Frequency dependency of single-core cable parameters

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ABSTRACT
This paper illustrates the great detail of information that can be obtained through application of finite element analysis (FEA) to obtain the series parameters of single-core power cables. FEA is a numerical method which computes the electromagnetic field solution corresponding to the fundamental principle of physics: minimization of energy.

Results are obtained for three different cases, with an increasing number of metal members in addition to the conductor. Analytic values for inductance at DC and high frequency are used as points of reference. The loss distribution within the cable is given for each case.

INTRODUCTION
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 a result, it is important to be able to predict the behaviour of cables under these conditions.

From DC up to power frequency the main challenge in predicting the series parameters of any cable originates from the magnetic field distribution produced outside the cable. The magnetic field distribution, which may be regarded as a “compression”: magnetic field energy inside the armour constitutes a part of the frequency band, while having no significance at the upper frequency limit considered (6 kHz). At low frequencies, cable loss increases with cable spacing (thermal effects ignored).

It is also well known that metal sheath loss at fundamental frequency will peak at a certain sheath resistance. (Sheath resistance includes the combined effects of resistivity and cross-sectional area.) A similar effect could be expected at variable frequency for a given cable design.

Cable design considered
Longitudinal metal members of a single core cable will typically include:

- Conductor (copper or aluminium).
- Lead sheath/aluminium laminate/copper wires.
- Steel armouring in the form of a single layer or two layers of carbon steel wires (magnetic), or alternatively copper armour wires (non-magnetic) on large, single core AC cables.
- Steel tapes as radial reinforcement for lapped paper/oil insulation.

The metal members considered are shown in Fig. 1. The members outside the conductor are added individually to the defined study cases, so that their impact on total cable loss may be investigated.

Basic considerations
The inter-axial distance between installed single-core cables plays an important part in identifying resistance and inductance within the lower part of the frequency band, while having no significance at the upper frequency limit considered (6 kHz). At low frequencies, cable loss increases with cable spacing (thermal effects ignored).

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Adding (magnetic) steel armour to single-core cables complicates the task of calculating inductance and AC loss. The magnetic properties of the armour introduce a change in the magnetic field distribution, which may be regarded as a “compression”: magnetic field energy inside the armour increases, while field energy external to the armour decreases. This holds both for DC and AC, and results in an addition to inductance at DC and low frequencies. An exception to this is found at higher frequencies, typically above 1 kHz, when the lead sheath is earthed at both ends. In this case the conductor and the lead sheath constitute a coaxial conductor pair, and the magnetic field at the armour is practically zero. Consequently, the armour cannot influence inductance or AC loss.