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Single Point Bonding of 3-core Submarine Cables

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SUMMARY

For most cable systems the ampacity, or cable rating, is limited by ambient thermal restrictions. In many windfarm export cable systems the thermal bottleneck is found to be the landfall area. This is especially true in cases where the cable is installed using directional drilling techniques, meaning that it is deeply buried inside a PE duct, often surrounded by soil with higher thermal resistivity than the seabed route. Typically, the severe thermal conditions are overcome by using a larger conductor cross section at the landfall. However, in some cases this may result in a very large conductor cross section (>1600 mm^2 Cu). In the worst cases the needed conductor cross section becomes larger than can be readily manufactured in a 3-core cable. In addition, just increasing the conductor size yields diminishing returns the larger the conductors become, due to e.g. increasing lead sheath cross-sectional area (which yields larger induced currents and losses), as well as skin effects in conductors.

This paper describes a low loss cable system adapted for use as a cable landfall system. The principle adopts the operating mode well known from underground/land cable systems comprising a single end bonding/earthing of the metallic screens of the power cores. This means that the circulating currents in the screens are eliminated and hence the metallic sheath losses are diminished. Hence the cable system comprises a system with two different designs;

1) the main section of 3-core submarine cable with semiconductive power core sheaths and;
2) a shorter section (0 – 5 km typically) with insulating power core sheaths.

The two cable sections can be jointed either by means of a factory made joint or a field installed joint. Grounding of only one end of the cable section 2) results in a standing voltage occurring in the open end, thus requiring a secondary insulation system over the metallic sheath which can withstand the standing voltage both in normal operation and in fault situation.

This paper is based on analytical modelling of the cable system where cables with both insulating and semiconductive sheath materials are used in a combined system. The results are presented with numbers and figures to give an overview of the expected magnitude of the currents, voltages and heat dissipations in such cable arrangement. Also, ampacity calculation examples are provided to highlight the increased cable rating or reduction of conductor cross-section for a certain required current transfer. For example, with this principle implemented alone the conductor cross-section can be reduced from 1800 mm^2 to 1200 mm^2. In combination with low loss (a-magnetic) armour material the conductor cross-section can be even further reduced.

Many of the input parameters have been obtained by laboratory experiments in small scale environments in addition to measurements conducted on full-scale 3-core cables. The aim of the work has been to demonstrate the single-point bonding of a defined section of the submarine cables as a viable and robust alternative for arrangement of cables in severe thermal conditions.

KEYWORDS

Wind farm cable connections, cable landfalls, single point bonding, cable rating, thermal rating bottleneck, 3-core Submarine Cables

1. INTRODUCTION

This paper describes the development of a low loss 3-core HVAC submarine cable system which is especially suited to application at the landfall of windfarm projects. The landfall zone is a common thermal rating bottleneck along an export cable route. This can be due to several factors:

- Deep burial: where it is necessary to route the cable beneath sea defences, cliffs or other similar obstacles, it is common to install the cable using the directional drilling technique. This can result in burial depths in excess of ten metres, in comparison to typical burial depths along the offshore route of 1.5 – 3m.
- Higher thermal resistivity: as the cable transitions through the landfall, it moves from being buried in fully saturated marine sediments to partially saturated soils onshore. The thermal resistivity of the onshore soils can be significantly higher than those found offshore.
- Ambient temperature: depending on the location of the cable route, the ambient temperature of the soil onshore may also be higher than that seen offshore.

All of these factors together cause a decrease in the current-carrying-capacity of the cable system. Table 1 shows a comparison of typical ambient conditions for the landfall part and the offshore part of an export cable route

Table 1: Comparison example of thermal conditions, typical values

Parameter	Landfall	Offshore
Burial depth	10 - 15 m	1-3 m
Soil thermal resistivity	0.8 - 1.2 K.m/W	0.4 - 0.7 K.m/W
Average ambient temperature	15 - 25°C	5 -15 °C

In addition, there are other factors that will influence the thermal resistance from cable surface to ambient (T4) like duct material, duct intermedia filling, etc.

For a typical HVAC submarine cable design, the implication of Table 1 above is that increased losses dissipated by the cable in the landfall will produce more heat in steady-state conditions. This can result in the use of larger conductor sizes at landfalls, however as wind farms continue to grow larger this requires 3-core cables with conductor sizes significantly larger than 1600mm^2 Cu. In the worst cases, this requires larger conductor sizes than can be readily manufactured for 3-core cables. Given that it is not possible to change the thermal environment in which the cable is placed, this paper investigates an alternative method which instead seeks to reduce the losses in the landfall section.

2. SYSTEM DESCRIPTION

The principle proposed adopts the single point bonded method well known from underground/land cable systems, where only one end of the metallic screens of the power cores is grounded. The metal screen at the other end is left ungrounded, resulting in a standing voltage along the metal screen which is at a maximum at the open circuit end. This bonding option means that the circulating currents in the screens are eliminated and hence the metallic sheath losses are diminished. As these losses generally represent about 20 - 25 % of the total losses in a 3-core HVAC submarine cable, this can give a substantial increase in the permissible current rating. A small charging current will flow towards the main cable section, where it will be drained through a local earth bond and/or the semi-conducting sheaths of the main offshore cable.

The cable system comprises a system with two different designs; the main section of 3-core submarine cable with semi-conductive power core sheaths and a shorter section (0 – 5 km) with insulating power core sheaths. The two cable sections can be jointed either by means of a factory made joint or a field installed joint. Typically, the landfall section will be limited due to practical reasons for pull-in forces etc., however this is specific to the route chosen. See Figure 1 for a schematic overview.

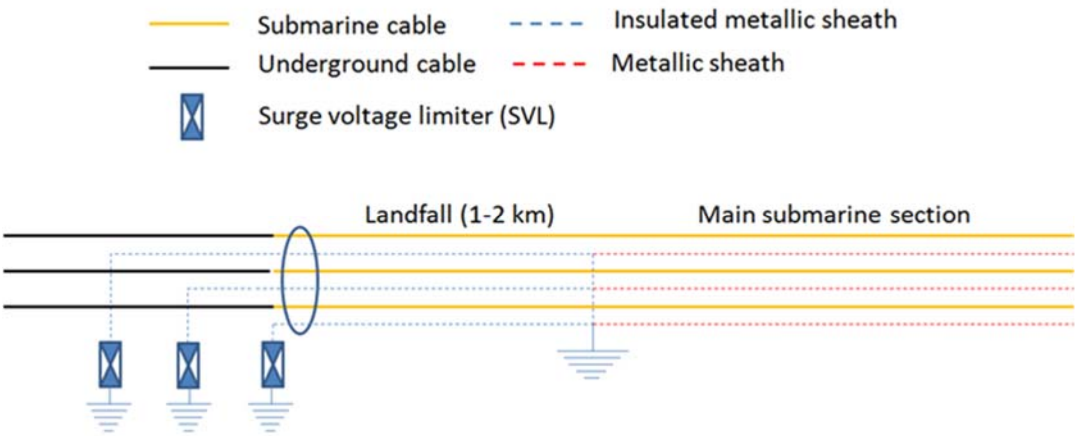

Figure 1 : Schematic lay-out of single point bonding

Impact on sheath voltage profile

Grounding of only one end of the metallic screen of the landfall section results in a standing voltage occurring in the open end, thus requiring a secondary insulation system over the metallic screen which can withstand the standing voltage both in normal operation and in fault situation. The magnitude of the standing voltage will be dependent on the length of the single-bonded section and the current of the conductor in normal operation and in faults. Normally a PE oversheath can handle a standing voltage of several kV/mm so the thickness of the secondary insulation system must be designed according to the above evaluations. Hence the length of the single-point-bonded section will be limited within a range that gives controllable voltages at the open circuit ends, as determined by an insulation coordination assessment.

Transient Over Voltages (TOV) can be handled by utilising surge voltage limiters (SVLs) in the open circuit end. The insulation coordination study will reveal whether SVLs are strictly necessary or not, however they are generally recommended in order to protect the electrical integrity of the PE oversheath where single point bonding schemes as deployed. The selection of SVLs should follow common practice for cable arrangements with TOV protected secondary insulation systems, as described in detail in CIGRE TB 797 “Sheath bonding systems of AC cables” [1].

For normal operation as well as in 3-phase short-circuit (symmetrical situation), the standing voltage can be calculated by use of standard equations found in published guidelines as in [2] and [3].
For a single phase earth fault (or non-symmetric situation) the conditions are more complex in terms of the distribution of the return current, and the system must instead be analysed by the complex impedance matrix method.

Also, analysing the transition zone between the grounded and insulating parts, a zone stretching from the joint point out to a few hundred meters on the submarine section, will require comprehensive model utilising the fully-coupled multiconductor telegrapher’s equations, taking into account current exchange between metallic elements through semi-conductive contact.

The transition zone must have the capability of interchanging the induced sheath currents between the metallic sheaths via the semi-conductive PE jackets, before entering the insulated cable section. The magnitude of these currents will be around 20 % of the conductor currents for cables with magnetic steel armouring, as can be seen from the empirical formulas from [4].

$$\lambda_1' = \frac{R_s}{R}\frac{1.5}{1+\left(\frac{R_s}{X}\right)^2} \tag{1}$$

Re-arranging this formula yields a factor to which the conductor current can be multiplied to obtain the sheath current:

$$F = \sqrt{\frac{1.5}{1 + \left(\frac{R_s}{X}\right)^2}} \quad (2)$$

For most 3-core armoured cables with lead sheath the relationship between the sheath resistance (Rs) and the sheath reactance (X) gives the factor (F) a value of around 0.2 This has also been verified with measurements on live cable systems, see [5]. For cables with non-magnetic armour the factor 1.5 in the numerator reduces to 1, as the use of non-magnetic armour does not lead to an enhanced magnetic field inside the cable.

3. MODELLING APPROACH

In order to investigate the voltage profile seen on the cable during both normal operation and faults, a series of numerical models have been built. This section provides a brief description of the relevant theory, along with references to which the interested reader can refer for more information.

Normal operation and Symmetrical fault

In the regime of normal 3-phase operation and in the event of a symmetrical 3-phase fault the standing voltage in the open metallic screen of a non-magnetically armoured cable can be found by the empirical formulae found in [2], section 3.1 utilising the formulas for trefoil formation;

$$\mathrm{E} = \mathrm{j} \cdot \omega \cdot \mathrm{I} \cdot 2 \cdot 10^{-7} \ln \frac{2S}{d} \quad (3)$$

where

E: Emf per unit length
d: Geometric mean diameter of lead sheath
I: Current in the conductor, either normal or during 3-phase fault
S: Axial spacing of phases (diameter of one phase)

For these balanced scenarios, no current will flow in the armour or ground. For a cable with magnetic amour, an increase in emf with a factor of 1.5 would apply, in line with what is suggested in formula (2).

Complex Impedance Matrix

To analyze the currents and voltages in the transition zone and the influence of a single phase to ground fault a complex impedance matrix is established. For power frequency applications the voltages, currents and impedances are represented by complex numbers to express their magnitude and phase angle. The currents and voltages in this system, consisting of parallel conductors, are represented in a complex matrix form and are modelled accurately by the multiconductor telegrapher's equations;

$$-\frac{d\boldsymbol{V}(x)}{dx} = \boldsymbol{ZI}(x) \quad (4)$$

$$-\frac{d\boldsymbol{I}(x)}{dx} = \boldsymbol{YV}(x) \quad (5)$$

where, for a power cable with n metallic conductors

x: Position along cable [km]
$\boldsymbol{V}(x)$: Vector containing voltages V_i at position x for each conductor i, i.e. $\boldsymbol{V}(x) = (V_1, V_2 \ldots, V_n)^t$ [V]
$\boldsymbol{I}(x)$: Vector containing currents I_i at position x for each conductor i, i.e. $\boldsymbol{I}(x) = (I_1, I_2 \ldots, I_n)^t$ [A]
$\boldsymbol{Z}$: Frequency dependent per unit length impedance matrix of dimensions n x n [Ω/km]
$\boldsymbol{Y}$: Frequency dependent per unit length admittance matrix of dimensions n x n [S/km]

A circuit representation of the cable system is shown in Figure 2. The per-unit-length resistances R_i and inductances L_i and M_{ij} as well as the per-unit-length capacitances C_{ph} are present for the entire cable system length. The conductances G_{ph} and G_t are only non-zero for the submarine sections, where semi-conductive sheaths are used.

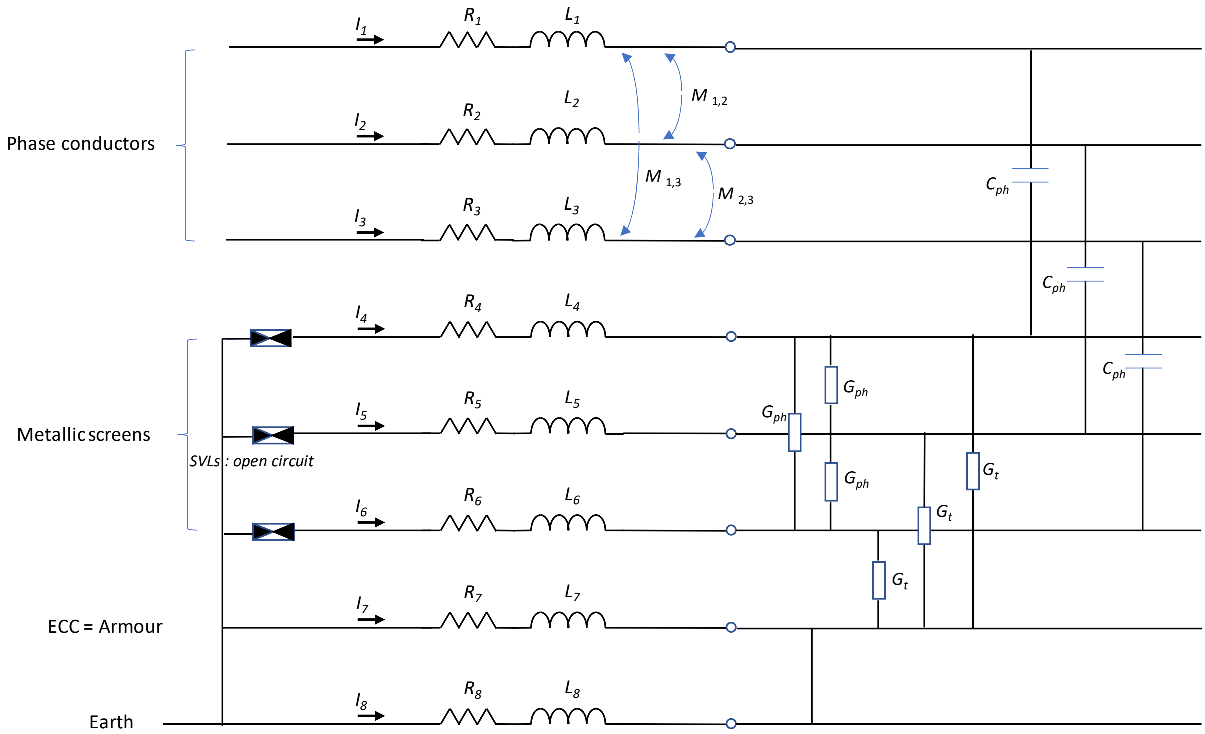

Figure 2 : Lay-out of impedance matrix relations

The different elements in Figure 2 represents

R_1......R_8:	Line resistance, per length unit
L_1......L_8:	Self-inductance, per length unit
$M_{i,j}$....$M_{j,i}$:	Mutual inductance between elements (i :1...8, j: 1...8) , per length unit [1]
G_{ph}:	Phase to phase conductance (metallic sheath-to metallic sheath), per length unit
G_t:	Conductance from metallic sheath-to-earth, per length unit
C_{ph}	Capacitance between conductor and screen, per length unit

The armour will act as an ECC and is deemed earthed along its entire length. In the case of the single phase fault, the modelling described in previous sections is utilized, but with the following boundary conditions:

(a) $I_4 = I_5 = I_6 = 0$ (at landfall termination, no currents in metallic sheaths; open SVLs)
(b) $I_1 + I_7 + I_8 = 0$ (Kirchhoff's current law; return path is armour and earth)
(c) $I_1 = I_{fault}$ (fault current injected in phase 1)
(d) $V_7 = V_8 = 0$ (armour is grounded along entire length)

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[1] For simplicity, in the figures only the mutual inductances between main conductors are shown. There will be mutual relationships between all conducting elements.

4. ANALYSIS

This section presents a brief overview of results obtained from the analysis for the cases of symmetrical and non-symmetrical faults. The cable system modelled is a Um/Un = 300/275 kV XLPE insulated cable with 1800mm^2 copper conductor, lead sheaths and double-wire armour. The length of the landfall section is assumed to be 5km.

Normal Operation

Assuming a maximum current of 1100A in normal operation, the sheath voltage profile obtained is shown in Figure 3.

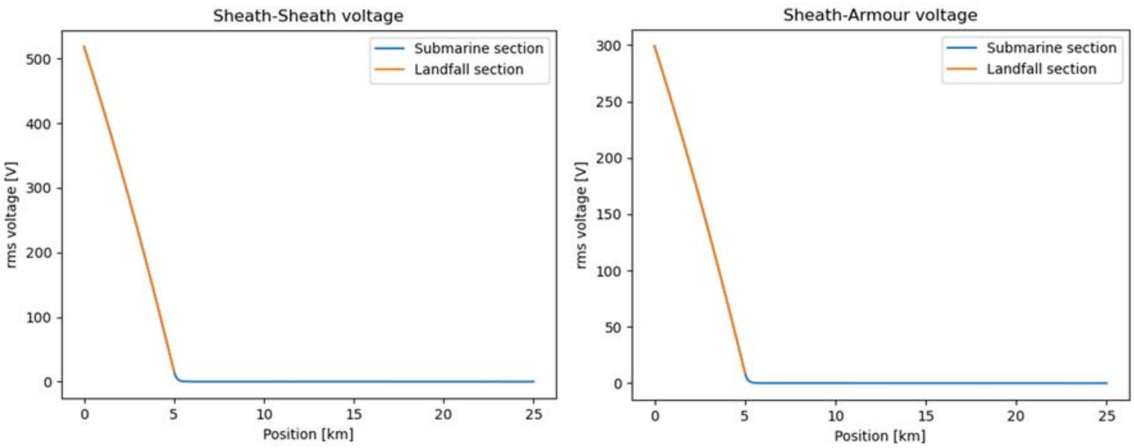

Figure 3 – Sheath-to-sheath and sheath-to-armour voltages in normal operation

Three phase fault (symmetrical fault)

The three-phase short-circuit is characterized by a steady-state short-circuit current of 25 kA rms. As the fault is balanced, the voltage magnitudes will be the same on all phases. It can be seen in Figure 4 that even for a 5km length, the worst-case sheath voltage is just below 6kV, which is well below the performance limit of a typical PE sheath.

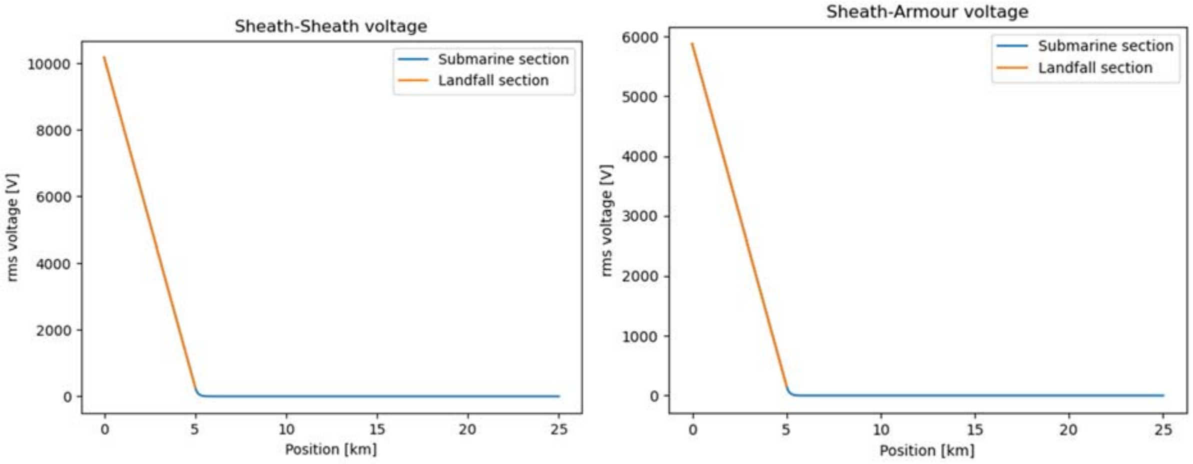

Figure 4 – Sheath-to-sheath and sheath-to-armour voltages for 25kA 3 phase fault

Single phase fault (non-symmetrical fault)

The single phase short-circuit is characterized by a steady-state short-circuit current of 13 kA rms. The other two core conductors are assumed to carry no current during the fault. Single core cable systems would typically have a separate earth continuity conductor; in this case such a function is provided by the armour. An earth impedance of 1.5Ω is assumed; higher impedances result in higher standing voltage.

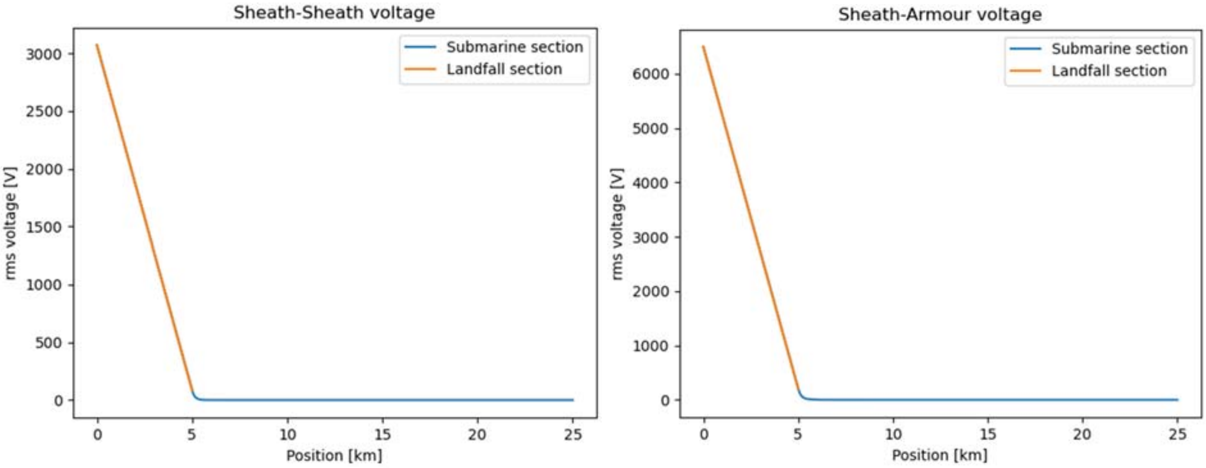

Figure 5 – Sheath-to-sheath and sheath-to-armour voltages for 13kA 1 phase fault

As can be seen from Figure 5, the sheath-to-armour voltage reaches approximately 6.5kV in the faulted phase. The sheath-to-sheath voltages are lower, the reason for this being that the fault current on the faulted phase induces voltages on all three sheaths which are in phase with each other. The magnitudes of the voltages on the two healthy phases are lower due to the lower mutual inductance between these sheaths and the conductor of the faulted phase. Again, the voltages are shown to be manageable provided that careful consideration is given to the design of the insulated sheath and the overall insulation coordination.

Ampacity Calculations

For a typical HDD installation scheme, the ampacity will increase by approx. 15 % when implementing the single point bonding concept described in this paper. On the other hand, the increased rating can be utilized to reduce the conductor cross-section if that is desirable; the single end bonded equivalent to the 1800 mm^2 two-side bonded cable suggests a cross-section closer to 1000 mm^2. Table 2 below displays rating values for a typical landfall installation (HDD). The example cable design used for comparison is a 3-core submarine cable with Um/Un = 300/275 kV, double-armoured with XLPE insulation system, copper conductor and lead sheath.

Table 2 : Cable rating values for typical landfall installation

Cable Design	Installation method	Burial depth	Conduit fill	Rating 2p bonding	Rating 1p bonding
300/275 kV 3x1x1800 mm^2	HDD duct, buried	15 m (center duct)	water	835 A	955 A
300/275 kV 3x1x1800 mm^2	HDD duct, buried	4 m (center duct)	air	880 A	1005 A
300/275 kV 3x1x1200 mm^2	HDD duct, buried	15 m (center duct)	water	-	862 A
300/275 kV 3x1x1000 mm^2	HDD duct, buried	15 m (center duct)	water	-	826 A

(For all cases in **Table 2***: Ambient temp = 15 °C, Thermal resistivity soil = 0.85 K.m/W, duct material = PE (3.5 K.m/W), duct dimensions (OD/ID =800/655 mm)*

Cable rating values assume continuous rating, which is known to be conservative in the case of a wind farm but provides an easily understood comparison in this case. A cable system installed at the deepest burial depth will have thermal time constant of several years and might not be dictating the thermal bottleneck. On the other hand, the air-filled part of the HDD (if not grout filled) will have a much more rapid thermal response so it could very well be the bottleneck for the system. These factors must be considered in a detailed thermal rating assessment with site specific conditions.

Conductance Measurement
Measurements were performed to obtain the conductance between the metallic layers of the cable system (to be used in the modelling and analyses). It is considered essential to take physical measurements, as the conductance will depend not only on the material properties, but also on the degree of contact between the laid-up cores, with further contributions made by the water inside the cable's cavities. These measurements were completed both on a short section of cable immersed in water (Figure 6 left) and on a longer section of cable immersed in water (Figure 6 right). In both test set-ups, one cable end is protruding out of the seawater, to which a voltage source and measuring probes can be connected. The submerged end of each sample was blocked to prevent direct connection between lead sheaths through the water (i.e. all current must travel through the semiconducting sheath). Both experiments were performed with cable submerged in water at a salinity level of 3.5 %.

The conductance between a pair of metallic elements inside the cable (e.g. two lead sheaths) was found by applying a known voltage between the pair and measuring the current drawn. By looping over all metallic element pairs and measuring applied voltage and drawn current, the conductance matrix can be constructed.

It was found that the sheath-to-sheath conductance is approx. 30 S/km, whilst the screen-to-armour conductance is approx. 50 S/km.

Figure 6 - Conductance Measurements on a 3-phase cable

5. CONCLUSION

This paper has presented an alternative cable system design which can be valuable in overcoming thermal limitations at the landfalls of wind farm export cable routes. By reconfiguring the landfall section of the cable with insulating PE sheaths to enable operation with single point bonding, the cable losses are significantly reduced. This can avoid the need for using extremely large conductor sizes for this part of the route and can be highly valuable in de-risking deep cable installations through areas of relatively high thermal resistivity soil. The analysis presented has shown that the standing voltages on the metal sheaths are manageable, subject to a full insulation coordination study being carried out.

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