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Effect of semi-conducting jackets on the performance of three-core armoured power cables

Andreas I. CHRYSOCHOS*
Hellenic Cables
Greece
anchryso@gmail.com

Dimitrios CHATZIPETROS
Hellenic Cables
Greece
dchatzipetros@hellenic-cables.com

Dimitrios N. KOSSYVAKIS
Hellenic Cables
Greece
dkossyvakis@hellenic-cables.com

Vasilios L. KANAS
Hellenic Cables
Greece
vkanas@hellenic-cables.com

Konstantinos PAVLOU
Hellenic Cables
Greece
kpavlou@hellenic-cables.com

Konstantinos TASTAVRIDIS
Hellenic Cables
Greece
ktastavridis@hellenic-cables.com

George GEORGALLIS
Hellenic Cables
Greece
ggeorgal@hellenic-cables.com

SUMMARY

Three-core armoured power cables are increasingly being used to interconnect the offshore wind farms, which have been rapidly expanding during the last decades, with the main grid. The power cores of these subsea cables, broadly known as export cables, typically have an extruded protective jacket over each core consisting of polymeric material, which must in principle be semi-conducting. The major aim this design has is to provide a common equipotential node, preventing the cable from potential damage caused by steady-state or transient overvoltages. Although these semi-conducting, jacketing materials have been used in subsea power cables for years, very few works with regard to their actual operation have been published. This paper focuses on the various aspects involved with the effect of the semi-conducting jackets on the cable thermoelectrical performance. Both capacitive and inductive coupling mechanisms are separately considered and the derived findings are attempted to be interpreted on a physical basis. The jacket conductivity appears to be the key parameter, affecting the cable performance at both steady-state and short-circuit conditions. A more realistic subsea link, consisting of cable sections of various design parameters with regard to cable impedance, is also studied. Guidance for design optimisation and special care, particularly for installation conditions strongly variable along the subsea route, is given.

KEYWORDS

Capacitive Coupling - Current Rating - EMT Software - Inductive Coupling - Offshore Wind Farm - Semi-Conducting Jacket - Submarine Cable

1. INTRODUCTION

The majority of modern submarine export cables connecting the offshore wind farms with the main grid are designed as high-voltage, three-core, armoured cables with cross-linked polyethylene (XLPE) insulation. Many different design alternatives and constructive layers are used for this type of submarine cables, depending on the conditions and requirements of each project. Among them, the polymeric cable jackets (oversheaths) have the main role of protecting the underlying lead sheaths from corrosion and abrasion.

In the majority of submarine export cables, these polymeric sheaths are made from semi-conducting polyethylene (PE) materials filled with carbon-black. The additional benefits of this material, compared to the insulating PE, are the following: Firstly, it provides voltage equalisation between the metallic sheaths and the armour, which is crucial to avoid dielectric breakdown during cable system transients [1], [2]; secondly, it cancels out the capacitive currents of the three phases in the metallic sheaths under balanced conditions, thus increasing the overall cable current carrying capacity especially in long submarine cables of higher voltage levels [1]; thirdly, it permits the sharing of the short-circuit current between the three metallic sheaths and possibly the armour, thus reducing the minimum cross-section area required for the flow of short-circuit currents without exceeding the maximum permissible temperature [2].

Although the use of semi-conducting jackets is extensive in cable industry, there are only few published works that examine their effect on the cable electrical performance. In [3], the influence of a conductive connection between cable sheaths is investigated using three-dimensional (3D) Finite Element Method (FEM) simulations. It is concluded that, due to these connections, circulating currents in cable metallic sheaths can occur even in unbonded configurations, resulting in sheath losses that are comparable to solid bonding. In [4], the effect of semi-conducting jackets is discussed with respect to loss measurements in cables with single-point bonding configuration. It is stated that the conductive jacket covering the sheaths enables circulating currents, although further investigation is needed.

This paper aims to give further insight into the effect of semi-conducting jackets on the performance of three-core armoured power cables. For this purpose, ElectroMagnetic Transient (EMT) software [5] is employed with the cable model being properly adjusted to represent a real three-core, submarine export cable with armour wires. The conductive connections due to semi-conducting jackets have been measured and modelled via equivalent per-unit-length shunt resistances. The cable model is subject to both capacitive and inductive coupling mechanisms, as already stated in [6]. The effect of each mechanism is separately considered and the results extracted are interpreted on the basis of the respective physics involved. Solid and single-point bonding configurations are examined, assuming both steady-state balanced and short-circuit non-balanced conditions. Current profiles along the cable are presented and evaluated, by varying the shunt resistances from insulating to more conducting levels. The effect of jacket material is assessed by evaluating the currents on the metallic sheaths.

Submarine export cables, used to interconnect offshore wind farms with the main grid, often extend to quite large distances in the order of tens of kilometres, where the interconnecting cable may encounter different ambient conditions. For this reason, assuming that the entire subsea link consists of a single cable design over the whole route is rather unrealistic, since such an assumption does not allow for design optimisation and cost saving. In practice, cables of various designs are often part of the same subsea link. These various designs may include different conductor sizes, which are connected by asymmetrical factory joints, and/or different armour materials, such as mild and stainless steel. For this reason, the in-series connection of two different cables is also examined in the context of the present paper, focusing on the transition zone formed between the two different cable designs meeting one another. Finally, a sensitivity analysis is performed by varying the equivalent shunt resistances of the semi-conducting jackets, simulating profile fillers under both water- and air-filled conditions. Useful guidance with regard to the overall effect of jacket material is provided, such that the electrical and thermal performance of the cable is improved.

2. MODELLING OF THREE-CORE ARMOURED CABLES IN EMT SOFTWARE

EMT software is a common but yet powerful tool for studies in power systems under steady-state or transient conditions [5]. The proper modelling of cable systems in such software requires the ability to calculate the cable per-unit-length parameters with adequate accuracy taking into account the cable geometry and material properties, while also considering the frequency-dependent effects resulting from eddy currents in all conductors and potential hysteresis phenomena in ferromagnetic elements. Existing routines in most EMT software consider systems of parallel, solid or hollow round conductors, whereas the analytical expressions used take into account only skin effect, ignoring any proximity or hysteresis effects [7]. In addition, some of the cable parts, such as screen and armour wires, are in reality twisted for reasons related to manufacturing and mechanical properties. The resulting twisting effects, which actually stem from and involve the 3D geometry, cannot effectively be simulated by the default cable models included in the majority of EMT available software.

The accurate modelling of three-core twisted armoured power cables can be performed with 3D finite element method (FEM). In this paper, the so-called short-twisted (ST) 3D periodic model is employed [8], [9], which is considered as the state-of-the-art in the modelling of such power cables. It has been proven that the ST periodicity captures the full electromagnetic behaviour of the cable in just a small slice of the cable, dramatically reducing the required model length to be simulated. In addition, due to the sophisticated rotated boundary conditions used, the ST 3D FEM is free of any end effects and can be considered as the most reliable, efficient and accurate model in the simulation of three-core twisted armoured power cables. Within this context, the per-unit-length series impedance matrix $\boldsymbol{Z}$ is calculated by employing the so-called J_S method [6], [10]. The aim is to obtain the cable impedance, taking accurately into account the fields induced by the helical conductor paths in the cable as well as any skin, proximity and field-dependent hysteresis effects. In addition, the per-unit-length shunt admittance matrix $\boldsymbol{Y}$ is also derived by employing the so-called energy method [6], [10].

Once calculated, the per-unit-length parameters are inserted in appropriate cable models in EMT software [11], which permit efficient time- or frequency-domain simulations. Focusing on cables under steady-state conditions, the telegrapher's equations in frequency-domain can be solved by employing multiple cascaded PI equivalents, which have been proven to be very accurate and stable under power frequency conditions [6]. This technique allows for the derivation of current and voltage profiles with respect to cable length while the different bonding types can be also implemented by proper circuit elements and connections. The conductive connections between cable metallic sheaths due to semi-conducting jackets have been first measured and then modelled via equivalent per-unit-length shunt (transversal) resistances [12], [13]. These are included in each PI equivalent to simulate their distributed effect along the cable length.

3. NUMERICAL RESULTS

A 3x2500 mm^2 aluminum export cable of nominal voltage 127/220 kV is considered. The cable has lead sheaths and is set in contralay configuration while its armour wires are made of either magnetic (low grade, mild) or non-magnetic (austenitic grade, stainless) steel. The per-unit-length parameters are first calculated by employing the J_S and energy methods on a ST 3D FEM, which simulates the cable with high accuracy. Next, the extracted matrices $\boldsymbol{Z}$ and $\boldsymbol{Y}$ are inserted in a series of cascaded PI equivalents in EMT software. The electric contact between the cable lead sheaths has been measured, exceeding the value of $5\,S/km$ in terms of the per-unit-length conductance G for the case of semi-conducting jackets. A total cable length of 20 km is simulated with a large number of PI sections to achieve a high spatial resolution.

3.1 Capacitive coupling

Since the telegrapher's equations are in principle mutually coupled, attention must be paid to proper, separate modelling of capacitive and inductive coupling. For the former, ideal voltage sources at nominal voltage are employed at both cable ends in EMT software with the resulting charging current flowing through the shunt admittance branch ***Y*** of the PI equivalent [6]. Assuming a solid bonding configuration, Figure 1 presents the current profile in the sheath of core *a*, when both insulating and semi-conducting jackets are considered. The remaining phases not shown in figure follow the same pattern.

In the case of insulating jacket, the charging current of each phase returns solely through the corresponding sheath [6], as expected. In the scenario of semi-conducting jacket, the charging currents in the three sheaths seem to be mutually canceled to a fairly high extent at first glance: Indeed, the maximum current being accumulated at the cable end in the semi-conducting jacket case is much lower than in the insulating case. However, a noticeable current, about 18 A, still appears to flow in sheaths, thus implying that another mechanism, besides capacitive coupling, comes at play. The authors believe that the charging current flowing through the conductor causes, via electromagnetic induction, an induced current which flows through the corresponding sheath. The magnitude of this current varies along the cable length and cannot be canceled by the semi-conducting jacket, since it is originated by the inductive coupling of the cable. The interpretation given for the origin of this current is further justified by noticing its phase angle, which differs from $\pm 90°$, which is the case for the insulating jacket.

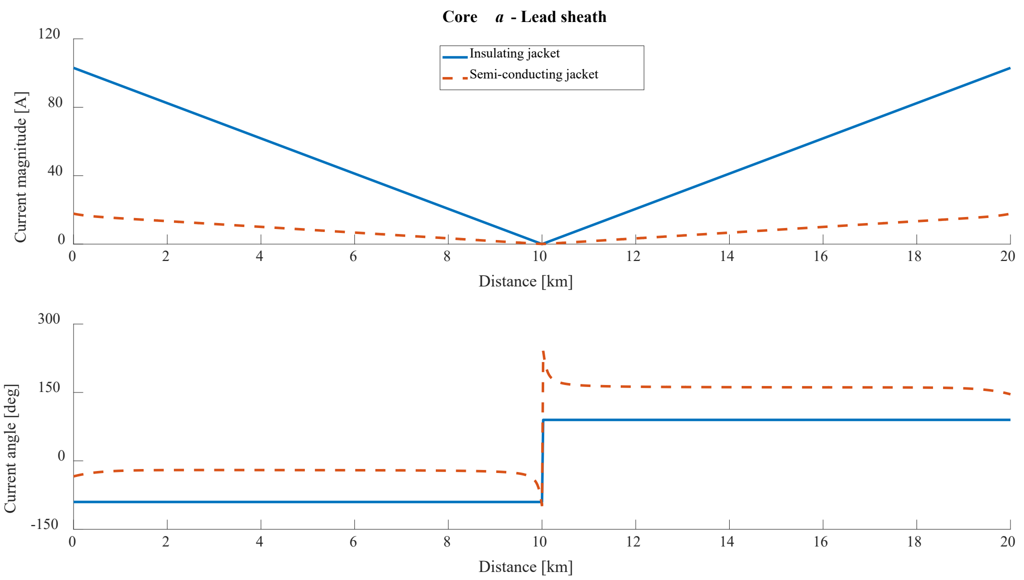

Figure 1: Cable in solid bonding. Current profile in lead sheath of core a under capacitive coupling.

Similar conclusions can be drawn assuming a single-point configuration, where the results are presented in Figure 2. The case of insulating jacket yields the typical pattern of charging current, which is gradually accumulated to the bonded cable end [6]. On the other hand, the current profile in the scenario of semi-conducting jacket is almost identical to the corresponding in the solid bonding configuration of Figure 1. The only difference is observed in the vicinity of the open end, where the magnitude of current decreases due to the progressively lower shunt conductance along the cable at this end. The above remarks further enhance the interpretation given also for solid bonding configuration, i.e., that besides the purely capacitive nature of sheath current, the charging current flowing in conductor has also an inductive effect on the current flowing in sheath, which cannot be nulled regardless of how much conductive the jacket material is.

It should be noted that the thermal contribution this charging current has on current rating has not been extensively discussed in the existing rating methods, although some reference is made also in [12]. Indeed, irrespective of its origin and nature, the capacitive current expected to flow in the metallic sheaths of the so-called 'SL-type, wire armoured' cables is not at all considered by the IEC 60287 standard method [14]. Although a rather short length with reference to export cables is examined in the present section, a total charging current equal to about 103 A seems to be accumulated in the sheaths of cable ends for insulating jackets and solid bonding, thus making the selection of jacket material, in conductivity terms, a rather crucial decision. Contrary to export cables, cables interconnecting the offshore wind turbines one another or, in other words, the so-called ‘inter-array’ cables typically consist of insulating jackets. In this latter case the jacket material does not allow to mitigate the generated charging current as much as in export cables, thus making the existing IEC standard current rating method rather questionable.

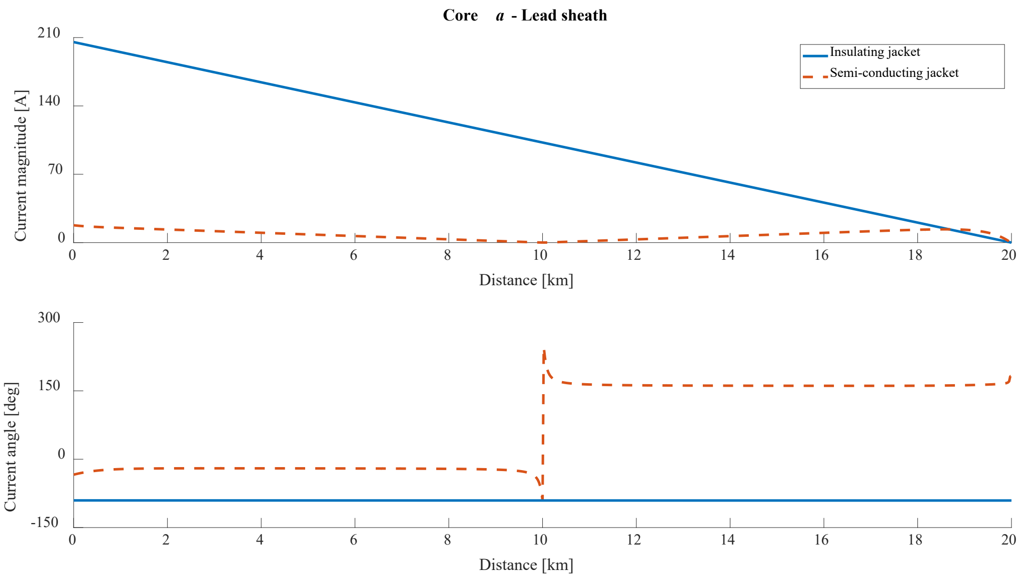

Figure 2: Cable in single-point bonding. Current profile in lead sheath of core a under capacitive coupling.

3.2 Inductive coupling

3.2.1 Steady-state conditions

For the inductive coupling, ideal current sources are used to inject a three-phase balanced current of 1 kA (rms) through the series impedance branch $\boldsymbol{Z}$ [6]. Figure 3 shows the current profile in sheath of core *a* for both insulating and semi-conducting jackets when the armour consists of mild or stainless steel wires. As expected, the magnetic permeability of the armour wires significantly affects the circulating currents on sheaths. The change from stainless to mild steel leads to an increase in the magnetic flux in the cable interior, which subsequently results in higher circulating currents and losses in the metallic sheaths [4]. Results also show that, apart from some minor differences in the current angle, the semi-conducting jacket does not affect the induced current flowing through sheath. This is justified by the fact that the related EMF is generated longitudinally along the metallic sheath [6], [8], thus not influenced by the radial conductivity of the jacket. Although semi-conducting jackets may be of relatively high longitudinal conductivity compared to cable insulating materials, this still remains several orders of magnitude lower than that of cable metallic components. Hence, the current induced in sheaths selects the conductive path offered by the metallic component.

The influence of bonding configuration is presented in Figure 4 for the cable with stainless steel. As shown before, in the case of solid bonding, the insulating and semi-conducting jacket yield the same current. In the scenario of single-point bonding, the insulating jacket exhibits negligible circulating current, as expected. On the other hand, the semi-conducting jacket results in an induced current almost identical to the case of solid bonding. Its magnitude decreases only in the vicinity of the open end, due to the progressively lower shunt conductance along the cable at this end. This behaviour, which has been also reported in [3], [4] for the case of single-point bonding, makes the distribution of measured cable losses in metallic sheaths difficult.

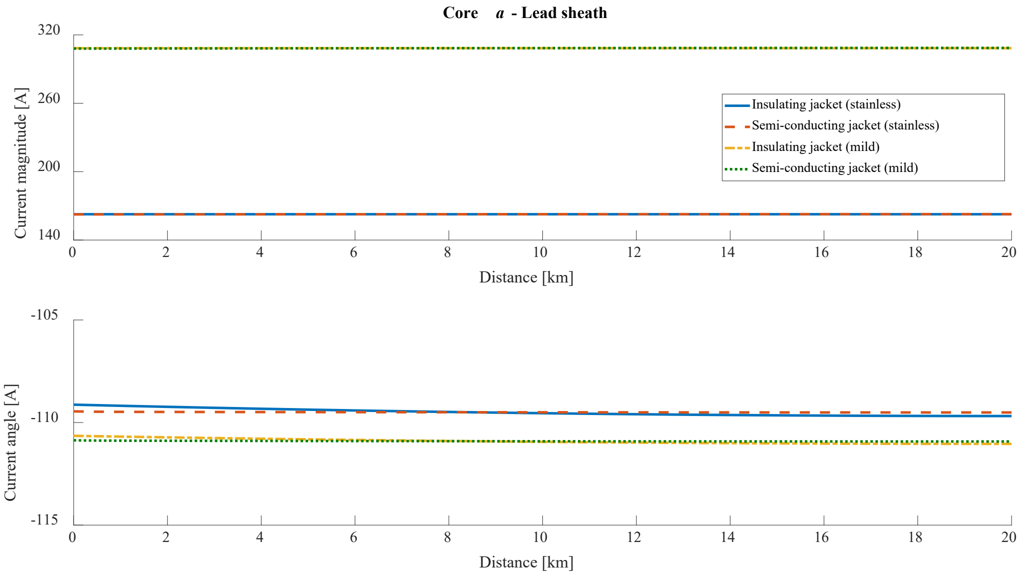

Figure 3: Cable in solid bonding. Current profile in lead sheath of core a under inductive coupling. Cable armour consisting of mild or stainless steel wires.

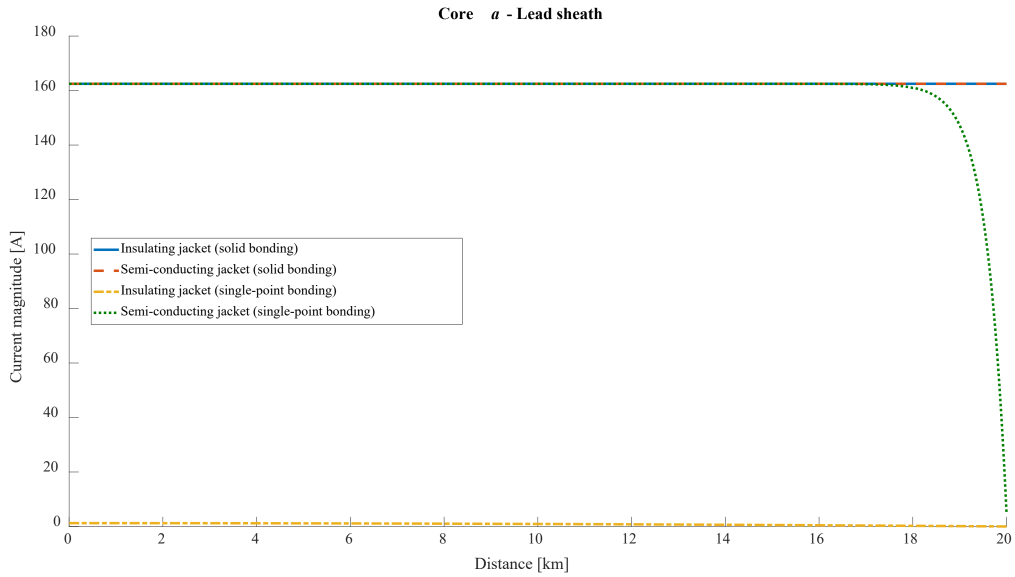

Figure 4: Cable in solid and single-point bonding. Current profile in lead sheath of core a under inductive coupling.

3.2.2 Phase-to-ground short-circuit

In the scenario of an internal fault, the presence of semi-conducting jackets is rather important, since they permit the sharing of the short-circuit current between the three metallic sheaths [2]. Figure 5 shows the current profiles in sheaths and armour for an internal fault at the middle of the cable, considering both insulating and semi-conducting jackets. The fault is assumed to happen on phase *a* and is fed from the feeder at the left side with a current of 10 kA rms. In the insulating case, the fault current returns mainly through sheath *a*, taking also into account the bonding of all sheaths and armour at both ends. In the case of semi-conducting jacket, there is a progressive transfer of the fault current from sheath *a* to the adjacent two sheaths as moving away from the fault location. Contrary to the insulating jacket, this sharing of the short-circuit current can be subsequently exploited to reduce the minimum cross-section area required for the flow of short-circuit currents without exceeding the maximum permissible temperature [2]. In the semi-conducting case, only few hundreds of meters, close to the vicinity of fault, remain affected in terms of peak current, though to a lesser extent, compared to the insulating jacket case.

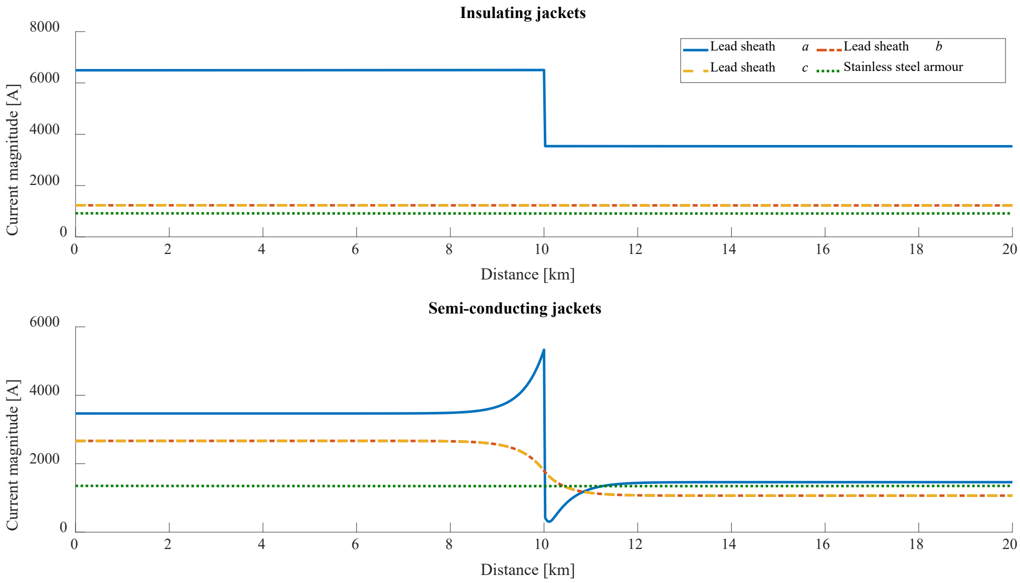

Figure 5: Cable under single-phase internal fault. Current profile in lead sheaths and armour.

The armour bedding is assumed to be fully insulating in the case considered in this section. It is possible in certain export cable designs that, besides jackets, also the armour bedding may be made of semi-conducting material. In such a case the return of the short-circuit current would be shared not only between sheaths, but also between the metallic sheaths and the armour, thus allowing for further reduction of the sheath cross-section area required to carry securely the short-circuit current.

3.2.3 Connection of different cables

In a cable link, the in-series connection of different cables is often the optimum solution mainly due to the change of installation ambient conditions along the route. Cables of various designs are often part of the same subsea link, which typically include different conductor sizes connected by asymmetrical factory joints and/or different armour materials, such as mild and stainless steel. As an indicative example, the connection of two cables consisting of different armour steel material is examined, where the cable lengths are 15 km and 5 km, respectively. Figure 6 presents the current profile in sheath of core *a* for both insulating and semi-conducting jackets.

In the scenario with insulating jacket, the induced current in lead sheath is unique. Its value can be adequately approximated by the weighted average of the circulating currents observed when the whole link consists of only one cable each time. With weights being the corresponding lengths, it holds that:

$$I = \frac{\ell_1 I_1 + \ell_2 I_2}{\ell_1 + \ell_2} = \frac{15 \cdot 308.4 + 5 \cdot 162.7}{15 + 5} \cong 272\ A \qquad (1)$$

which is very close to the real value of 272.9 A. For a higher precision, the impedances instead of the corresponding lengths should be used in the above calculation.

In the case with semi-conducting jacket and at regions away from the transition point, each cable exhibits its own induced current, which is equal to the corresponding observed when the specific cable is only considered. Specifically, the semi-conducting jackets allow for the continuous circulation of induced currents, forming a transition zone for the sheath current between the two cable sections, where the current varies between the two extrema. The above observation may have a significant impact on the current rating calculations, where special care might be required concerning the location of a factory or sea joint, particularly where significant variation in installation conditions is encountered.

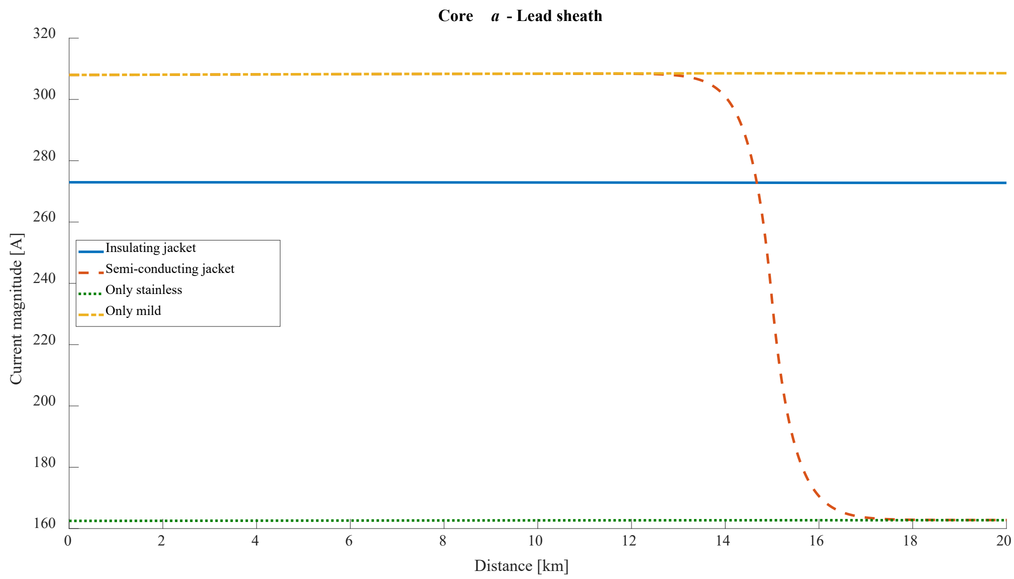

Figure 6: Connection of two different cables. Current profile in lead sheath of core a under inductive coupling.

The range and symmetry of transition region is mainly affected by the value of the equivalent per-unit-length shunt conductance G. A sensitivity analysis is performed in Figure 7 by varying this value, simulating both air- and water-filled profile fillers conditions [12], [13]. With the increase of G by a factor of 5 and 10, the transition region progressively narrows. This is expected since the increase of G facilitates the faster sheath current redistribution along the cable route. As a result, the final current value of each region is reached in less distance from the transition point. Finally, by assuming water-filled profile fillers, the transition region becomes even narrower, due to the resulting smaller shunt resistances.

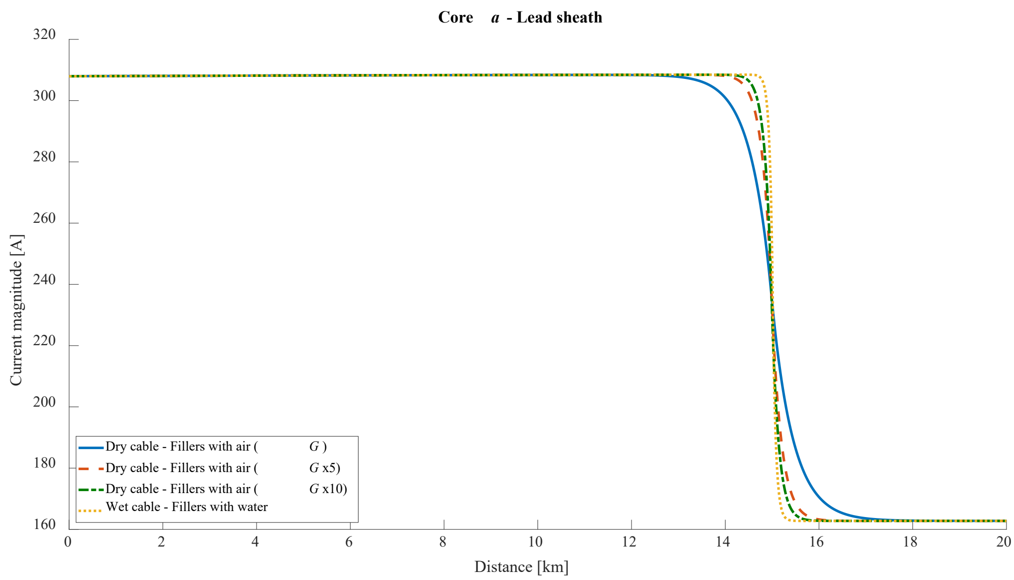

Figure 7: Connection of two different cables. Current profile in lead sheath of core a under inductive coupling. Investigation between dry and wet cable.

As already mentioned before, when semiconducting sheaths are used, the behavior illustrated in Figs. 7 and 8 should also be expected for the case of a factory joint between dissimilar conductor cross sections (normally also employing different lead sheath thicknesses) or a sea joint, even if the armouring material remains the same for both sections connected together. In this case, the lead sheath current in the transition zone will mainly be defined by the difference between the cross sections connected and the design thicknesses of the lead sheaths, provided that the length of each section is adequate to allow for the sheath current to reach a constant value.

4. CONCLUSIONS

The effect the semi-conducting jackets have on the performance of three-core armoured power cables is evaluated in the present study. The distributed nature of cable impedance is approached via EMT software, where sophisticated models accounting for capacitive and inductive coupling mechanisms are employed. The capacitive coupling mechanism is first considered: Interesting findings, not being published before in the existing literature, are presented with regard to the current circulating in sheaths. The capacitive current tends to return entirely through the metallic sheath when absolutely insulating jackets are assumed, while appears to get cancelled to a large extent when semi-conducting jackets are selected. However, a noticeable current still remains in that latter case, implying that another mechanism, besides capacitive coupling, acts behind. The authors believe that the remaining current is attributed to the inductive effect of the charging current flowing in the conductor. It is pointed out that the thermal effect these charging currents may have on cable current rating has not at all been discussed by the existing international standards.

The inductive coupling mechanism is subsequently discussed. The current circulating in sheaths even under single-point bonded conditions for semi-conducting jacketing material verifies what has already been published in the existing literature: The three semi-conducting jackets effectively form a common, equipotential node which gradually act as a multiple-point bonding configuration. This observation can be particularly exploited to increase the short-circuit withstand capability of the cable, since the fault current can be potentially shared via the three sheaths instead of returning solely through a single sheath.

Interesting results, referring to actual cable installations, where cable sections of various impedances may be in series connected, are finally presented. Indeed, cable sections of various parameters which significantly affect the cable impedance, such as the conductor size or the armouring material, are often connected in series in reality, thus forming a subsea link of variable cable impedance. In the hypothetical case that fully insulating materials were selected, the current circulating in sheaths would be unique. However, multiple sheath current levels appear in the more realistic case that semi-conducting jackets cover the metallic sheaths. These, semi-conducting jackets actually allow for the continuous circulation of induced currents, forming a transition zone for the sheath current between two different cable sections. This can have a significant impact on the current rating calculations, particularly in points where special care might be required, as for instance the location of a factory or sea joint, where significant installation condition variations are encountered.

BIBLIOGRAPHY

[1] T. Worzyk "Submarine power cables" (Springer, Germany, 2009)

[2] Working Group SC B1.27 CIGRE. "Recommendations for testing of long AC submarine cables with extruded insulation for system voltage above 30 (36) to 500 (550) kV" (CIGRE, number 490, 2012)

[3] S. Sturm J. Paulus F. Berger "FEM analysis on influence of semiconductors in 3-core submarine power cables regarding cable losses" (JICABLE, France, 2019)

[4] S. Sturm et al "3D-FEM modelling of losses in armoured submarine power cables and comparison with measurements" (CIGRE, France, 2020)

[5] H. W. Dommel "EMTP theory book" (Bonneville Power Administration, USA, 1986)

[6] A. I. Chrysochos et al "Capacitive and inductive coupling in cable systems - Comparative study between calculation methods" (JICABLE, France, 2019)

[7] A. Ametani "A general formulation of impedance and admittance of cables" (IEEE Transactions on Power Apparatus and Systems, volume PAS-99, number 3, 1980, pages 902-910)

[8] COMSOL AB "Modeling cables in COMSOL Multiphysics®: An 8-part tutorial series" (COMSOL Multiphysics® v.5.6., Sweden, 2020)

[9] J. C. del-Pino-López P. Cruz-Romero "Use of 3D-FEM to improve loss allocation in three-core armored cables" (Energies, volume 14, number 2434, 2021)

[10] Y. Yin "Calculation of frequency-dependent parameters of underground power cables with finite element method" (Department of Electrical Engineering, University of British Columbia, Canada, 1990)

[11] J. C. del-Pino-López M. Hatlo P. Cruz-Romero "A 3D parametric analysis of three-core armored power cables series impedance" (SEST, Spain, 2018)

[12] T. Kvarts C. G. Cojocaru "Inherently safe designs of fibre optic cables integrated in three-core submarine power cables" (JICABLE, France, 2019)

[13] J. Karlstrand E. Olsen M. Hatlo "Electromagnetic coupling in HV and EHV three-core submarine cables during test and operation" (JICABLE, France, 2019)

[14] Standard 60287-1-1 IEC. "Electric cables - Calculation of the current rating - Part 1-1: Current rating equations (100 % load factor) and calculation of losses - General" (IEC, 2014, pages 1-136)