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THE NORNED HVDC LINK – CABLE DESIGN AND PERFORMANCE

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ABSTRACT

The NorNed link is the longest submarine power cable system ever with a distance of 580 km. The bipolar HVDC system with ± 450 kV dc represents the state-of-the-art of "classic" HVDC technology while modern production and installation technology helped to push forward the limit of HVDC power transmission. This paper describes some of the characteristics of the power cables in the NorNed link.

KEYWORDS

NorNed, HVDC, mass-impregnated cable, submarine cable.

INTRODUCTION

The cables for NorNed were supplied by two manufacturers. Technical data given in this paper relate to the cables supplied from one manufacturer for approx. 70% of the cable route.

NORNED HVDC CABLE LINK

The NorNed link connects the Dutch to the Norwegian national power grid. Since these grids belong to different power frequency control areas in Europe (UCPTE and Nordel, resp.) they are asynchronous. For this reason, but mainly due to the extreme length of the link, an HVDC connection is the only feasible technology for the task. The HVDC converter stations are situated in Feda (Norway) and Eemshaven (Netherlands) within a few kilometres from shore. The cable route between the converters is approx. 580 km.

The link has a bipolar configuration with a 12-pulse converter in each converter station [1]. The valve stack is mid-point grounded and feeds two cables at ± 450 kV. The arrangement is a very attractive solution for a single converter block scheme for extremely long cable transmissions. The transmission voltage is effectively 900 kV giving fairly low cable current and low losses. The total losses are 3.7 % at nominal 600 MW operation. The DC link is further designed to operate continuously at 700 MW with all converter cooling equipment in operation.
The converter midpoint ground in Eemshaven constitutes the zero DC Voltage potential reference for the DC side. This is accomplished by a midpoint reactor which also blocks 6-pulse harmonic currents otherwise injected into the DC cables. The midpoint in Feda is isolated from ground with an arrester to protect the midpoint from over-voltages. The bipole configuration is shown in Figure 1 [1].

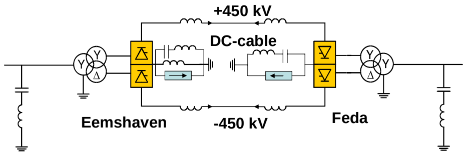

Figure 1. NorNed main circuit configuration

CABLE ROUTE

The challenging cable route includes the following components:

- Trenched land cable in the Netherlands
- Submarine cable in the tidal flats off the Netherlands, with strict environmental installation requirements, and risks of moving sands changing the thermal cable ambient
- Long portions of flat sea bottom with boulder fields with water depth <100 m
- The Norwegian trench with up to 400 m of water
- Steep tunnels in Norway

Thermal conditions

A comprehensive assessment of the thermal conditions of the cable ambient is crucial for a successful cable design. Given the extreme length of the cable route, even a very small change in conductor size would imply enormous cost changes for the project.

A sufficient conductor area must be provided to keep ohmic losses low enough so that the conductor temperature limit (50ºC) will not be exceeded. As the thermal conditions vary along the cable route the use of various conductor areas would be a tempting solution. However, using many different conductor cross sections would impair flexibility in production and installation seriously. Experience from other long-haul cable projects [2] shows that a small number (two or three) of different areas is best for logistic considerations and production flexibility.

The thermal soil resitivity in the sea bottom has been assessed from soil samples retrieved during the route survey. As the sea bed is quite similar in structure along the shallow portion of the route the samples are considered representative. Adding a comfortable safety margin, values

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of 0.7 and 0.8 m*K/W, resp. were used for the thermal design in the shallow route portion.

Another very important factor is the ambient temperature of the soil where the cable is buried. The ambient soil undergoes annual temperature variations. The annual temperature course at a certain burial depth can be described as a sinusoidal curve, the zero line being identical to the zero line of the sea floor variation. However, the amplitude of the variation in burial depth will be smaller as the depth increases, and the crest values will occur with a certain time delay weeks or months after the surface summer crest. The temperature at the cable *locus* can be described as [3]

$$\mathbf{T(z,t) = T_a + A_o e^{-z/d} \sin\left[\frac{2\pi(t-t_o)}{365} - \frac{z}{d} - \frac{\pi}{2}\right]} \qquad (1)$$

where

$T(z,t)$: is the soil temperature at time t (d) and depth z (m).
T_a is the average soil temperature (ºC).
A_0 is the annual amplitude of the surface soil temperature (ºC). A sinusoidal variation between a maximum and a minimum temperature is assumed.
d is the damping depth (m) of the annual fluctuation.
t_0 is the time lag (days) from an arbitrary starting date to the occurrence of the minimum temperature in a year.

The damping depth is given by $d = (2D_h/\omega)^{1/2}$, where D_h is the thermal diffusivity and $\omega = 2\pi /365 \ d^{-1}$. The thermal diffusivity values are taken from IEC-853-2 appendix D. A good consistency of this model with measured values is reported e.g. in [4].

Many times the soil surface temperature is being used for the thermal cable design. Using the maximum temperature at burial depth which often is a few degrees lower can reduce the required conductor area.

CABLE DESIGN

270 km of the cable route is covered with a two-core bipolar cable design called FMI (Flat Mass-Impregnated), cf. Fig. 2. The rest of the route is covered by a pair of single-core cables.

The FMI cable comprises two individual cable cores with 2x790 mm^2 Cu. Each of these cores follows the classical HVDC mass-impregnated design with the following elements:

The keystone shaped copper conductor has a copper filling factor of 98%. The profiled wires are made in an extrusion process rather than wire drawing, for better dimensional control and better conductivity.

The compound insulation is made from high-density cable paper and a high-viscous mineral-based insulation compound. The paper density is over 1 g/cm^3. The paper thickness and lapping parameters such as gap width and tension, are designed to provide optimum electric strength at high bending performance.

Figure 2. Double-core FMI cable

The lead sheath and PE-oversheath are applied in a combined uninterrupted process and provide perfect water-tightness and good mechanical protection of the cable core. A pressure reinforcement of galvanized steel tapes is applied on top of the PE sheath.
The two cores of the FMI cable are put together to form a flat cable with a polymeric spacer profile and a tape before entering the armouring machine. The armour consists of counter-helical wound zinc-coated steel wires. During armouring the wires are coated with bitumen for improved corrosion protection. It should be noted that the cable, although it contains a mineral-oil impregnated insulation, does not constitute an environmental hazard [5].

The single-core cable is installed between kilometre 270 and kilometre 420, counted from the Dutch coast. It has the same core as the FMI cable except that the cross section is 700 mm^2. It also has a counter-helical wire armouring, the wires being 5 mm in diameter.

Fibre-optical temperature measurement

The near-shore portion of the FMI cable is equipped with a fibre-optical element containing single-mode fibres for temperature measurement. The fibres allow for a distributed temperature measurement along the power cable. The monitoring unit is installed in the converter building for continuous monitoring of the temperature profile. This system serves several purposes:

- Detection of possible hot-spots
- Detection of changes in the sand cover of the cable
- Localisation of possible cable damages

When the sand cover over the cable is changed by water currents or storms the thermal properties also will change. This can be detected by comparison of actual temperature profiles with those recorded directly after commissioning. The operator now can decide upon the need for correction of the submarine situation.
A damage of the power cable cores will most probably also cause a damage of the optical fibres. By OTDR measurements (Optical Time Domain Reflectometry) possible damages of the fibres can be localized with large accuracy [4].

Dielectric design

The cable insulation had to meet the requirements listed in Table. 1.

Rated voltage	± 450 kV
Maximum operation voltage	± 463 kV
BIL	900 kV

Table 1. Electric requirements

The rated voltage is state-of-the-art for mass-impregnated HVDC cables and has been used in a number of projects since 1992, such as the Baltic Cable and Swepol projects. In these projects the insulation thickness was 19 mm. Since the small size of the NorNed conductor can lead to high stress values close to the conductor, an insulation thickness of 20 mm was chosen.

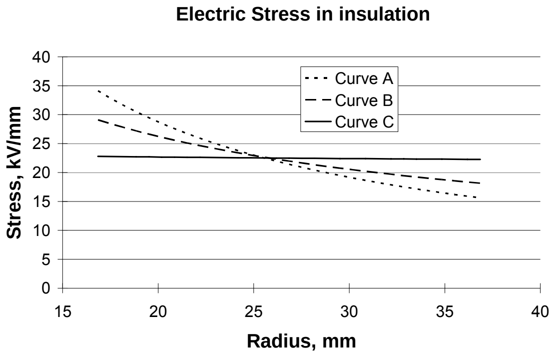

Figure 3. Stress distribution

The stress distribution in the insulation is much dependent on the load situation of the cable. Fig. 3 shows the stress distribution as a function of the radial position in the cable insulation. Curve A represents the situation when the cable is subjected to voltage without load current. It is equivalent to the distribution in an ac cable. Since the stress distribution is controlled by the specific resistivity $\rho=\rho(E, T)$ the stress will decrease close to the conductor. Curve B shows the steady-state stress distribution when the cable is under voltage but without current. Different ambient temperatures do not change this curve. When the cable is subjected to current, the ohmic losses generate a temperature gradient in the insulation. The stress distribution changes drastically. The new stress distribution requires the transport of space charges to satisfy the Poisson equation. This transport takes some time depending on the mobility of the space charges. Curve C shows the stress distribution at full load after stabilization of the space charges.

The stress distribution has been calculated according to the formulae given in [7].

Joints

For a smooth installation at sea the joints must not be much larger in diameter than the cable is. They should be flexible and have similar mechanical properties as the cable has. They must fullfill the same tensional and electric requirements. Stiff joints based on prefab components are not suitable for this type of cables.

Factory joints, installation and repair joints are all based on the same flexible cable core joint. This core joint includes a conductor weld and a semi-automatic insulation lapping procedure. After lead sheathing the joints are vacuum-dried and hot-oil impregnated.

Finally, the installation and repair joints are armoured in a patented semi-automatic armouring machine.

TESTING

Given the enormous capital investment of a long-haul cable link a comprehensive test program is important to secure reliability and availability of the cable link. Guidelines for the design of the test program were the Cigré recommendations for test of dc cables published in Electra 171 and 189.

Type tests according to the Cigré recommendation comprise the following test sequence on cables and accessories:

- Tensional bending test
- Load cycle test
- Polarity reversal test
- Lightning impulse test
- Switching impulse test

The tension in the tensional bending test is determined by the design laying depth of the cable and includes a safety margin. For the FMI cable (double core) a pulling force of approx. 10 tons was applied while the single-core cable was pulled with approx. 5 tons.

The load cycle test includes 20 cycles with 8 hours current heating and 16 hours cooling in each cycle. The current was 824 A. 10 cycles were run with positive polarity and 10 cycles with negative polarity. The test voltage was $1.8*U_0=810$ kV in the heating phase and $1.55*U_0=698$ kV in the cooling phase. For ambient temperature control the test cable was placed inside tubes with constant temperature water circulation. Type tests were conducted at 5ºC and 34ºC ambient temperature to reflect the extremities at the

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installation sites. In order to comply with the Cigré recommendations special provisions were made to prevent oil migration from the terminations into the cable.

The polarity reversal test is designed to resemble the reversal of power flow in the cable link. In HVDC systems with "classic" current source converters the power flow is reversed by changing the polarity at constant current flow direction.

Finally the test cables are subjected to impulse testing where the impulses are superimposed on a dc voltage with opposite polarity. Test levels are 450 kV dc voltage and 900 kV impulse crest voltage. On a 450 kV dc voltage an impulse with -900 kV is superimposed. Fig. 4 shows a typical voltage curve during such an impulse. Both switching impulses and lightning impulses were performed with both polarities. After the stipulated 900 kV impulses the test voltage was increased in steps of 50 kV in order to determine the performance limit of the cables. The resulting hold voltages were well beyond 1000 kV.

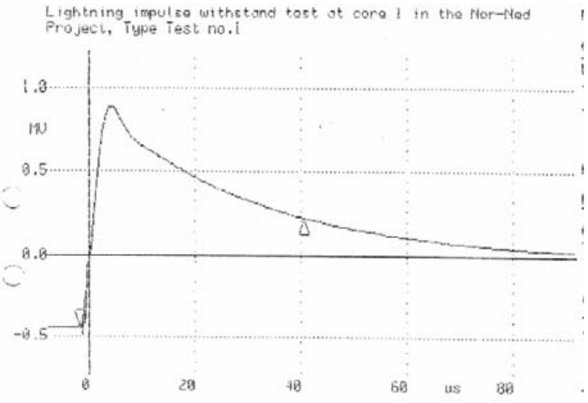

Figure 4. Lightning impulse oscillogram

These tests were conducted on both types of cables (double-core and single-core) and the joints. For MI cables made by this supplier the installation joints are always identical to the repair joints and can be qualified by the same tests.

During manufacturing the cable lengths were subjected to numerous routine tests. Tests levels were $1.8*U_0$ or $2.0*U_0$ depending on the position in the manufacturing process.

Each delivery length (between 47 km and 154 km in length) was subjected to a Factory Acceptance Test and, after loading on-board the ship, to still another high-voltage test. For this test, a special dc-GIS test termination was developed for use in the confined space on board [8].

INSTALLATION

The installation of almost 600 km of a double circuit of submarine cable requires enormous logistic efforts and technical skills. Although the water depth in the larger part of the route was less than 100 m, the conditions in the tidal flats off the Netherlands imposed a major challenge. Not only that the heavily loaded cable ship could navigate some portions only during high tide but also strong tidal currents and strong winds made the installation complicated. During cable laying, and especially during jointing, the cable ship is restricted in its ability to manoeuvre. For this reason there are certain limits in wave height, swell intensity, wind speed and the ship-to-wind angle for laying operations. Only when a time window of acceptable weather conditions over a sufficient time span appears in the forecast, an operation such as laying or jointing can be commenced. Especially during the winter on the North Sea these weather windows can be scarse.

SUMMARY

Although the idea of transporting electric power by submarine HVDC cables from Norway to Western Europe has been discussed at least since 1933 [9] the technical means for this project became available with sufficient reliability only in the recent years. Optimized production methods and high-level quality assessment of materials and processes allow the production of very long lengths of HVDC submarine cables possible. The NorNed link demonstrates that power cable links over very long distances are feasible and economical.

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