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 capacitance may be considered constant for the frequency range up to the 100th harmonic (6 kHz at 60 Hz fundamental), the challenge then lies in predicting the series parameters (resistance and inductance) within the frequency range DC to 6 kHz.

The longitudinal metal constituents, cable spacing and temperature are of main importance for identification of (frequency dependent) series parameters. Cable current will also be of significance if materials with non-linear magnetic properties are included – typically these will be steel armour and/or steel tapes for axial and radial reinforcement. For paper insulated cables stainless steel or bonze tapes are used as reinforcement for AC cables, while magnetic steel tapes are typically used for DC cables. When disregarding differences originating from the insulation system (extruded vs. lapped insulation), the single core cable design is quite similar for AC and DC. This applies both to land and submarine cables, with an exception for sturdier armouring of submarine cables.

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 conductors. The bulk of magnetic energy, or (inductive) reactive power, can be allocated to this external region. In other words, cable inductance is dominated by the external field at (very) low frequencies.

The long trusted formulae of IEC 60287 were developed for power frequency only. This can easily be verified by comparing the results of simple, analytic expressions for inductance at DC and at the upper frequency limit considered here (6 kHz).

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.

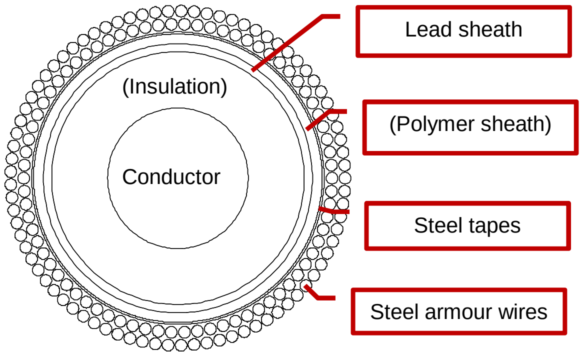

Fig. 1: Single-core cable's metal members

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).

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.

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 amour 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.