# **Cable Impedance Data**

Andrew J. Urquhart, Murray Thomson, 4 June 2015, version 1.2

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| Version | Data | Revisions |
| 1.0 | 14 August 2014 | Original version |
| 1.1 | 13 January 2015 | Finite element simulation data represented with one conductor impedance for each conductor, including neutral strands.  Averaging included allowing for the rotation of the sector cores relative to the concentric neutral due to the cable lay.  Analytical method now includes AC resistance corrections according to IEC 60287. |
| 1.2 | 4 June 2015 | Added more detailed contents list describing the impedance data file format.  Amended the resistance of the neutral strands such that the resistance per unit length defined by BS 7870 applies to the completed cable length, not the wire length (longer, due to the Waveform lay pattern of the concentric neutral).  Conductor and circuit impedances from the finite element simulation now present impedances for all of the neutral strands as a single conductor, by applying a Kron reduction (since all neutral strands are bonded together and have the same voltage at cable terminations). |

# Data archive contents

This data archive contains 12 impedance data files relating to Waveform cable, defined according to British Standard BS 3988:1970 [1] and British Standard BS 7870-3.40:2001[2].

An additional file is included describing the method used to implement the geometry of the sector shapes in the analysis and simulation software.

Six cable types are considered:

* 3-core 95 mm2
* 3-core 185 mm2
* 3-core 300 mm2
* 4-core 95 mm2
* 4-core 185 mm2
* 4-core 300 mm2

For each cable type, two files are available. These contain impedances from:

* Analytical method: modified Carson’s equations [3], with conductor resistances including AC resistance corrections according to IEC 60287 [4]
* Simulation method: finite element analysis, based on the FEMM solver [5]

A paper describing these two impedance modelling approaches is in preparation.

# Impedance data format

The impedance data is provided for frequencies of 50 Hz, and for integer harmonics up to 500 Hz, followed by further data for 1 kHz, 1.5 kHz, 2 kHz, 2.5 kHz and 3.15 kHz (the 63rd harmonic).

Each impedance data file contains several impedance matrices in Ω/km, described as follows:

Conductor impedances (only for data derived from simulation): the self-impedance and mutual impedance of conductors. The reactance here includes flux linkage from the conductor to an arbitrary simulation boundary.

For 3-core cables this is a 5x5 matrix for sectors 1 to 3, concentric neutral () and ground () in the form:

For 4-core cables this is a 6x6 matrix for sectors 1 to 4, concentric neutral () and ground () in the form:

Circuit impedances: the self-impedance and mutual impedance of circuits with a ground return path.

For 3-core cables this is a 4x4 matrix for sectors 1 to 3 and concentric neutral () in the form:

For 4-core cables this is a 5x5 matrix for sectors 1 to 5 and concentric neutral () in the form:

Phase impedances: assuming a perfect multi-grounded neutral, the Kron reduction is applied, as in [3], to give a 3x3 phase impedance matrix. Caution is advised in using such data for 4-core cables as cables may also be deployed with the concentric neutral bonded to ground, but without connecting the neutral sector to the concentric neutral (such that the neutral and grounding are isolated, as in a TN-S network [6]).

The data has the following form:

Sequence impedances: the impedance matrix transformed into sequence components, as in [3], with zero sequence , positive sequence and negative sequence , in the form:

# Kron reduction of neutral strand conductors

The finite element method used for the impedance data requires a separate simulation for each conductor. In order that the conductor impedances can be averaged to allow for the cable lay rotation, a separate simulation is needed for each neutral strand. For the example of the 3-core 95 mm2 cable, this results in a 34x34 matrix of conductor impedances (3 sectors, 30 neutral strands, and the ground).

However, the voltage difference between the strands is zero, and so these can be considered as one combined conductor, as in the analytical methods, with the impedances for the above example reduced to a 5x5 matrix. This uses a Kron reduction method, as in [7]. It should be noted that this is a separate process to the Kron reduction that may be used to combine the neutral and ground conductors as a multi-grounded neutral.

The method proceeds as shown in the following example, described for a simpler case of a cable with three sectors, two neutral strands and and the ground conductor . This gives a 6x6 conductor impedance matrix, re-ordered here so that the neutral strands are at the lower right of the impedance matrix.

Row is now subtracted from row . All the neutral strand voltages are equal so and , giving:

The current from neutral strand is now added to that from strand , giving:

The total current in the neutral is given by:

And the voltage of all neutral strands is equal to that on strand so and , giving:

Partitioning the impedance matrix between rows and , and between columns and gives:

This provides a 5x5 matrixwhere:

# References

1 BSI: ‘BS 3988:1970 Wrought aluminium for electrical purposes - Solid conductors for insulated cables’ (British Standards Institution, 1970), p. 16

2 BSI: ‘BS 7870-3.40:2001 LV and MV polymeric insulated cables for use by distribution and generation utilities’ (British Standards Institution, 2001), p. 14

3 Kersting, W.H.: ‘Distribution System Modeling and Analysis’ (CRC Press, 2012)

4 BSI: ‘BS IEC 60287-1-1:2006 Electric cables - calculation of the current rating’ (British Standards Institution, 2006), p. 31

5 Meeker, D.: ‘Finite Element Method Magnetics Version 4.2 User Manual’, http://www.femm.info/Archives/doc/manual42.pdf, accessed April 2015

6 Cronshaw, G.: ‘Earthing: Your Questions Answered’*IET Wiring Matters*, 2005, **16**, (Autumn), p. 7.

7 Beharrysingh, S.: ‘Phase unbalance on low voltage networks and its mitigation using static balancers’. Loughborough University, 2014