Lillebælt – Manufacturing, installation and commissioning of world’s first 420 kV 3-core submarine cable

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ABSTRACT
In this paper, the experiences of the design, production, installation and commissioning of the world’s first 420 kV 3-core submarine cable are presented. The scope of the project was to replace the two 400 kV overhead lines crossing the Lillebælt (Little Belt) with underground and submarine cables. Through detailed project engineering including seabed surveys, soil investigations and intense dialogue with authorities the optimal layout for the project was found. This paper covers all aspects in relation to the cable system, from conception to the realization of the project and the decommissioning of the old overhead lines.

KEYWORDS
420 kV 3-core submarine cable, submarine cable burial methods, EHV, XLPE, world first, parallel circuits.

INTRODUCTION/BACKGROUND
In November 2008, the Danish Parliament agreed on the principles on which the future expansion of the electricity transmission grid in Denmark should be based. This agreement was based on the work done by the Electric Infrastructure Committee [1].

Amongst others, the agreement implied:

• That the visual appearance of selected sections of the 400 kV grid will be enhanced (decided 2009).
• That the whole of Denmark’s 132/150 kV transmission grid will be placed underground in future (the future Cable Action Plan).
• That new 400 kV overhead lines can only be built to replace old overhead lines in their existing right-of-way agreements. Otherwise 400 kV underground cables must be used.

The commitment to improve the visual appearance of the 400 kV grid, which involved six visual enhancement projects, was part of the new guidelines for undergrounding and expanding the transmission grid in Denmark.

The decision of the selected projects was based on the conclusions in the Visual Enhancement Report [2]. Initially, the state-owned environmental centres and Energinet.dk pinpointed 22 possible sections whose visual appearance had the potential to be enhanced. Following a detailed review, the 22 sections were reduced to six. The six projects were chosen on the basis of an assessment of the environmental impact of the entire 400 kV grid, taking aspects such as people, protection areas, former county landscape designations, coastal zones and coast protection lines in consideration - One of these six projects was the project to cable the overhead lines crossing the Lillebælt Strait.

SCOPE OF THE LILLEBÆLT PROJECT
The overall scope of the project was to replace the double 400 kV overhead line systems crossing the Lillebælt strait, which is the strait between the Danish island of Funen and the Jutland peninsula.

Figure 1: Overview map of Denmark.

A total of 2 x 12 km overhead lines were removed at the strait crossing and on land.

The project consisted of 3 parts:
• Cabling offshore and underground
• Building two transition substations/compounds
• Decommissioning of and rerouting of overhead line

The new cable part consisted of two 420 kV circuits each approx. 13 km in length divided in 1 km of underground cable system on the Jutland side, 7.5 km of submarine cable system in the Lillebælt strait and 4.5 km of underground cable on the Funen side next to the town Midelfart.

The substation part even included design of substations specifically designed for the project to accentuate the visual enhancement of the project. In addition to this, shunt reactors were installed in an existing substation nearby.

ENGINEERING
The two 400 kV connections across the Lillebælt strait are two of the most important lines in the Danish electricity system: therefore the engineering solution should end up with a solution that was robust in every way.

It should also be noted that during the engineering process, it was not known if the solution would have to account for six single core submarine cables or two 3-core submarine cables.
Cable Route Considerations

From the start of the project several different cable routes were considered. A solution where the cable was routed in parallel with the motorway E20 and across the bridge was investigated and rejected. Another alternative was to cross the nature park on the Hindsgavl Peninsula but that was also rejected and in the end the route on figure 2 was the one selected as this route implied the lowest impact on neighbours and nature - and it was still deemed technically feasible.

Figure 2: Cable route of the Lillebælt project.

Jutland Underground Cable Route

The two circuits on the Jutland side where approx. 1 km in length and traversed a nature protected area, a forest, a minor topographic depression and a main road.

Through detailed planning with the onshore civil contractor and a good working relationship with the local authorities in Fredericia a feasible method of installing the cables was found.

Figure 3: Jutland Underground Cable Route.

Funen Underground Cable Route

Due to a European Natura 2000 habitat area inside the Færø Sound the submarine cables had to make landfall earlier than first anticipated, which meant that the underground cable route would have to go through a local golf course. Other than that, the route went through open farmland, the cable transition compound only interrupted by small roads, a minor topographic depression and a small protected stream.

Through an early involvement and a constructive dialog with the owners of the golf course a careful installation method was derived that was acceptable both in relation to preserving the golf course as much as possible and to have a viable route to install the cables in.

Lillebælt Strait Submarine Cable Route

The Strait of Lillebælt is known for its strong currents and relatively deep waters. Therefore, the task was to find a route that took these aspects into consideration.

In addition to this, crossing of the shipping lane was an area of concern. A consultancy was given the task to investigate the density of the marine traffic in the area. Based on this investigation a report was written, on which the decision of splitting the circuits up into two separate routes placed several hundred meters apart in the shipping lane was made. This was to mitigate the risk that a ship anchor could damage both circuits - in case of a ship in emergency dropped its anchor.

The layout of the cables in the narrow straight Færø Sound between the small island Færø and Funen (see figure 5) was a difficult task because the steep slopes from the shores only gave very limited space for laying and separating the cables.

Route Investigations

When the routes had been selected a number of investigations were initiated.

Onshore

On the onshore part the thermal resistivity of the soil was measured on preselected points of the route. These points were selected based on a desktop study of the soil maps that were available on the route, and the measurements were used to specify the ambient conditions on which the cable was to be designed.
Offshore
On the offshore part a geophysical seabed survey was conducted to verify seabed surface and topography, and to investigate how the geological layers below the seabed were built up. Based on these results a number of locations were chosen to verify the findings of the geophysical survey by a geotechnical survey with CPT and Vibrocore analysis of the seabed. Based on these results a general picture of the seabed condition was achieved and put into alignment sheets as shown in figure 6 below. From this documentation a BAS was made for the routes.

Figure 6: Example of Alignment Sheet.
The results from the surveys also fed into the ambient conditions on which the cables were to be designed.

Ambient Conditions
Ambient data and cable configuration used for the design of the cables are listed in tables 1 and 2 below.

<table>
<thead>
<tr>
<th>Number of Cables</th>
<th>2 (3-core) / 6 (single)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum distance between cables</td>
<td>8 m</td>
</tr>
<tr>
<td>Maximum sea depth</td>
<td>50 m</td>
</tr>
<tr>
<td>Maximum burial Depth</td>
<td>1.5 m</td>
</tr>
<tr>
<td>Thermal Resistivity of the seabed and landings</td>
<td>0.8 K·m/W</td>
</tr>
<tr>
<td>Maximum temperature of the seabed/landings</td>
<td>15 °C</td>
</tr>
</tbody>
</table>

Table 1: Ambient data and cable configurations used for submarine cable design

<table>
<thead>
<tr>
<th>Number of Cables</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance between phases / circuits</td>
<td>0.4 / 8 m</td>
</tr>
<tr>
<td>Burial Depth</td>
<td>1.4 m</td>
</tr>
<tr>
<td>Thermal resistivity of the soil and backfill</td>
<td>0.8 K·m/W</td>
</tr>
<tr>
<td>Maximum temperature of the soil</td>
<td>15 °C</td>
</tr>
<tr>
<td>HDD distance between phases / circuits</td>
<td>1 / 10 m</td>
</tr>
<tr>
<td>HDD depth</td>
<td>5 m</td>
</tr>
<tr>
<td>Thermal resistivity of bentonite</td>
<td>0.7 K·m/W</td>
</tr>
</tbody>
</table>

Table 2: Ambient data and cable configurations used for underground cable design.

Electrical Requirements
During the feasibility stage of the project several different options determining the required transmission capacity were proposed. Three of these options were chosen to serve as the basis for the tender of the project. The 3 options where chosen based on the scenarios for a second Storebælt HVDC link between the two synchronous systems in Denmark.

- Option 1 was taking the point of reference in the existing situation, where only one Storebælt HVDC connection (600 MW) exists, and no other will be built in the future.
- Option 2 was taking a point of reference in a situation where a second Storebælt HVDC connection is present, but serving only as a reserve connection (600 MW).
- Option 3 was taking a point of reference in a situation where a second Storebælt HVDC connection is present with full transmission capacity (600 MW).

The current requirements were set as follows:

<table>
<thead>
<tr>
<th>Option</th>
<th>$I_{	ext{continuous}}$ (A)</th>
<th>$I_{	ext{on}}$ (A)</th>
<th>$I_{	ext{on}}/I_{	ext{cont}}$</th>
<th>$I_{	ext{on/off}}$ (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>750</td>
<td>1355</td>
<td>1.8</td>
<td>750</td>
</tr>
<tr>
<td>2</td>
<td>750</td>
<td>1355</td>
<td>1.8</td>
<td>750</td>
</tr>
<tr>
<td>3</td>
<td>1130</td>
<td>2115</td>
<td>1.8</td>
<td>1130</td>
</tr>
</tbody>
</table>

Table 3: Current Requirements for Lillebælt.
This meant that the cable suppliers had to produce three different designs for the cable systems - one for each option.

Short circuit levels were set to 40 kA for 1 second.

In addition to this, the insulation levels for the cable system had to be able to operate on levels above IEC values. This is because the Danish 400 kV grid is operated above the IEC max continuous voltage of 420 kV, at Lillebælt the value was 421 kV. Tests on the cable would therefore need to be performed with a higher $U_0$ than stated in IEC 62 067.

Procurement
The tender qualification was run through the EU-tendering system, where 4 suppliers were selected to make a bid for the project. The Tender was open for the use of either single core submarine cables or 3-core submarine cable. The Tender bids from the different suppliers were the base for the decision of which of the 3 different options for the transmission capacity was to be selected.

During the negotiations for the cable contract it was quickly realized by Energinet.dk that solution 2 was the optimum choice and that a three core design had significant advantages over the single core alternative. In the end the contract was awarded to ABB.
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TECHNICAL SOLUTION

General submarine cable design

After ABB were involved in the project, the work with detailed optimisation commenced. The following main issues were considered:

- Technical feasibility of cable designs, such as 2 x 540 MW continuous load and 2 x 940 MW short term load requirements.
- Installation cost, such as availability of suitable installation vessels (including burial in seabed).
- Suitability for pulling through HDD’s.
- Life time costs, such as cable cost, losses and risk for external damage (part of the route is crossing a shipping lane) etc.

The initial evaluation showed that:

- Both 3-core and single-core cables could be manufactured and handle the required load, hence evaluated neutral.
- A large part had to be pre-excavated due to difficult soil conditions, burial of only two 3-core cables rather than six single core cables would be a significant advantage, hence evaluated pro 3-core.
- Single core cables would have higher losses and risk for external cable damage will increase with increased number of cables, hence evaluated pro 3-core.

The conclusion was that a 3-core cable would be the most cost-efficient solution for the submarine part of this project.

Specific cable design

Figure 7: 3-core 420 kV submarine cable

The specific cable design is based on a typical three core XLPE cable design although larger.

Conductor

There are different issues to consider when choosing conductor material, such as:

- Metal cost, evaluated in favour for aluminium.
- Insulation stress (due to larger conductor necessary when using aluminium), evaluated in favour for aluminium.
- Cable weight, evaluated minor advantage for aluminium
- Final cable size, evaluated minor advantage for copper

When considering the items above, it was decided to use longitudinal water sealed 1400 mm² aluminium conductor.

Insulation

A conservative approach was applied when choosing insulation wall thickness due to the fact that this was a new product.

Longitudinal water barrier

Semi-conductive swelling tapes are used as longitudinal water barrier between insulation screen and lead sheath.

Radial water barrier

The radial water barrier is of lead alloy, which is a well proven concept used for more than 60 years.

Protective sheath

Each lead sheath is protected by a PE-sheath. It is important for long 3-core cables that the cable metal sheaths are electrical connected, mainly for neutralizing capacitive current in the sheath but also to avoid voltage difference between the phases during various types of system fault. Therefore the sheath is made of a fully extruded semi-conductive PE.

Assembly

The complete assembly include three 420 kV power cores, three polymeric fillers and one loose tube FO cable. The complete assembly is held together by using semi-conductive tapes.

Armour

For mechanical/protection reasons wire armour is necessary, the standard choice on 3-core cable would be galvanized steel wires. However, due to relatively high armour losses in galvanized steel armour in combination with the very high voltage level, it showed to be economical advantageous using non-magnetic stainless steel wire armour.

Final dimensions

The overall diameter of the cable is approx. 290 mm and the weight in air is approx. 110 kg/m.

Accessories

Onshore/offshore transition joint

The onshore/offshore transition joints are basically standard components for onshore use.

Offshore repair joint

Figure 8: Offshore Repair Joint

The electrical parts of the offshore repair joints are basically standard components for onshore only modified with additional radial water sealing and mechanical protection. The optical part of the offshore repair joints is a standard joint for F.O. cables. Electrical and optical joints are encapsulated in a larger outer steel casing.

Terminations

Each of the two circuits was terminated with outdoor terminations placed on steel stands.
Link-boxes
All link-boxes were designed for safe access and grounding of metallic screen in case repair of one circuit should be necessary when the second circuit is still online.

Bonding System
Jutland
Single-end bonded land cable sections were installed on the Jutland side of the strait. Due to risk of lightning impulses from the connected overhead lines, in addition to surge-arracers on the phases, surge-arracers on the metallic screens were installed adjacent to the outdoor terminations. Furthermore the grounding system was designed with two transposed non-insulated EGC wires in order to minimize induced screen-voltages caused by short circuit currents up to approx. 40 kA. These induced screen-voltages could be up to 11 kV.

Funen
Two conventional cross-bonded land cable sections were installed on Funen. Due to risk for lightning impulses from the overhead lines also the screens of this section was protected with surge-arracers, although in this section the surge-arracers were placed underground in link-boxes adjacent to the joints. The induced screen-voltage in this section could be as high as 10 kV.

TYPE TEST
One of the key focus points in the project was to get a reliable cable which was tested according to the standards. As part of an internal feasibility study an experimental 420 kV 3 core cable had already been manufactured prior to the Lillebælt project came out for tender. Fortunately this design was very much in line with the cable proposed from ABB to the Lillebælt, hence it was possible to build a type test circuit soon after the contract was awarded to ABB. Ingoing components in the type test circuit were 420 kV 3-core cable, Rigid Sea Joint and AIS terminations.

The type test was completed and approved in the spring of 2013.

PRODUCTION
The cables for the Lillebælt project were produced at the ABB Karlskrona factory in Sweden. The production facilities were already suitable for this size of cable hence only some minor equipment such as roller ways had to be adjusted prior to production start of the two lengths (each 7.5 km) 420 kV 3 x 1400 mm² submarine cables.

Due to the relatively short lengths, no factory joints were necessary. The integrated fibre optic cable was monitored during assembling, armouring, loading and installation.

INSTALLATION
Offshore
Installation in the Lillebælt was beforehand known to become a challenging operation, but the installation of the two 420 kV 3-core cables was to become one of the most challenging installations in the history of Energinet.dk. Especially the protection of the cables was difficult due to the seabed topology and very strong currents.

Landings
The landings were performed with 300 meter long pipes, which afterwards were filled with low thermal resistivity bentonite to accommodate for the thermal hotspot in the landings.

Burial
The trenching for the cables was significantly more challenging than first anticipated because the seabed conditions assumed from the investigations were not completely in accordance with the real conditions. The seafloor from the Jutland side was the most challenging part as seen on figures 9 and 10. Alternative method for dredging had to be implemented and a suction device was made for that trench. On the other parts the ROV trencher and jetting tools were used.

Figure 9: Multibeam survey before installation of the Western 420 kV system.

Figure 10: Multibeam survey after installation of the Western 420 kV system

Submarine Cable Laying
Once the trenching was completed the laying of the submarine cables was commenced. Both campaigns were performed without any problems.

Unplanned joint
Due to a mechanical damage to one of the cables prior to loading onto the installation vessel, a repair joint had to be installed after the laying of the cable. However, as result of extensive planning and advantageous weather conditions, the installation work of both cables and the repair joint was finalized in time and exceeded expectations.

Onshore
Jutland
On the Jutland side the protected nature zone was partly crossed by using HDD's and partly by direct burial close to a treeline up towards the topographic depression where HDD’s were used. From the topographic depression to the cable transition substation the cables crossed a main road via HDD’s.
Funen
One of the challenges of the installation onshore was the cable route through the golf course. Through early involvement of the golf course owners and skilled work of the civil contractors, the cable systems were successfully installed with only minor impacts for the users of the golf course.
Another challenge was, that the cable route ran mainly alongside the existing 400 kV overhead lines, which, if a fault occurred on the overhead line, could result in dangerous induced voltage levels in the parallel cables during installation of cables, joints and terminations. As a consequence new methods/instructions for safe jointing, termination and general handling of the cables had to be made, also a number of special grounding tools had to be designed and manufactured.

COMMISIONING
After installation of the two parallel circuits (submarine cable, underground cable and accessories), a Site Acceptance Test (SAT) was performed on both circuits. Main parts of the SAT were:

- Sheath tests on onshore parts.
- OTDR tests on integrated FO cables
- HVAC (LF) test of both completed systems.

Initially the tests were planned to be 322 kV (1.4x Uo) for 1 hour per phase, however after the introduction of a repair joint into one of the circuits, it was agreed to increase the voltage on that circuit to 374 kV (1.7xUo).

After six hours of HVAC testing the world record cable system was ready for handing over from ABB to Energinet.dk. The two circuits were energized in November and December 2013 respectively.

DECOMMISSIONING OF OVERHEAD LINES
After the cables were commissioned the works to dismantle and decommission the overhead lines were initiated. The most challenging part was to dismantle the two belt crossing pylons which were 120 meters high.

In the end of 2014 all pylons and foundations had been removed and the 5 year long project came to an end.

CONCLUSION AND LESSONS LEARNED

Safety
When designing High Voltage- and optical accessories for cable systems such as Lillebælt, it is important use solutions that allow safe work methods, when installing / repairing cable systems with adjacent parallel systems online. In general all exposed metallic parts of cable must be direct grounded in the joining container at any time, in such a way that no difference in electrical potential can occur between cable system and worker. Apart from accessories also manuals, methods, time schedules and training of workers have to be adapted to this extended safety philosophy.

Submarine Route
Surveys are not always enough - in special areas a video investigation could be used as verification of the multi beam results.

Type test
When performing type tests on complicated submarine cable systems with joints / transition joints, terminations etc. it is essential that both constructors and manufacturers allow for some time slippage in the type test time schedule. In the Lillebælt project the type test was not completed according to time schedule mainly due to issues with auxiliary equipment. However due to the fact that the type test cable was available from start of the project this did not impact the overall project time schedule.

REFERENCES

GLOSSARY

AIS: Air Insulated Switchgear
BAS: Burial Assessment Study
CPT: Core Penetration Testing
ECC: Earth Continuity Conductor
FO: Fibre Optic
HDD: Horizontal Directional Drilling
HDPE: High-Density Polyethylene
HVAC: High Voltage Alternating Current
HVDC: High Voltage Direct Current
IEC: International Electrotechnical Commission
MB: Multi Beam
OHL: Overhead Line
OTDR: Optical Time Domain Reflectometer
PE: Polyethylene
ROV: Remotely Operated Vehicle
SAT: Site Acceptance Test
XLPE: Cross-Linked Polyethylene