Frequency dependency of single-core cable parameters

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It is expected that the need to obtain frequency dependent cable parameters is growing, for example in relation to future HV cable links, and that these may be needed both for AC and DC cables. There are also examples of cable links that are designed for initial operation at (HV) AC, with planned subsequent conversion to HVDC. As capacitance may be considered constant for the frequency range up to the 100^{th} harmonic (6 k Hz at 60 Hz fundamental), the challenge then lies in predicting the series parameters (i.e., resistance and inductance) with reasonable accuracy within the frequency range: DC to 6 kHz.

When identification of series parameters is concerned, mainly longitudinal metal constituents are of importance. When disregarding differences in insulation system, the single core cable design is quite similar for AC and DC, and this applies to land and submarine cables except for the armour.. Submarine cables will usually be designed with heavier mechanical reinforcement in the form of (additional) armour.

The metal members of a single core cable will typically include:

- Conductor (copper or aluminium)
- Lead sheath/Al sheath/Cu wires, possibly with steel tape radial reinforcement
- Steel armouring in the form of a single layer or two layers of carbon steel wires (magnetic) or Cu armour wires on single core AC cables (non-magnetic)

The inter-axial distance between installed cables also play an important part in identifying resistance and inductance in the lower part of the frequency band.

Although the standard does not explicitly state this, the long trusted, and empirically based, formulae in IEC 60287 were developed for power frequency only. This can easily be verified through comparison with simple, analytic expressions for inductance at DC and at the upper frequency limit (6 kHz). It is also well known that metal sheath losses cause a fundamental frequency power loss that peak at a certain inter-axial distance, and are reduced both for increasing and decreasing distance. A similar effect could be expected at a fixed inter-axial distance and varying frequency.

This paper describes the great detail of information that can be obtained through application of finite element analysis (FEA) to single-core cables. FEA is basically a numerical method which identifies the electromagnetic field solution based on the fundamental principle of physics: minimization of energy. When considering longitudinal currents only, two-dimensional FEA will not impose any practical limitations with respect to computational power/time required.

For the sake of simplicity, this study is limited to assigning constant magnetic permeability to magnetic steel members (armour), thus excluding possibly significant non-linear effects. Even for this simplified case it is revealing to see the inherent complexity in power loss distribution between the metal members as functions of frequency. Obtaining similar behavior by means of simple formulae is considered unlikely to succeed within the frequency range considered here.

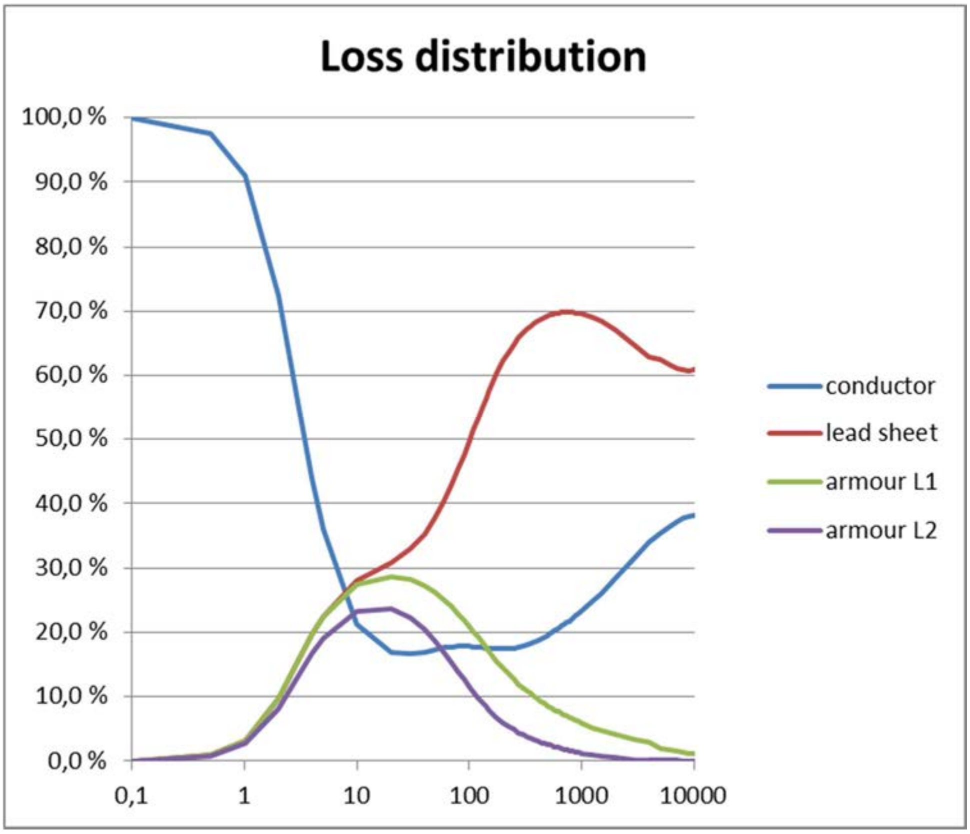

Fig. 1. Example of loss distribution for the metal members obtained for a typical HVDC cable

The loss distribution shown in Fig. 1 clearly illustrates that calculation of single-core cable resistance and inductance is anything but straightforward, even when (possibly) non-linear properties of the armour are ignored.

Conclusions:

- The nature of HV power cables is far more complex than they are normally given credit for, and they may severely influence overall power system properties.
- The finite element method is an extremely useful analysis tool that has been far too long overlooked in everyday electrical power engineering.