Efficiency of cable transposition to decrease the induced voltage on linear third-party installations

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ABSTRACT

A new standard sets a very low maximum induced voltage for metal pipelines protected against corrosion, which represents a size difficulty when an underground link is planned in their vicinity.

This study intends to show how the cable transposition technique makes it possible to greatly reduce the level of induction on third party installations, in order to facilitate the development of the electricity distribution grid.

KEYWORDS

Underground cable systems, cable transposition, induced voltage, shelter currents, European standard EN 15280:2013, energy transition, offshore wind farms connection.

INTRODUCTION

RTE is involved in the energy transition through its construction of a network capable of carrying renewable energy. Among the major challenges that this poses are projects for connecting offshore wind generation necessitating the building of underground links of great length, typically in a double line arrangement.

In many places, cohabitation between energy transmission installations and other linear installations can only be envisaged by allowing for the levels of electrical influence as imposed by regulations and standards. These requirements which have to be complied with can represent major constraints for electricity transmission network projects.

In particular, the recent standard NF EN 15280 (September 2013), which deals with specific aspects of corrosion in metal pipes, imposes an induced voltage limit of just 15 V under operating conditions.

The authors propose to show, by means of this presentation, the effectiveness of the cable transposition technique in significantly reducing the level of induced electromotive force (emf) on third party installations.

The transposition of the cables is performed at each joint bay: it involves switching the positions of each phase, always in the same direction.

STRUCTURES STUDIED

The HV installations (225 kV) under consideration here, are long distance underground links, which implies certain characteristics:

- laid in a trefoil configuration,
- earthing by sectionalised cross bonding of the sheaths in order to ensure an acceptable level of induction along the sheaths.

In the case of two transposed links, the rotations of the cables are simultaneous and always in the same direction.

BACKGROUND

Sheath currents play an essential role in this study. It is generally believed that sectionalised cross bonding of the sheaths allows their cancellation.

Let us see why, by recalling a number of fact, this is generally accepted for a single underground link and while it is not the case for a double link, before addressing the effects of the transposition below.

The sectionalised cross bonding of the sheaths is presented as follows for the general case of a single link:

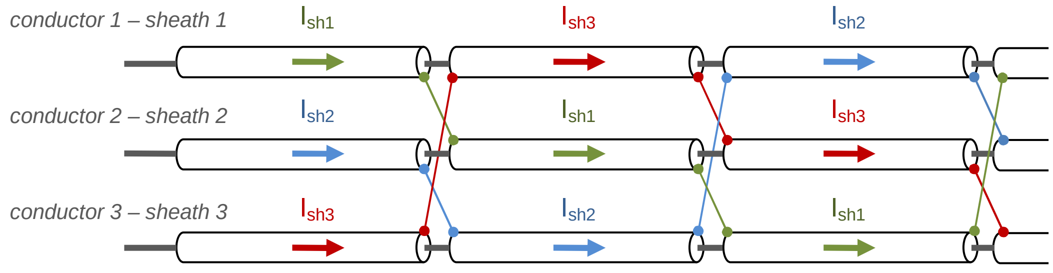


Fig. 01: Schematic diagram of the sectionalised cross bonding of the sheaths

Each ternary section comprises three elementary sections, which orders the switching of the sheaths. When the elementary sections are of the same length, it makes it possible to cancel out the circulation of the currents in the sheaths by optimising the vector composition of the induced emf along the ternary sections so that it is equal to zero.

On the other hand, when the joint bay positioning constraints impose length differences between the elementary sections, the emf induced along the ternary sections does not cancel out and there is thus a current circulation generated within the sheaths.

By chance, thanks to the symmetry of the trefoil installation and to sectionalised cross bonding of the sheaths always being in the same direction, each sheath circuit is induced in the same way with a phase shift of $2\pi/3$ from one circuit to the other. Therefore these sheath currents form a balanced three-phase system, of low current amplitude that has no significant influence on the induced circuit.

We have therefore chosen, without any influence on the induction results, to model the sectionalised cross bonding, where the sections have the same length such that this three-phase balanced non-influencing component is cancelled out, so that other effects are more easily identified.

Likewise for the case of two links, which exhibits the same phenomenon.

Let us add that the transposition of the cables does not change these sectionalised cross bonding effects because it causes the simultaneous rotation of cores and sheaths.

It therefore appears that in the general case of a single underground cable, the contribution of the sheath currents is not decisive in calculating the emf induced on a third party installation. The modelling can then be simplified and not incorporate the cable sheaths.

On the other hand, where there are two parallel underground links, a circulation of the sheath currents is created, because of the magnetic coupling between the two links.

The influence of these currents primarily acts on the induced emf on a third-party installation, which places them at the centre of our analysis.

Below we shall see how the transposition of cables acts equally well on induction linked to load flow currents as on those originating from sheath currents.

PRESENTED CASE

The case used to illustrate this approach, is very close to an actual investigated case: that of a parallel arrangement of a water pipeline and a double underground 225 kV link connecting offshore wind turbines over a distance of 27.8 km (without modelling the undersea link which has different characteristics and would interfere with the analysis).

The spacing between the axes of the two installations is 10 m (constant) and the parallel alignment exists over a distance of 3.8 km.

A first cross-bonding (switchover of the sheath) occurs at 3 % of the length of the parallel section and a second at 95 %. Three joint bays are located between these two cross-bonding bays. These five bays make it possible to identify transpositions over the length of the parallel section.

The trefoil installation results in a spacing of 350 mm between the axes of each cable.

The induction current is 1800 A for the hypothesis of a single underground link and 900 A per link for the hypothesis of two underground links.

The electrical substations located at the ends of the underground links have low earth resistances, which favours the circulation of the sheath currents and accentuates their effects.

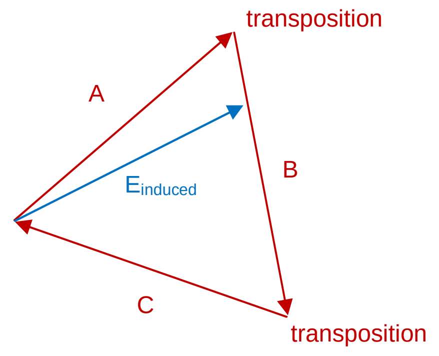
TRANSPOSITION EFFECTS FOR A SINGLE UNDERGROUND LINK

According to what has previously been noted, the transposition of the cables for a single underground link is of interest because it demonstrates its effect on the transit in the cable cores without interference from the sheath current.

Transposition mechanism

During the rotation performed by a transposition, the induced emf undergoes a phase shift of $2\pi/3$.

Assuming parallel alignment along the whole length of three sections of the same length, the vector representing the cumulative emf then describes an equilateral triangle. The modulus of this curve describes a well-known curve, which exhibits a maximum value divided by three relative to what would be obtained without transposition.



The induced voltage $E_{induced}$ follows the path A-B-C.
Its modulus is shown below:

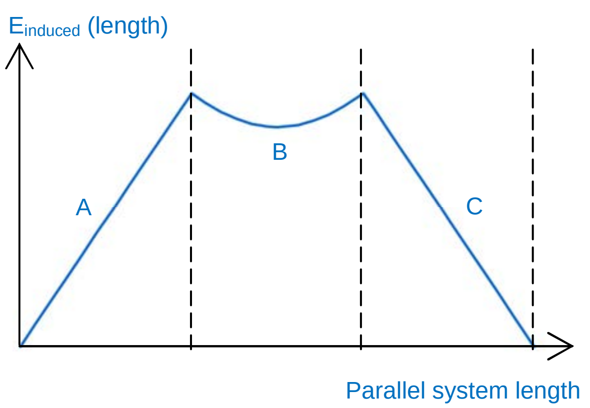


Fig. 02: Effects of transposition on the induced voltage

Results for the case studied

The emf induced on the water pipeline is approximately 14 V if the inductive link is not transposed and is about 4 V if it is transposed. The transposition yields considerable attenuation.

It is possible to visualise the positions of the joint bays where the transpositions are performed at the locations of the peaks on the curve.

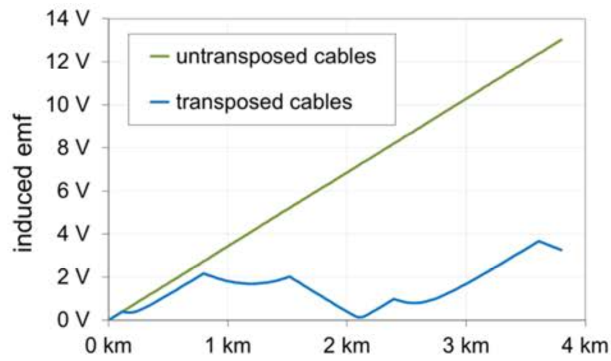


Fig. 03: Attenuation due to transposition

TRANSPOSITION EFFECTS FOR A DOUBLE UNDERGROUND LINK

Let us first of all assume that transit currents are a fixed input parameter (900 A per cable), as is typically required by simulation software.

What we will observe will facilitate the analysis of the actual case, at the end of the presentation, where the cores are integrated in the system of conductors each influenced by all the others. Indeed the influence of the distortion of the core currents arises, which makes the interpretation of the results more complex.

Non-transposed links

In the case of a double underground link, the magnetic coupling of the two links generates induced currents in the sheaths, the shape of which depends on the phase combination and the orientation of the trefoil of one link relative to the other.

A priori it could be assumed that the most interesting combination is the one that is conventionally presented for the attenuation of magnetic fields:

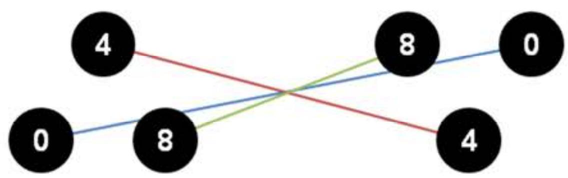


Fig. 04: A priori optimum combination

This combination is presented as optimum for magnetic fields because the barycentres of the phase pairs of the same primary-to-secondary phase shift are confused.

In reality, we can see that the associated sheath currents have combined to result in one of the worst combinations! We likewise see that the transposition, by ordering the sheath currents, allows the combination to once more become a winning combination.

Amongst all the possibilities, the presented combinations correspond to the two most favourable cases and the two least favourable cases. The intermediate cases are not of particular interest.

Combination	Sheath currents
C1  Sum of the sheath currents: 29.7 A	Left : I_{sh_0} = 4.49 - j 2.09 A I_{sh_4} = 4.49 - j 2.09 A I_{sh_8} = 4.49 - j 2.09 A Right : I_{sh_0} = 4.49 - j 2.09 A I_{sh_4} = 4.49 - j 2.09 A I_{sh_8} = 4.49 - j 2.09 A
C2  Sum of the sheath currents: 28.8 A	Left : I_{sh_0} = 4.53 - j 1.60 A I_{sh_4} = 4.53 - j 1.60 A I_{sh_8} = 4.53 - j 1.60 A Right : I_{sh_0} = 4.53 - j 1.60 A I_{sh_4} = 4.53 - j 1.60 A I_{sh_8} = 4.53 - j 1.60 A
C3  Sum of the sheath currents: 2.59 A	Left : I_{sh_0} = -38.6 + j 11.0 A I_{sh_4} = -38.6 + j 11.0 A I_{sh_8} = -38.6 + j 11.0 A Right : I_{sh_0} = 38.3 - j 11.8 A I_{sh_4} = 38.3 - j 11.8 A I_{sh_8} = 38.3 - j 11.8 A
C4  Sum of the sheath currents: 0.22 A	Left : I_{sh_0} = -37.3 + j 11.2 A I_{sh_4} = -37.3 + j 11.2 A I_{sh_8} = -37.3 + j 11.2 A Right : I_{sh_0} = 37.3 - j 11.1 A I_{sh_4} = 37.3 - j 11.1 A I_{sh_8} = 37.3 - j 11.1 A

Fig. 05: Sheath currents of non-transposed links

It can be seen that the cases C1 and C2 have quite low sheath currents, but all in phase, which results in a significant total (highly inductive).

By contrast, cases C3 and C4 have higher sheath currents, but with one link in antiphase with the other, which results in a very small total.

Recall: these results have the (non-influencing) currents generated by the elementary sections of different lengths (currents I'_{sh}) removed, as illustrated for case C3:

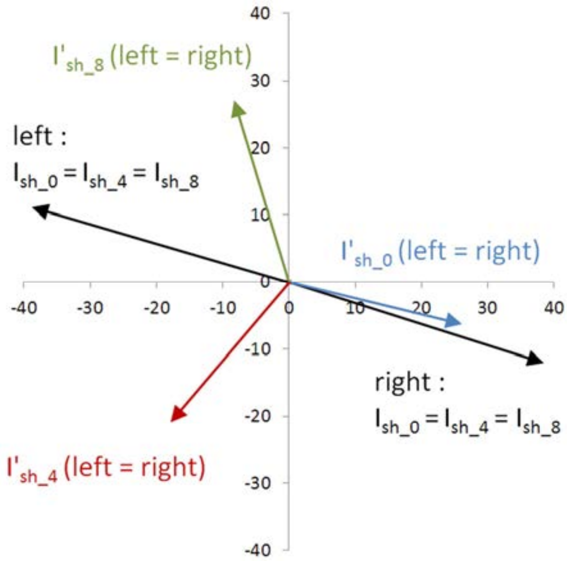


Fig. 06: Breakdown of the real sheath currents for the C3 case

The emfs induced by these different combinations are as follows:

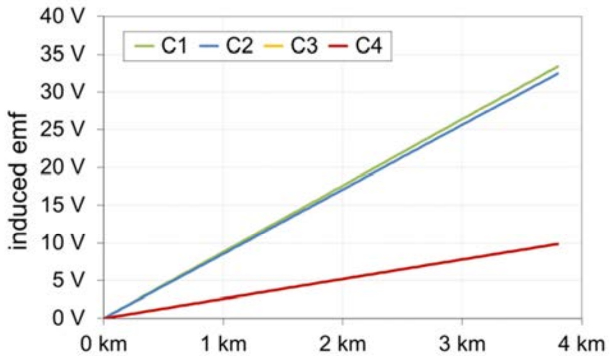


Fig. 07: Results of the combinations

The results of C3 and C4 can be superimposed.

To be able to interpret these results in detail, it must be possible to distinguish the contribution of the cores and sheaths according to the combinations.

With this in mind, the following results originate from a forced cancellation of the sheath currents. The results of C1 and C2 can be superimposed, as can those of C3 and C4.

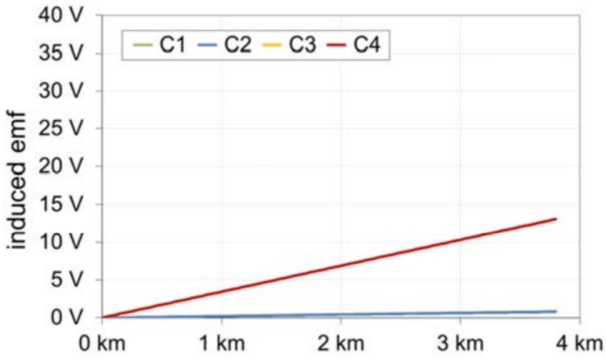


Fig. 08: Results of the combinations with the sheath currents cancelled

The comparison of the two simulations shows that:

- The currents circulating in the cores have no significant influence for the C1 and C2 cases (induction originating primarily from the sheath currents),
- The currents circulating in the sheaths have a small reducing influence for cases C3 and C4.

Transposed links

The effect of the transposition is to phase shift the sheath currents so that they are out of phase, creating a quite small vector sum and considerably reducing their amplitude.

The modelling yields the following results:

Combination	Sheath currents
C1  Sum of the sheath currents: 1.48 A	Left : I_{sh_0} = 0.31 + j 0.10 A I_{sh_4} = -0.09 - j 1.06 A I_{sh_8} = 0.52 - j 1.05 A Right : I_{sh_0} = 0.31 + j 0.10 A I_{sh_4} = -0.09 - j 1.06 A I_{sh_8} = 0.52 - j 1.05 A
C2  Sum of the sheath currents: 1.44 A	Left : I_{sh_0} = -0.07 - j 1.69 A I_{sh_4} = 1.92 + j 0.76 A I_{sh_8} = -1.15 - j 1.08 A Right : I_{sh_0} = -0.07 - j 1.69 A I_{sh_4} = 1.92 + j 0.76 A I_{sh_8} = -1.15 - j 1.08 A
C3 	Left : I_{sh_0} = -1.28 + j 1.10 A I_{sh_4} = -4.00 - j 0.77 A I_{sh_8} = -0.49 - j 2.04 A Right : I_{sh_0} = 2.64 + j 2.62 A I_{sh_4} = 0.18 + j 0.01 A

Sum of the sheath currents: 0.13 A	I_{sh_8} = 2.96 - j 1.04 A
C4  Sum of the sheath currents: 0.01 A	Left : I_{sh_0} = -2.45 - j 0.38 A I_{sh_4} = -1.22 - j 0.12 A I_{sh_8} = -1.93 - j 1.05 A Right : I_{sh_0} = 1.23 + j 0.42 A I_{sh_4} = 2.34 + j 1.08 A I_{sh_8} = 2.04 + j 0.07 A

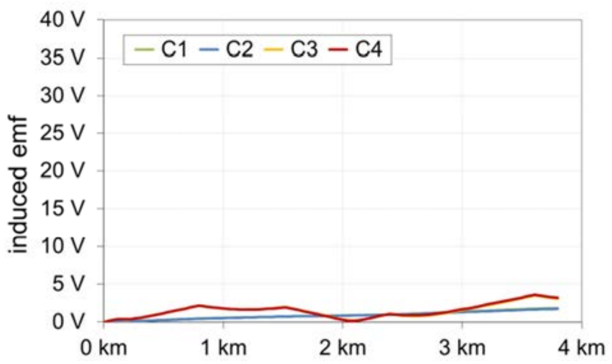
Fig. 09: Sheath currents of transposed links

It can be noted that all cases have sheath currents the sum of which has been divided by 20 thanks to the transposition.

As a result of this, the contribution of the sheath currents to the induction on a third party installation is no longer significant.

Recall: these results have the currents generated by the elementary sections of different lengths removed.

The emfs induced by these different combinations are as follows:



Zoom x 10:

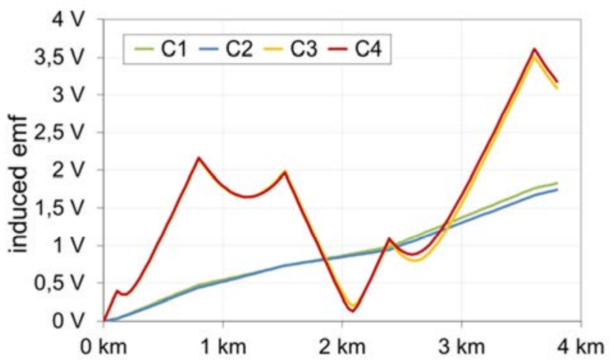


Fig. 10: Results of the combinations with transposition

As previously, to be able to interpret these results in detail, it must be possible to distinguish the contribution of the cores and sheaths according to the combination.

The results below are based on a forced cancellation of the sheath currents (results C1 and C2 can be superimposed, as can those of C3 and C4):

Fig. 11: Results of the combinations with the sheath currents cancelled

The comparison of the two simulations shows similarities with the preceding comparison:

- The currents circulating in the cores have no significant influence for the C1 and C2 cases (induction originating primarily from the sheath currents),
- The currents circulating in the sheaths for cases C3 and C4 have such a low influence that it cannot be identified (the induction originates almost entirely from the core currents).

Finally it likewise appears that:

- In all cases, the transposition of the cables results in a highly advantageous reduction in the induction acting on a third party installation.
- Resulting from the transposition, case C2 is once again the "ideal combination" with a reduction by a factor of 19!

Taking into account of the influence of the conductor system on the cores

Instead of imposing a balanced 900 A three-phase transit system as a source of induction, we impose three-phase voltage sources (Un = 225 kV) at the two ends of the links, which is most appropriate to the reality of the grid.

By adjusting the phase shift between these two voltage sources, we can generate a transit of the order of 900 A, while allowing the cable cores to be influenced by the system of conductors.

The results of this approach do not significantly modify those that we obtained previously, even if the currents in the cores are henceforth no longer a balanced inductive system: a residual component is superimposed on that of the sheaths.

Non-transposed links

We obtain results almost identical to those result obtained previously:

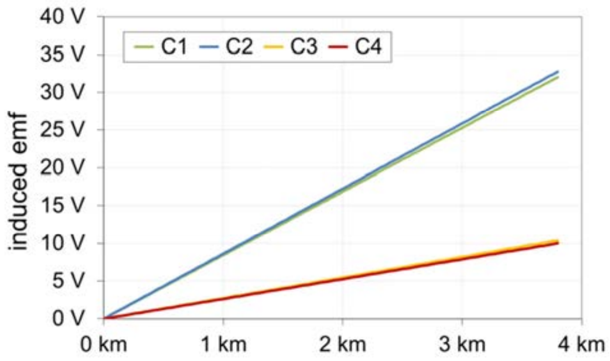


Fig. 12: Results of the combinations, cores influenced

Indeed, it is observed in all possible combinations that the sheath currents are modified, but that it is always possible to identify their vector behaviour as a function of the combinations.

The form of the residual component of the core currents is likewise sensitive to the combination of the cables, with an effect comparable to that of the sheaths.

For example, for the C4 case, the residual components of each of the two links are strong, but in antiphase thus compensating each other perfectly, exactly as it has been possible to see previously for the sheaths.

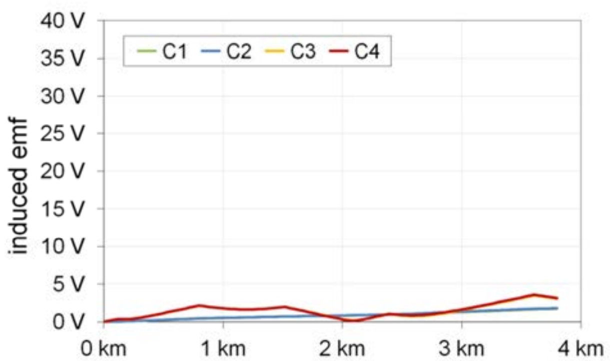
Finally if a vector superposition of each sheath current is performed with 1/3 of the total of the core currents of the same link, a vector system is obtained that is very close to that of the sheaths in the preceding case (balanced load flow currents).

In effect, the calculation shows that if a residual component is artificially included in the core currents which were initially balanced, it returns via the sheaths while providing very good compensation for this imbalance.

This is precisely what occurs here, with a residual component in the core currents which results naturally from the mutual influences: this component returns to a great extent via the sheaths.

Transposed links

Likewise we obtain results almost identical with the results originating from the assumption of balanced core currents:



Zoom x 10:

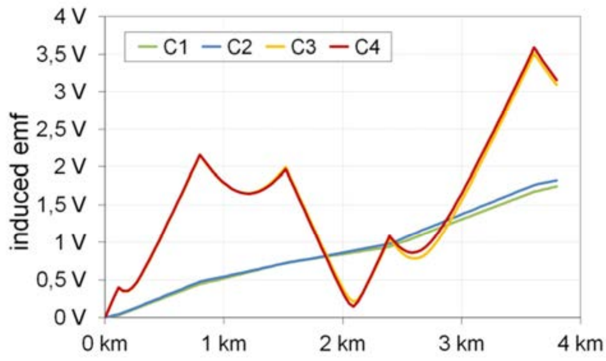


Fig. 13: Results of the combinations, cores influenced, with transposition

In the same way as for non-transposed links, if a vector superposition of each sheath current is performed with 1/3 of the total of the core currents of the same link, a vector system is obtained that is very close to that of the sheaths of the preceding case (balanced load flow currents).

The compensation for the residual component of the core currents also takes place here via the sheaths.

Simultaneously the effect of the transposition is likewise to considerably reduce the residual component of the core currents, in particular for cases C3 and C4.

CONCLUSION

The transposition of the cables acts simultaneously on the currents in the cores and in the sheaths to considerably reduce the effects of induction on third party installations.

It can considerably facilitate projects for the routing of underground links at negligible extra cost.

Its relevance for projects for the connection of offshore wind turbines, typically with an underground double line is obvious.