1. INTRODUCTION

The construction of the double 150 kV link between Tihange nuclear power plant and the new high-voltage substation in Avernas is Belgium's largest underground link ever built.

These double link, which has been energized in November 2003, had a dual aim: first, with the contribution of three other new links (Avernas - Tienen: two 21 km links; Avernas - Brustem - Landen: one 24 km link), to secure power supplies in the area extending between Brussels and Liège and, second, to supply power to the high-speed train line between Brussels and the German border (see figure 1).

![Diagram of the different links](image)

Figure 1: Diagram of the different links

2. HISTORICAL BACKGROUND OF THE LINK

The initial project of a 380 kV overhead line between Tihange and Landen had been included in Belgium's 1985-1995 national development plan for power generation and transmission facilities, and the project was started accordingly in 1989.

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After a series of modifications, the federal government finally accepted in 1999 a mixed overhead-underground design for the link, which would start overhead for 4.5 km (380 kV) and continue underground for some 27 km with a bundle of 150 kV cable.

Due to the advice of the regional government and some opposition from the public, the project was further modified and resulted in the present project: the exit from the nuclear plant site and the crossing of the river Meuse where the plant is situated (2 km) is overhead and includes a new 380/150 kV substation; via a transition compound the remainder of the link is underground (30 km).

3. PROPERTIES OF THE CONTROLLED BACKFILL

Elia, the Belgian Transmission System Operator (BTSO) imposed very strict transmission capacity requirements, which resulted in having a 150 kV link comprising three cables per phase, the third cable being installed only to face the situation in case one circuit should fail. However, in order to avoid the cost of a third cable, the option has been chosen to have a system with two cables per phase laid in flat configuration. This was based on a number of hypotheses; one of these is the adoption of a backfill resistivity value (generalised in Belgium) of 0.7 K.m/W instead of the usually adopted 1 K.m/W. In order to verify this calculated value, a series of in situ tests were performed applying the innovative TDR technique (Time Domain Reflectometry). The paper referenced [1] describes the organisation and the conditions under which these tests were performed, and gives the results, which substantiated the hypotheses.

4. AUTHORIZATIONS

The various permits (for which the requests have been introduced in May 2000) were issued mid-2002. Furthermore, in order to reassure the authorities and the public, a series of monthly consultation meetings were organised in each municipality along the route of the underground cable while the construction was in progress.

Nevertheless, numerous appeals were presented by local committees to the Belgium’s highest judicial body (the State Council) in order to stop the link crossing their land, but all these appeals were finally rejected.

Also several stipulations were included in the permits, resulting in the route of the link having to be repositioned locally to avoid running along roads with housing on either sides. Among these stipulations, one of the most important was the requirement for installing a special shielding against magnetic fields each time the links were distant of less than 30 m from housings and schools (in application of the ‘precaution’ principle).

5. SHIELDING AGAINST MAGNETIC FIELDS

Underground cables are often presented as the solution to avoid any problem due to EMF.

This is of course true for the electric field, but not that obvious as far as the magnetic field is concerned.

Mainly when the cables are laid in flat configuration in order to ensure a higher ampacity, as it is the case here, the magnetic field in the immediate vicinity of the cable is far from being negligible.

Although it decreases very quickly with the distance it remains quite high in the close vicinity of the cables. Due to stipulations included in the permits, about one fifth (about 7 km) of the total length had to be shielded.

5.1. Choice of the shielding technique

Shielding techniques for cables are studied by the BTSO since 1996. All kinds of shielding techniques have been considered: ferromagnetic materials (grain oriented steel...), use of highly conductive materials like aluminium or copper and use of passive loops. The first approach was experimental, followed by computer modelling (FEM-BEM) after validation. The comparison of these different techniques led to the conclusion that the use of conductive material offered more advantages than that of ferromagnetic materials. The main reasons were that, with ferromagnetic materials, the shield needs to be closed (or nearly closed) around the cables and also requires a good protection against corrosion (at present, however, these problems seem to have been overcome). Therefore, the proposed solution was to use aluminium plates of 3 mm thickness. These plates can be put horizontally or folded on the
edges in order to form a U-shape shield laid as a lid on the cables. The shielding mechanism results from the eddy currents flowing into the plates (Lenz law). It has been shown [2], [3], that the efficiency of such plates is not much different whether purely horizontal or folded. However, with folded plates the width of the trench can be reduced significantly. On the other hand, a U-lid cannot easily be installed because it interferes with the backfilling (risk of void under the lid and impact on the thermal behaviour).

For this reason, the U-shape was replaced by a H-shape made of two vertical plates, placed in the trench before the backfilling, and horizontal plates installed at the suitable depth during the backfilling (see figure 2).

This approach has important consequences on the construction work. Indeed, for practical reasons, the shielding is not continuous but made of separated 2 m length plates. For a horizontal or a U-shape shielding, the continuity between adjacent plates, although important, is not decisive, because the eddy currents can always flow in a closed loop in each plate. This is no longer the case for a H-shape shield where a very good continuity needs to be achieved between the successive vertical plates. Moreover, in the absence of contact between vertical and horizontal plates, the vertical plates need to constitute a close loop. Therefore, at regular interval, a bridge is installed between the lateral plates. In that respect, the technique resembles the passive loop technique but it has a better efficiency thanks to its lower inductance (no need to tune with capacitors at 50 Hz).

All these features could not be analysed by the classical 2 D models, which have been validated on horizontal and U-shape layouts but not on the H-shape. Hence, they have been analysed first on laboratory models and then validated by 3 D mathematical models.

These studies showed also that the continuity between the horizontal plates was not important at all. Therefore they were installed with a gap of several centimetres between each other and the vertical plates in order to ensure easy fault location and repair in case of oversheath fault in the cable.

The final layout used for shielding the link is shown on figure 2.

5.2. Corrosion and thermal behaviour

It has been shown that the corrosion by the soil was not an important concern as long as the pH of the soil remains between specific limits and the alloy contains more than 95% aluminium and no copper. A long duration control of the electrical potential of the plates was decided anyway. DC and AC corrosion has also been addressed. This kind of corrosion depends on the current density of the stray currents.

In order to reduce the leakage currents between vertical and horizontal plates it was decided to keep a gap between them.
On the other hand, if the leakage currents remain very low, the eddy currents in the plates are quite high and could lead to unacceptable losses. This limits the minimal distance between the horizontal plates, responsible for the highest losses, and the cables.

5.3. Practical results and costs

Figure 3 shows measurement results taken at two different places of the link with and without shielding. At those places, the distance between both circuits is about 4 to 5 m. However, as it is not exactly the same it is difficult to calculate a shielding factor. The order of magnitude here is about 8.

Depending of the fastening technique used (bolts, rivets, welding) lower or higher efficiencies can be achieved. Shielding factors higher than 10 have been measured in places where the welding technique was systematically applied; this result is close to the theoretical maximum given by the 3D computer model.

The total cost involved by the shielding is not easy to evaluate because it is the first time this technique is applied. For the present project, the additional cost per shielded unit length was about 16%.

![Figure 3: Magnetic field, with and without shielding, measured at 0 and 1 m above ground (distance between circuits: 4 to 5 m)](image)

6. CROSS-BONDING

6.1. Cross-bonding (of the metallic screens)

In order to suppress the circulation currents in the metallic screens that reduce the ampacity of the link, two possibilities exist: single point bonding or cross-bonding of the screens [4].

As the link is very long (30 km), single point bonding would generate unacceptable voltages on the metallic screens.

Using a cross-bonding method, advantage is taken of the fact that the induced voltages are symmetrical: by adding three vectors of the same amplitude, but phase-shifted by 120°, resulting in a null vector.

A major section (distance between two points of the link were the screens are bonded together) is divided into three equal minor sections (L1, L2, L3). The cable screens are interrupted at the cable joints between L1 and L2 and between L2 and L3 and the screen connections can be bonded to another joint in the manhole (cross-bonding).

6.2. Transposition (of the phases)

The condition of having equal lengths of minor sections is enough to get a null resulting vector if the system is symmetrical, which is the case when a trefoil configuration is used (same distance between
the phases). In the case of flat configuration, the distances between the phases are not equal. To cope with this, transposition of the phases (similar with long-distance overhead lines) is performed at the same locations where the cross-bonding of the metallic screens is applied [4].

6.3. Direct cross-bonding

With classic cross-bonding, the interruptions on the screens at the joints are protected against overvoltages with surge voltage limiters (SVLs).

Checking (and maintenance) of the SVLs would be a huge task on such a long double link, and should be avoided, as it must be performed during availability of the link.

As the SVLs only have a protective function, they can be avoided if the elements they protect have sufficient intrinsic protection.

The electrical constraints on Belgium’s 150 kV network have been calculated before, and have resulted in imposing the interruption of the elements in the joint in order to withstand 150 kV surge voltage, and 75 kV surge voltage between each element and the earth.

A special joint technique has been designed and qualified by the cable manufacturer in order to meet these requirements in addition to the tests specified in IEC 60840 [5].

Direct cross-bonding system is systematically applied in Belgium on the 150 kV underground link since 2000.

6.4. Installation of SVLs in the two minor sections following the transition compound

Overvoltages of atmospheric origin would result in the propagation, through the cable, of the surge waves caused by lightning strikes on the overhead line to which the underground link is connected.

The characteristics of the lightning surge adopted after a sensitivity analysis on the various parameters were: 100 kA peak – 1.2/50 µs, which is a deterministic approach of the problem, consistent with the reports presented in the scientific literature Electrana n° 28 [6] and 47 [7].

The results of the first simulations (without SVLs) showed that the amplitude of the surges between screens decreases in the underground link with the distance to the location of the lightning stroke in the overhead line and that the amplitude is at its highest at the first permutation of screens (gradual attenuation of the surge wave with the propagation in the cable).

In order to avoid oversizing of the direct cross-bonding joints, only the first minor sections of the circuit (nearest the overhead line) need to be protected by SVLs (see figure 4).

![Figure 4: Principle of the direct cross-bonding and position of the SVLs](image)

New simulations demonstrate that a reduction of the surges in the first major section of the circuit was clearly noticeable but a shift of the surge was noticed at the screen interruptions of the next major section of circuit. Nevertheless, the surges in this section were strongly reduced and acceptable for the current design of the joints.
7. CONSTRUCTION AND SCHEDULING

The energizing of the link was planned at the beginning of November 2003 to schedule with a maintenance of the nuclear power plant.

Taking into account this requirement, the dates on which the building permits were received and the agreements with the Belgian railways (regarding power supply for the high speed train), the construction had to be complete within about one year.

As most of the route of this double link runs along a disused railway line, it was possible to provide a track parallel to the trenches, allowing to work simultaneously on several sections of the underground link. This solution made possible a high progress rate.

The contractor provided also throughout the construction period a high number of teams charged with specific tasks (clearing of brush, road crossing, cable pulling, …). The workforce for the construction numbered 170 in all.

The construction was completed on time.

8. TESTS AFTER INSTALLATION

Two major dielectric tests were performed after the installation of a high-voltage cable link:

- DC test on the PE-oversheath
- AC test on the high-voltage insulation

8.1. DC tests on the oversheath

The dielectric integrity of the sheath gives a good indication on the way the cables have been installed in the trench. The voltage applied depends on the thickness of the sheath and on the involved length (partial or complete). For the partial length (one drum), the applied DC voltage is $2.5e + 5$ kV during 2 minutes ($e =$ thickness of oversheath). On the complete finished cable length, the test voltage is 10 kV during 1 minute.

8.2. AC test on the high-voltage insulation

This test, performed after installation of the complete finished cable system aims at checking the integrity of the system for commissioning - mainly that of the accessories assembled on site.

In Cigré report [8], a first recommendation was made for AC testing on site after installation. The conclusions were that AC voltage withstand testing at levels of 2 $U_0$ to 3 $U_0$ will give the most reliable results.

Since 1997, BTSO imposed the AC tests after installation for XLPE cables on the 70 and 150 kV network. The test voltage is 2 $U_0$ (81 kV or 174 kV) respectively 30 minutes for 70 kV and 15 minutes for the 150 kV links.

AC - test conditions for the double 30 km link

With the actual available test installation (see picture 2) and a test level of 174 kV, the maximum available power is 22 MVA at 25 Hz. In order to test the total length of 30 km in one time, the needed power is 47 MVA.

![Picture 2: AC-test](image)

![Picture 3: Stop joints](image)
The Belgian experience with the premoulded joints at 150 kV, where about 200 similar joints have been successfully tested, allows to work on a statistical basis.

The link was divided in 3 parts, two parts of about 12 km length (needed power was about 19 MVA) that have been tested, and a remaining part of 6 km that has not been tested. Nevertheless, before delivering power to the network, the complete link has been connected to the network for at least 6 hours.

Tests were carried out on part 1 using the overhead line of 1.5 km from the 380/150 kV transformer substation to the transition compound and on part 3 from the 150 kV substation.

At the end of each test length, temporarily stop joints were installed (see picture 3). This principle avoids having to install on-field terminations for testing.

<table>
<thead>
<tr>
<th>Part 1 – tested</th>
<th>Part 2 – not tested</th>
<th>Part 3 – tested</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feeder A</td>
<td>60</td>
<td>39</td>
</tr>
<tr>
<td>Feeder B</td>
<td>66</td>
<td>33</td>
</tr>
</tbody>
</table>

Table I: Number of tested joints

77 % of the total number of joints were successfully tested at 2 U0 – 15 minutes.

9. OPERATION OF THE LINK UNDER EMERGENCY CONDITIONS

Considering the nominal characteristics of the 3 monobloc transformers 400/165/36 kV with a basic power of 185 MVA each and the ampacity of the cable = 1100 A, it can be concluded that with the double link in service, the limit is given by the transformer (120 % in the summer, duration of maximum 12 hours).

In practice, the double link will be normally used at 60 % of its maximal cable load possibilities. This means that with only one link, the load on one cable will reach a maximum of 120 %.

During operation under such conditions, it is important to know where hot spots on the link are situated, and to monitor them. This monitoring is possible thanks to the integrated optical fibres for temperature measurements embedded in one phase of each cable link.

The distributed temperature of the two types of integrated optical fibres (multimode and singlemode types) will be measured with the commercially available systems.

The integrated optical fibre link of 30 km is divided in several parts for the multimode principle, with a maximum length of about 4 km and a spatial resolution of 1 metre. Complementary, the entire link can be measured with the singlemode principle having a maximum length of about 30 km and a spatial resolution of 10 metres.

10. FAULT LOCATION

Once a year, the link will be tested on the integrity of the PE-oversheath. Indeed, the locating of a cable insulation fault is often achieved through sheath fault location (i.e. important damage on the cable).

The use of magnetic shielding over several metres makes classic pinpoint location impossible. For this reason, each section of aluminium shielding is electrically connected at each end to the next closest earthing box. A galvanic insulation (gap of about 10 cm) is present between successive horizontal plates and the interconnected vertical plates.

Two steps are still necessary when supposing that there is a fault under a shielded section:

− Firstly, through preliminary location by reflectometry, using the propagation between the screen of the cable and the shielding which is connected with an aluminium wire to the place of measurement (earthing box).
− Secondly, pinpoint location on the horizontal plates. The maximum precision of this location will be 2 m (dimensions of the plates).
11. CONCLUSIONS

After 14 years of technical studies and discussions with authorities and administrations, the double 150 kV mixed (overhead-underground) link between Tihange nuclear power plant and the new high-voltage substation of Avernas has been energized in November 2003. The construction itself took one year.

Among the conditions imposed by the authorities in the permits, was the obligation to reduce the magnetic field in those areas where the underground cables run at a distance less than 30 m from housing and schools. Various systems were compared, and finally the option was taken to use highly conductive materials. An H-shape layout was chosen, composed of aluminium plates installed over one-fifth of the total length of the link, entailing a significant extra cost. Fortunately, the results matched the expectations.

Like systematically in Belgium since 2000 for underground 150 kV links, the direct cross-bonding principle was applied, thereby avoiding for the BTSO the constraints relating to SVLs, except at the first two junctions closest to the overhead line, where, for reasons of not wanting to pointlessly oversize the direct cross-bonding joints, the choice was made to install SVLs.

The BTSO has adopted since 1997 the AC test for post-installation testing of all the 70 and 150 kV links. Considering the length of this link, a technical and economic study was performed, which permitted working on a statistic basis by successfully testing only 77% of the link.

Taking into account the very strict stipulations imposed by the BTSO regarding the transmission capacity of the link, it was essential that the locations of the hot spots be known. This requirement was met by incorporating optical fibres in one of the three phases.

The 150 kV double link between Tihange nuclear power plant and Avernas substation is the longest ever (30 km) underground link built in Belgium.

12. BIBLIOGRAPHY

[1] A. Gille, G. Geerts, J-P. Mella, Pr. Dimitri Xanthoulis, N. Fonder: On-site follow-up of the characteristics of controlled backfill, using the Time Domain Reflectometry moisture-measurement method (Jicable 2003 – Article C.8.1.7.).


