Alternating current (AC) resistance of helically stranded conductors

Information from Cigré

The electrical resistance of bare, helically-stranded conductors (aluminium and aluminium alloy), intended for use in overhead distribution and transmission lines, depends on the conductor cross-section area, the conductivity of the aluminium alloy, the lay length of the aluminium layers, and the presence or absence of a steel reinforcing core. The presence of a stranded steel core can increase the resistance due to core magnetising effects. Cigré brochure 345 describes a process of AC resistance calculation for bare stranded aluminium conductors both with and without a steel reinforcing core.

In order to determine the AC resistance of an ACSR conductor one must account for the following:

- *DC resistance*: Increases with strand resistivity and length.
- *Temperature*: DC resistance increases with temperature.
- *Skin effect*: Alternating current forces current to the outer section of the strands and to the outer layers of the conductor.
- *Core losses*: Eddy current and magnetic hysteresis losses in the steel core increase the effective resistance of the conductor.
- *Transformer effect*: Magnetic coupling of current in the aluminium strand layers through the steel core increases non-uniformity of the current density in the layers, particularly for three layer conductors.

The methods described in Cigré brochure 345 can calculate AC resistance for both homogeneous and non-homogeneous steel core conductors. A listing of a detailed MathCad program is included.

Bare stranded aluminium conductors, with and without steel reinforcing cores, have been used for over 80 years for the transmission of electric power at high voltage. These conductors consist of one or more layers of aluminium wires stranded concentrically (with alternate right-hand and left hand directions). When steel reinforced, the conductor core consists of one or more galvanised steel wires. The steel core and aluminium layers provide mechanical strength, but the aluminium wires carry most of the current.

Whether there is a steel core or not, alternating current flowing in the aluminium wires causes skin effect within the conductor and, at frequencies of 50 to 60 Hz, skin effect increases the resistance by between 1% and 10% for conductors having diameters varying from 20 to 50 mm, respectively.

In ACSR, the alternating current produces an alternating axial magnetic flux in the steel core which further changes the current distribution between aluminium layers, and increases the effective AC resistance by as much as 5% to 20% for three-layer and single layer ACSR.

The conductor is not isothermal, since there will be a radial temperature gradient, and there may also be a longitudinal temperature gradient.

Direct current parameters

With direct current, the current density within an isothermal solid cylindrical or tubular conductor is uniform. Provided that good contact is made with all the strands, the distribution of the current density within an isothermal homogeneous stranded conductor carrying direct current is also uniform. In the case of a bimetallic conductor, such as ACSR, the current density within each metallic section is inversely proportional to the resistivity of that section.

The resistance per unit length R of a conductor depends on the resistivity ρ and the cross-sectional area A. Since the resistivity is temperature dependent, the resistance also varies with the temperature *T* of the conductor.

Alternating current parameters

In order to determine the parameters that affect AC resistance, it is necessary to study the effects on the resistive and the internal inductance.

Parameters that affect AC resistance

The current density distribution within any conductor carrying alternating current is rarely uniform. With solid cylindrical and tubular homogeneous conductors, there are skin and proximity effects. With stranded homogeneous conductors, variable contact resistances between strands may also affect the current distribution. With stranded steel-cored aluminium conductors (ACSR) the alternating magnetic flux in the core may cause hysteresis and eddy current losses in the core and a profound redistribution of current density in the layers of non-ferrous wires.

The effect of frequency (skin effect)

The AC resistance of any conductor depends on the frequency of the current, as this determines the magnitude of the skin effect. At power frequency, there is usually negligible variation in the resistance with frequency in the case of a monometallic conductor. With steel-cored conductors, such as ACSR, however, there may be a significant effect of frequency, because the radial distribution of current density in the nonferrous section and the power loss in the steel core both depend on the frequency.

Since not all the magnetic flux due to filaments of alternating current near the centre of a homogeneous conductor cuts the whole conductor, the inductance per unit area will decrease towards the surface. Hence, the current per unit area will increase towards the surface of the conductor. Theoretical studies give factors for skin effect calculation, which is the ratio between the AC and DC resistances, for an isolated non-magnetic solid circular cylinder with negligible capacitive current as a function of conductor radius.

Theoretical studies based on measured results have proposed an explicit solution to equation for power frequencies, where the error varies from 1,6 % to 3,8%. In the case of a stranded non-magnetic conductor this includes the skin effect factor, provided that the DC resistance is calculated at the temperature of interest. For steel-cored conductors, such as ACSR, some authors have used the diameter of the steel core for calculation, but this neglects the effect of the magnetic flux in the core on the skin effect.

Effect of temperature

Temperature has a significant effect on the resistance of most aluminium (and copper) conductors. The increase in DC resistance with temperature amounts to approximately 4% for every 10°C change in conductor temperature.

Transformer effect and iron losses

Iron losses were taken into account. It assumed that current density was uniform in the non ferrous section and that currents followed the spiraling wires.

Earlier analyses of the transformer effect modeled the effect of the steel core in an ACSR conductor by employing equivalent circuits, but these models identified the core loss with each layer of the conductor, rather than with the core, although they did indicate non-uniform distribution of current density between the layers of aluminium wires. The first model to include the layer resistances and inductances due to the circular and longitudinal magnetic fluxes employed complex values for the layer currents, but not for the permeability of the core and the magnetic loss angles. These discrepancies were partially rectified and fully accounted for in subsequent studies. The effects of the temperature and the tensile stress in the conductor on the permeability of the core were analysed.

It has been shown both analytically and experimentally that both the current density and its phase angle vary both within and between layers. The steel used in the core is virtually unique for different conductors. The curves provided in the computer programme in Appendix A of the brochure were taken from an appropriate reference but the programme does permit changes in steel parameters. The curves provided are sufficiently accurate for general use.

Parameters that affect AC conductor impedance (Z)

The non uniform distribution of the current density in a conductor, due to the skin effect and the transformer effect, also influences the internal inductance, particularly with steel cored conductors.

The internal conductance increases sinusoidally in ASCR conductors with increasing current to a maximum value and then decreases as the magnetic saturation of the steel sets in. The internal inductance decreases as the frequency increases (range 25 Hz to 60 Hz). Increasing the tensile stress, in the range 0 - 290 MPa, will decrease the relative permeability of the steel core.

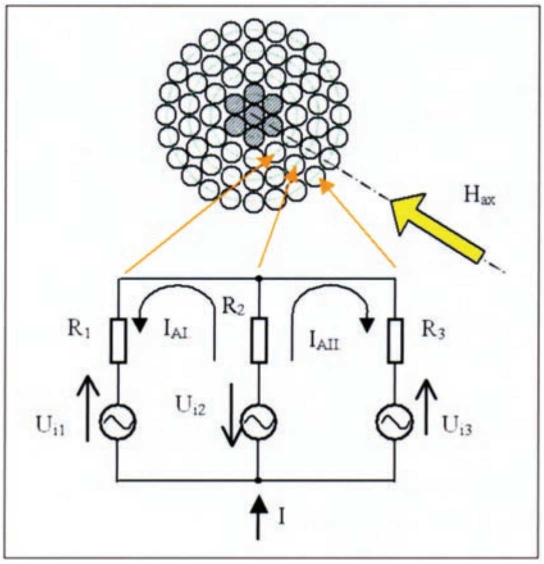

Fig. 1: Induced voltages and currents in aluminium layers of a three-layer ACSR conductor.

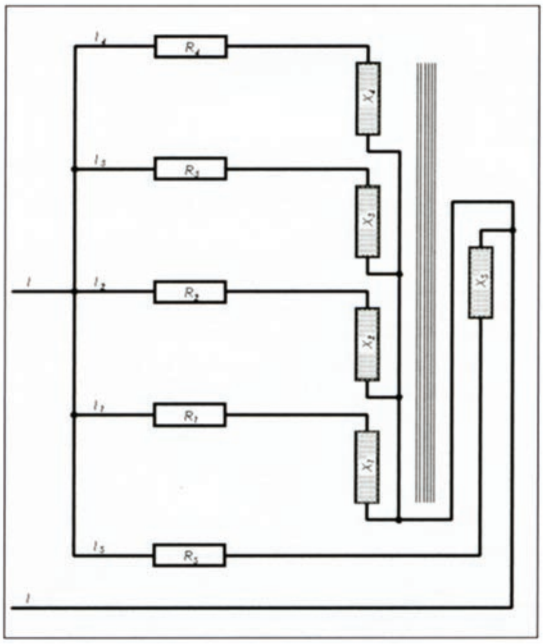

Fig. 2a: Cross section of ACSR with four layers of Aluminium Wires.

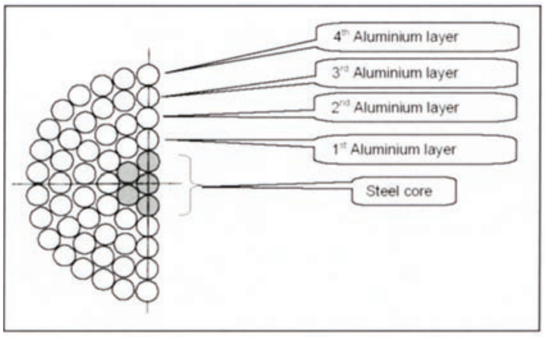

Fig. 2: Electrical representation of four layers Aluminium Wires.

Uneven current distribution

According to the test results it was verified that the highest current density is not in the outside layer, caused by "skin" effect, but in the middle-layer because of the transformer effect inducing current in the wires as a result of the magnetization of the steel core.

R_1 - R_3: Resistance of aluminium layers

U_{il} - U_{i3}: Induced voltage in aluminium layers

I_{AI} - I_{AII}: Induced current component in aluminium layers

Electrical representation of ACSR conductor

The primary circuits substitute the aluminium layers while the secondary circuit substitutes the steel core. In the substitutions diagram "I" symbolises the current in the conductor, which is equal to the sum of the current in each layer (I_1, I_2, I_3, I_4.)

According to calculation, about 80% of AC incremental loss is produced in the Al-layers and only 20% of it arises in the steel-core. The variation of components (ΔRA1, and ΔRAc) of AC resistance of conductors can be seen in Fig. 3.

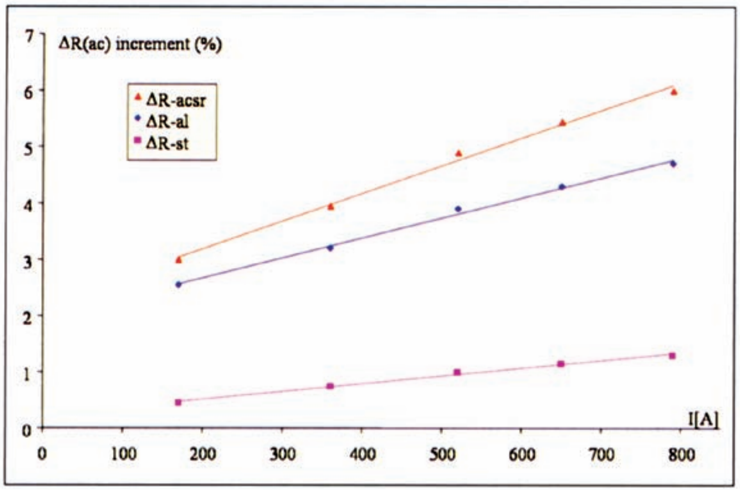

Fig. 3: Main components of AC resistance of a three layer ACSR conductor (ACSR 500/65).

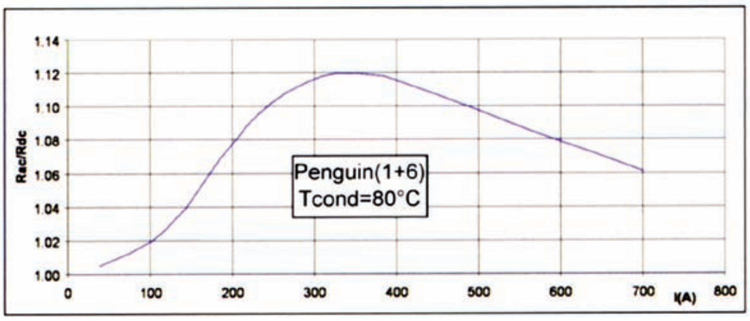

Fig. 4: Variation of AC/DC resistance of Penguin conductor.

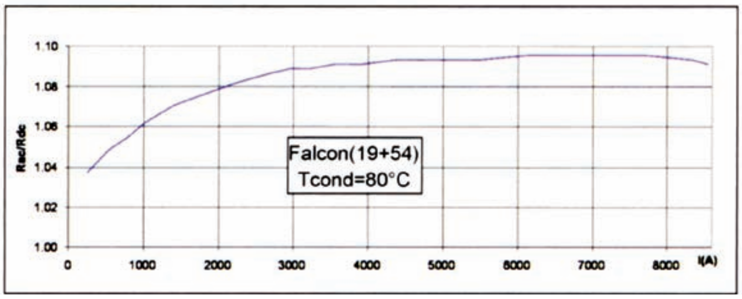

Fig. 5: Variation of AC/DC resistance ratio of Falcon conductor.

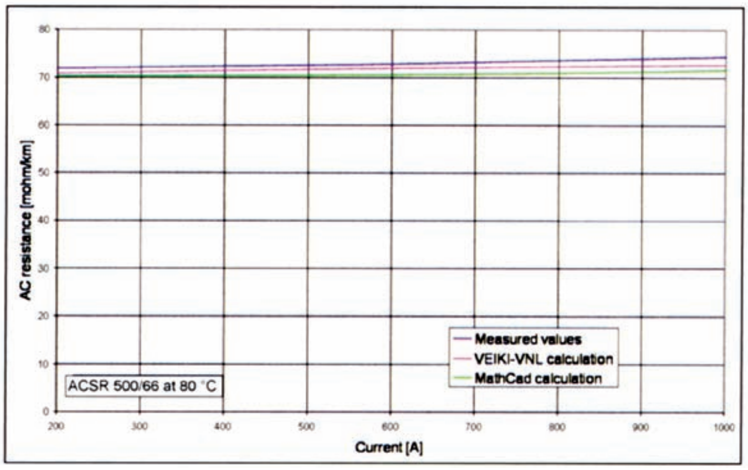

Fig. 6: Measured and calculated results for ACSR 500/65 conductor.

The cause of increase of AC resistance in comparison to the DC resistance, is mainly uneven current distribution, which strongly depends on the induced voltage in the Al-layers. This voltage is the function of the stranding angles of the layers.

AC resistance calculation for 1 and 3 layer aluminium strands

A computer programme based on the transformer model described above, was used to calculate the AC resistance of the following conductors. The calculated value of AC/DC resistance ratio of one layer and three layers conductor as a function of loading current are presented in Fig. 4 and 5.

The increase in AC resistance is not linear with current density. Rather, a peak resistance is reached at a current density of 3 to 5 A/mm^2 after which the resistance either flattens out or declines.

Comparison of measured and calculated values

A calculation method was developed by Muftic (Eskom) using MathCad software. This method was based on the model in Appendix A of the Cigré brochure 345. Another computer program was developed by Guntner and Varga (VEIKI-VNL Ltd.) for AC resistance calculation. This program is based on the model shown in Appendix B of the brochure. An ACSR 500/66 conductor was used in the calculation:

The measured and the calculated values with two different methods can be seen in Fig. 6.

From Fig. 6 it can be deduced that the measured AC resistance values are very close to the calculated results with both computer programs being based on the theory of uneven current and temperature distribution of ACSR conductors.

Conclusion

The theory surrounding the current distribution in stranded conductors is well researched and documented. Prior to the advent of modern day mathematical programmes, it was not possible to rapidly calculate the AC resistance value in a short time. This necessitated simplification of the detailed model to allow engineers to determine approximate values of AC resistance. This sufficed whilst the current densities used were generally well below I A/mm^2. However, in recent time with the pressure to relieve congestion due to trading and other factors being prevalent, current densities of up to 4 A/mm^2 have been experienced. This implies that the present simplification is not sufficient. This document has managed to describe the model relating to the determination of AC resistance as well as indicate the comparison of the use of the model to actual measurements. Appendix A of the brochure allows the user to develop programmes capable of calculating AC resistance for any type of bare overhead conductor.

Acknowledgement

This paper was published in the April 2008 issue of Electra, the members' journal of Cigré, www.cigre.org, and is republished with permission.

Contact Ken King, Cigré,
Tel 011 886-6573, kingk@merz.co.za ❖