INTERNA

Study Committee B1

Insulated Cables

10693_2022

Sequence Impedance of Submarine Cables

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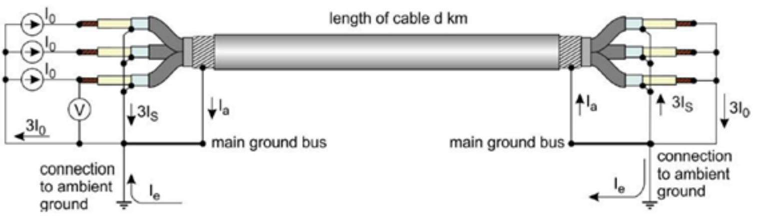
Motivation

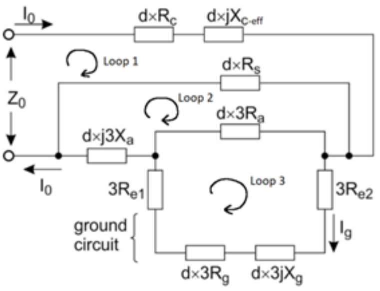
- OWF developer(s) rely on accurate & reliable cable sequence impedance data to optimize the overall electrical system design & operation, where submarine cable(s) constitute a major part considering the long length(s).
- Contrary to its reliable application to underground cable(s), Cigre TB 531 analytical calc. for modern 3-c submarine cable(s) is not trivial to implement and contains some intrinsic shortcomings.
  - *a.* *Parallel earth return through cable armour* is missing in power-frequency Z_0 calc
  - *b.* *Seabed earth return resistance* has been forgotten in the conductor resistance for Z_0 calc. (table 12)
  - c. Application to Z_1 calc. *at higher frequencies* is not considered
- An improvement on existing TB 531 analytical calc. for submarine cable(s) is highly desirable from the industry.

Missing R'_E Discovered after submittal of the paper

Method/Approach

- Improved analytical calc. method for Z_1 (power & higher frequencies) is developed from *first principles*
- Improved analytical calc. method for Z_0 (power frequency) is developed from classic *circuit theory*





R_c, R_s, R_a, R_g - per unit length a.c. electrical resistance of conductor, metallic screen/ sheath, armour, and remote ground return

$X_{c\text{-}eff}$ - effective conductor inductive reactance consisting of conductor internal inductance and conductor-sheath mutual inductive reactance

X_a - sheath-armour mutual inductive reactance,

X_g - armour-remote ground return mutual inductive reactance

R_{e1}, R_{e2} - two sheath grounding resistances at either cable connection end (often neglectable for offshore cables)

Improved Analytical Calculation Method

$$Z_1 = R_1 + jX_1$$

$$R_1 = R_c[1 + \lambda_1' + \lambda_1'' + \lambda_2]$$

$$R_c = LF_{core} \cdot R_{dc}[1 + F_a(y_s + F_{m-shield} \cdot y_p)]$$

$$X_1 = LF_{core} \cdot [\omega L_{c-int} + F_{m-enhance}(\omega L_{cs} + \omega L_{ss})]$$

$$Z_0 = R_0 + jX_0 = R_c + j \cdot X_{c-eff} + \frac{3R_s\left[j \cdot X_a + \frac{R_a(R_g + j \cdot X_g)}{R_a + R_g + j \cdot X_g}\right]}{R_s + 3j \cdot X_a + \frac{3R_a(R_g + j \cdot X_g)}{R_a + R_g + j \cdot X_g}}$$

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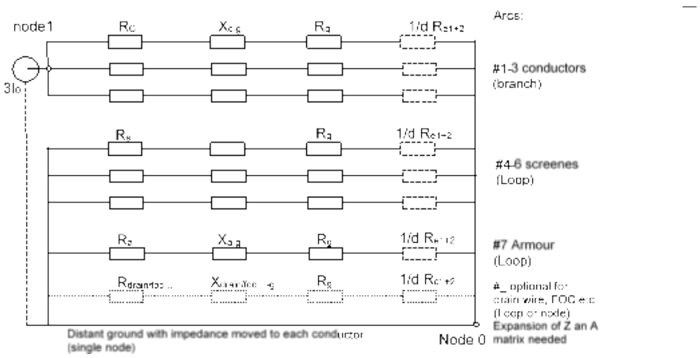
Method Validation & Benchmarking

- 3-core submarine export cable (220 kV 1000mm^2 Cu conductor, SL type and SS armour) from Cigre WG B1.56 work CS8
- Benchmarking against CIM method and FEA method

Circuit topology for creating the incident matrix A for the CIM method



Conductor 1
Conductor 2
Conductor 3
Screen 1
Screen 2
Screen 3
Armour

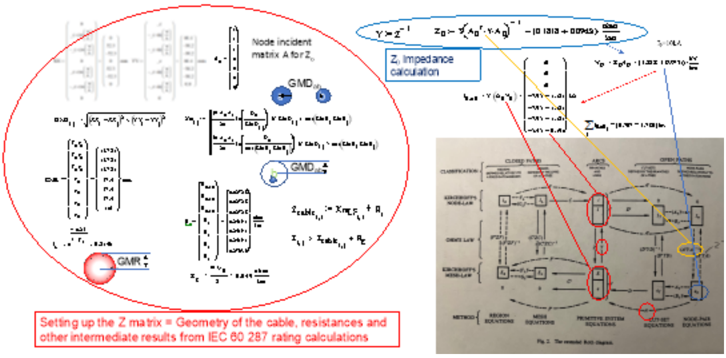
Node 1 to 0

Loops = 0

Node Incident matrix A for Z_0
Uniquely describes the topology of the circuit as an oriented graph

#Columns: #Nodes-1;
#Rows: #Arc's

Complex Matrix method (applying systems structures/incident matrix)



Setting up the Z matrix = Geometry of the cable, resistances and other intermediate results from IEC 60 287 rating calculations

Parameter	Analytical results [Ω/km]	FEA results [Ω/km]	CIM results [Ω/km]	TB531 results[1,3] [Ω/km]	Variation [%]
Z_1	0.0397+0.1193j	0.0390+0.1184j	0.0397+0.1193j	0.0397+0.1193j	
R_1	0.0397	0.0390	0.0397	0.0397	-1.8 / 0 / 0
X_1	0.1193	0.1184	0.1193	0.1193	-0.8 / 0 / 0
[1] TB 531 modified with eddy currents and including effect of y_p and y_s on R_s and y_s on $X(f_c \cdot r_c)$					
Z_0	0.1819+0.0934j	0.1831+0.0954j	0.1818+0.0945j	~~0.1639~~+ 01193j	+17%
R_0	0.1819	0.1831	0.1818[2]	**0.2129** ~~0.1639~~	0.7 / -0.15 / ~~-11~~
X_0	0.0934	0.0954	0.0945[2]	0.1005	2.1 / 1.1 / 7.1

[2] known issue with implementation of Lay Factors on inductances, if $LF_x = LF_{...}$ is used - perfect alignment between Analytical and CIM results.
[3] Adding R_E to Zo in TB531 table gives the expected higher resistance, compared to adding the extra metallic return path of the armour (Check: good corelation if amour resistance is set very high)!

TB 531 Table 10 Single core cables

Single-core cables	POSITIVE-SEQUENCE	ZERO-SEQUENCE
SOLID BONDING	$Z_d = [Z_a - Z_s] - \frac{(Z_m - Z_x)^2}{Z_s - Z_x}$	$Z_0 = Z_a + 2Z_s - (Z_m + 2Z_x)\frac{(Z_m + 2Z_x + 3X_x/2)}{Z_s + 2Z_x + 3X_x/2}$

VS

TB 531 Table 12 Submarine Armoured cables

POSITIVE-SEQUENCE	ZERO-SEQUENCE
$Z_d = [Z_a - Z_s] - \frac{(Z_m - Z_x)^2}{Z_s - Z_x} + R_a \lambda_2$	$Z_0 = R(1 + Y_s) + jX_a + 2Z_s - \frac{(Z_m + 2Z_x)^2}{Z_s + 2Z_x}$

Missing R'_E
In Table 12
-Not mentioned in the paper!

$$Z_{ii} = R'_E + R_{ii} - j.X_{ii}$$

R'_E still included in Z_s Z_m and Z_x

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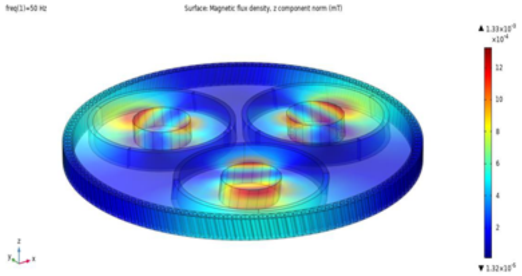
FEA model Based on slightly modified standard model



Higher Frequencies Application

- All existing IEC 60287-1-1 formulae involving frequency components may still be used at higher frequencies by simply updating parameter *f* and ω.
- The sheath magnetic field shielding effect factor, Fm-shield, adopts a similar approach as per IEC 60287-1-1 section 2.4.2.5 and is expected to become stronger as operating frequency increases under Lenz's Law.

Comparison of Z_1 results of high frequencies and at high temperature				
Frequencies	Analytical results	FEA results	R_1 Variation	X_1 Variation
50 Hz	0.0397+0.1193j Ω/km	0.0390+0.1184j Ω/km	-1.8 %	-0.8 %
200 Hz	0.1621+0.3825j Ω/km	0.1390+0.3662j Ω/km	-14.3 %	-4.3 %
500 Hz	0.2785+0.7277j Ω/km	0.2409+0.7157j Ω/km	-13.5 %	-1.6 %
1000 Hz	0.3241+1.2906j Ω/km	0.3141+1.2794j Ω/km	-3.1 %	-0.9 %
2000 Hz	0.3624+2.4549j Ω/km	0.3916+2.3964j Ω/km	8.1 %	-2.4 %
5000 Hz	0.4344+5.9746j Ω/km	0.4838+5.7391j Ω/km	11.4 %	-3.9 %

According to the design experience from an offshore wind developer, a positive sequence impedance value uncertainty of less than 2 % at power frequency and up to up to 15% for harmonics is considered acceptable for system study, compared with a much bigger discrepancy than observed between Cigre TB531 analytical method and some commercial system study packages (e.g. PSCAD). However, the uncertainty on harmonics could be ground for further investigations.

Conclusion & Future Work

- An improved analytical calc. method has been developed for submarine cable sequence impedance calc, with calc. results being benchmarked by both CIM method and FEA method.
- Suggested future works would include,
    a. Results comparison & benchmarking against site sequence impedance measurement(s)
    b. Method improvement & factor quantification considering magnetic armour(s)
    c. Method improvement for parameter calc. at higher frequencies
- Collaborate with Cigre DK, UK and SE national committee to work on calc. standardization through future WG.