS at 20°C

Considering the uncertainty on the resistivity given in ASTM B193-02, $\Delta\rho = 0.3\%$, one can calculate the following uncertainty for the linear resistance: → ΔR = 0.41%

Comparing this precision, where great care must be taken during the conductor preparation and handling (sample cut, length measurement, and resistivity measurement), with the overall uncertainty of the on-the-line measurements method, one can easily conclude that getting the value by the weighting procedure is not worth the effort. And this specifically when knowing that the on-the-line measurement takes only few minutes, does not require to cut the conductor (material and time savings), can be repeated at any time on the production cable length and provides more accurate results.

Moreover, off-line measurements towards design improvement are more precise and allow for conductor conception related cost savings. Table 1 summarizes the differences in the two methods.

Relevance of the precision

The precision of the measuring apparatus has a direct impact on the dispersion of the measured values. Considering the usually admitted normal distribution (Gaussian), precision is defined as its standard deviation σ.

Fig. 8 shows that 68.2% of the measurements fall within ± σ, 95.4% within ±2 σ and 99.7% within ±3 σ. This means that in targeting the conductor design to a mean value lying at 1 σ below the device precision, one statistically gets 15.8% of the measured values out of specifications.

To ensure almost all measured values are under specifications, one should target a mean value lying at 3 σ below the specification. This means, for precisions of 0.1% and 0.4%, designing the conductor with a mean resistance that is respectively 0.3% and 1.2% below its specification. This difference can be converted into direct material savings.

Conclusions

In this paper, the authors demonstrate that the use of on-the-line linear resistance measurements greatly improves the efficiency of design validation and process controls, integrating the effect of all the usually individually measured parameters.

The measurement takes only few minutes directly on the production line without the need to cut the conductor and thus, without loss of material. It can be repeated along the production for process control or for design improvement (for example adaptation of assembling lay-length of the individual layers).

Besides these advantages, the importance of measurement precision is highlighted. An improved precision can significantly permit a finer tuning of the conductor design, getting closer to the specification limits and hence allowing material saving. ■

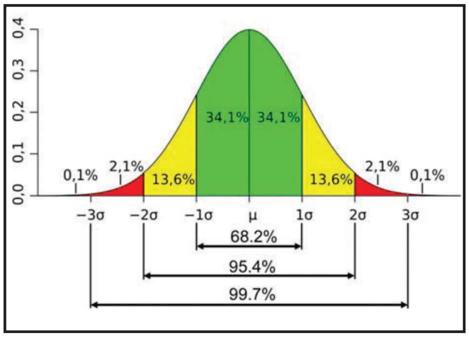

Fig. 8. Gaussian distribution.

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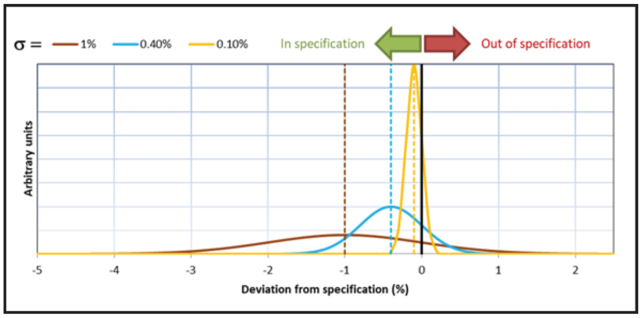


Fig. 9. Measurements distribution for different precisions with a target design value lying at 1 σ below specification.

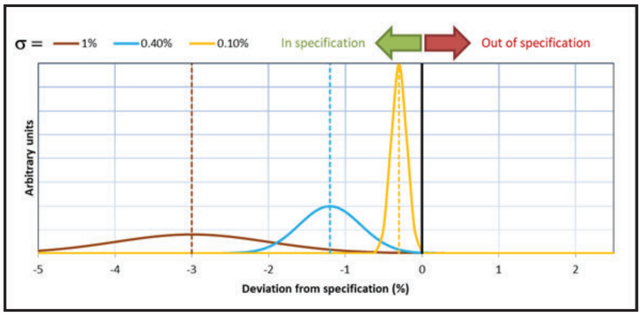
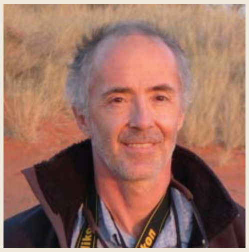


Fig. 10. Measurements distribution for different precisions with a target design value lying at 3 σ below specification.

Dardel



Arbet-Engels

Boris Dardel has been R&D manager at AESA, SA, Colombier, Switzerland, since 2016. He is responsible for designing and leading R&D processes, specifically linked to the measurement of electrical resistance for energy cables. He holds a Ph.D. degree in condensed matter physics from the University of Neuchatel in Switzerland. **Vincent Arbet-Engel**s is CEO/Managing Director of AESA, a leading manufacturer of test equipment for the cable industry. He holds an M.S. degree and a Ph.D. in electrical engineering from the University of California, Los Angeles (UCLA), and M.S. and B.S. degrees from the Swiss Federal Institute of Technology in Lausanne (EPFL) in microengineering. This paper, which was presented at Interwire 2019, Atlanta, Georgia, USA, May 2019, won a Silver Certificate Award in the electrical category.

Comparison	Weighting method	Resistance measurement
Precision	0.4% (at best) with great care	0.1-0.2%
Need to cut the conductor	Yes	No
Dependent on material conductivity	Yes	No
Dependent on material density	Yes	No
Depending on stranding accuracy	Yes	No
Quick and easy	No	Yes

Table 1. The difference between the weighing method and the resistance measurement method.