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NorNed – World's longest power cable

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SUMMARY

The NorNed cable was commissioned on 6 May 2008 after three years of intensive engineering and construction. It was important for this efficient implementation that a core project team had been maintained over a relatively long period, preparing all licences, all major supply contracts, etc.

The paper will describe the way of detailed engineering, manufacturing and installing altogether 1160 km of high voltage cable, some of it in form of a two core cable and a major part as ordinary single-core cable.

The strict magnetic compass deviation requirements as well as environmental concerns related to the magnetic field set up by a single cable led to the special two-core mass-impregnated cable used in the NorNed project. In the northerly deeper part of the cable route ordinary single-core cable was applied.

The North Sea is a rough working place and the work scope offshore was far beyond all other known submarine power cable projects. How NorNed managed the resulting challenges is being described. The extensive offshore jointing activities have resulted in experiences which are important for future projects of a similar kind.

After having been laid, the cables were protected by water jet trenching over close to 97% of the cable route. The rest, including the crossings, has been given protection by rock dumping.

Following successful after installation test NorNed experienced two offshore cable failures and had to mobilise extra vessel spreads in order to get the situation restored.
This has led to a discussion about test methods and the sequence of work.

KEYWORDS
HVDC transmission, Cable design, Cable installation, Cable experience

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1 INTRODUCTION

NorNed, the 580 km HVDC (High Voltage Direct Current) interconnection between Norway and the Netherlands, was put into operation on 6 May 2008 after several years of planning and three years of intensive detailed engineering, manufacturing, testing and construction work.

The project consists of two distinct parts, namely the converter stations at both ends of the route and the cable system. This paper will briefly explain the chosen transmission system; else the focus will be on the cable system.

At the date of reporting the link has been in operation for 18 months. With respect to revenues the NorNed case has been a success in spite of some setbacks in the form of cable failures. The last half year of operation has been stable without significant interruptions.

2 BACKGROUND AND OVERVIEW

When the feasibility of NorNed was positively concluded in 1992, the cost was based on a monopole scheme with sea electrodes. The capacity was therefore set to 600 MW, which at that time was considered to be a realistic rating for one cable. The concept was also built on the positive experience with Skagerrak, Fennoscan, Baltic and Kontek HVDC links. All four links are still being operated with sea electrodes with very limited complaints.

The first pre-engineering process was completed for the monopole concept and licensing notices transmitted accordingly to the Netherlands, Germany, Denmark and Norway.

The pre-engineering work included an extensive modelling of the influence from the electrodes on the electrical field distribution. The basis for sending notices was the conclusion that the area of influence after all was limited and that any problems in the influenced area could be mitigated without prohibitive costs.

The public processes raised stronger concerns than expected related to the electrolytic process at the electrodes, to the possible unforeseen effects of the magnetic field set up by the current in the cable and also to the aspects related to the possible stray current influence on infrastructure in the area close to the electrodes.

The chlorine development at the anode is well known. Toxic by-products are formed, which can be accumulated in biotops over long periods of time.

The concerns regarding the magnetic field are hard to solve with one single cable, especially in the very shallow waters of the Netherlands and Germany.

One concern is the navigation by magnetic compasses where the maximum allowable deviation was set to 5^o. This is impossible to fulfil in some sections of Waddensea where the water depth is 8-10 m only, with one single-core cable.

The other even more intricate question, which needed an elaborated answer, was (and still is) the influence from the magnetic field on all sorts of marine species.

It is a fact that many of the species in these waters navigate by means of the earth magnetic field. Hence, it is possible that their navigation could be influenced by this type of disturbing field. However, from observing the conditions around all the single-core cable schemes in Skagerrak and in the Baltic Sea, there is no sign that such disturbance has any significant influence whatsoever. This is, of course, extremely difficult to prove since monitoring of marine life at upto 550 m depth is not really feasible.

Much focus was also put on the risk for corrosive influence from the electrode stray currents on infrastructure. When the southern electrode was placed reasonably close to the converter station at Eemshaven to avoid extraordinarily long electrode cables, the area of increased earth potential stretched sufficiently far into the mainland to generate difficult questions from gas pipeline owners onshore with respect to corrosive effects. Although these can be calculated and mitigated, it leaves the cable owner with the burden of proof and therefore a cost which is hard to predict and control.

All these aspects led NorNed into a process of re-thinking its transmission configuration.

It is easy to start thinking that you in such a situation need to isolate the current and let the return current be led back close to the other current path in order to minimise the field. But how can this be done without dramatically increasing the cost?

Creative interdiscipline co-operation released the NorNed concept. It is fair to say that NKT's flat-type two-core cable, which was used in the Kontek project in 1996 inspired the development in the direction of taking into use a "simplified bipole". The concept was for the first time used with the old Cross Channel link (1961-84). NorNed is the first project to take this transmission scheme into use with ±450 kV. Since the system utilises both a positive and a negative full voltage, the term simplified bipole seems adequate.

The clue with this concept is that the cost of stations does not increase dramatically because it is only served by one set of transformers and has the same number of thyristors, however, distributed in six thyristor columns. The principle single line diagram is shown in figure 1.

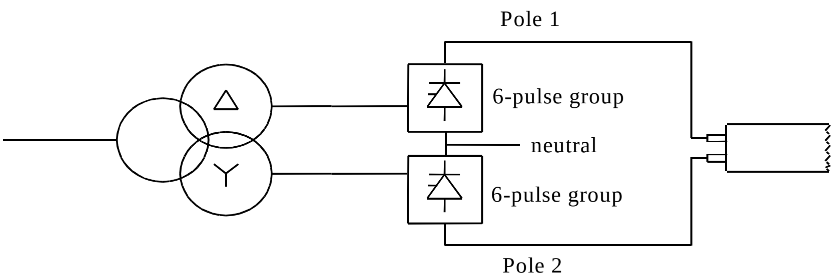

Figure 1 - The simplified bipole principle

As already indicated, the cable solution for the new NorNed bipole concept was inspired by the Kontek two-core cable. The flat-type cable was even for a period considered used for the whole 580 km route.

Over time a more conservative approach was chosen, leading to use of mass-impregnated cable throughout the route. The two-core concept was, however, maintained to cope with the magnetic field limitations in the Netherlands and Germany.

The two-core mass-impregnated cable is consisting of two complete single-core cables with common armouring. It can be seen as two single-core cables bundled in the factory.

The advantage with this cable design besides the minimised magnetic field, is that it can be handled by one turntable on the cable installation ship. It also reduces the number of trenching operations and/or rockdump operations to one. It also provides advantages in terms of predictability and product safety regarding in-line jointing operations (field jointing offshore).

The disadvantage is more complicated handling of the cable during laying and potential repair operations since the two-core cable can only be bent in one direction. NorNed has, however, already proven its repairability two times during commissioning work.

The repairability aspect, however, caused use of single-core cables in the deep part of the route, which is across the Norwegian trench and in the outer part of Fedafjord (410 m). The deeper the water, the more burdensome the handling for repair operations will be. In deep waters, the magnetic field causes less concern than in the shallow waters further south.

An overview of the chosen cable system is shown in figure 2 below.

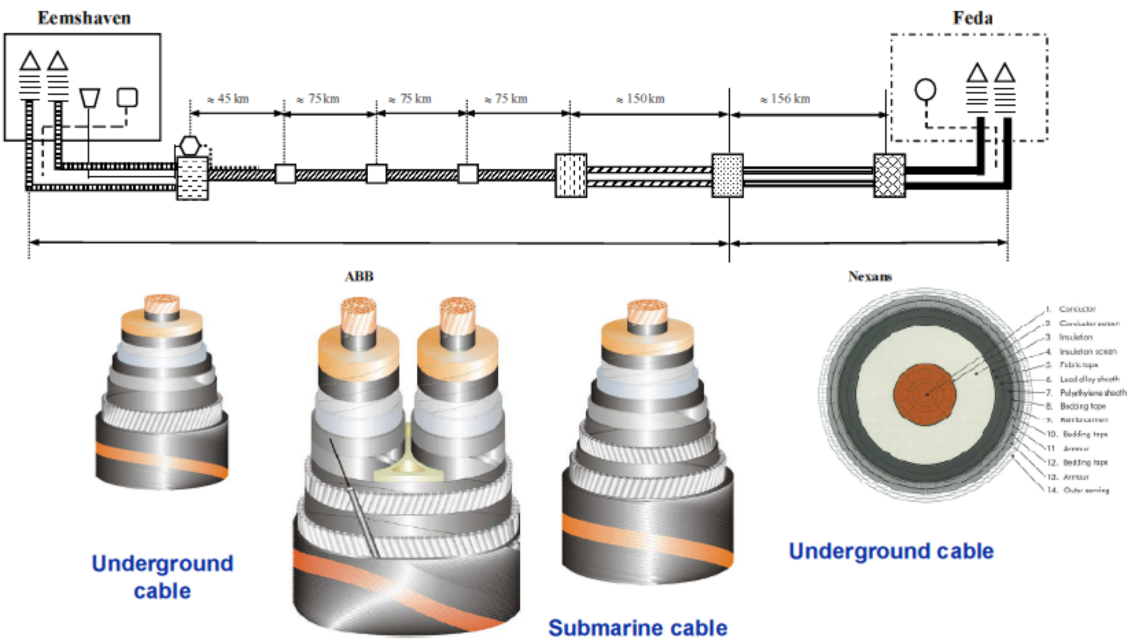

Figure 2 – Cable types

The extraordinarily long planning period of NorNed from 1994 to 2004 was partly caused by contractual unbalance between the Dutch and Norwegian parties. The key to successfully start the implementation was a renewed arrangement with a 50/50 cost and revenues sharing between TenneT and Statnett. This created a ground of common interest which enabled building an organisation for the implementation, which could rationally and efficiently make decisions for the project. In this context, it was also important that it was possible to secure continuity of some key resources from the planning period.

This long period turned out to be an important and valuable contribution to the fast and efficient execution of the project. All licences, crossing agreements and main supply contracts were in place and implementation could start immediately after the construction decision in December 2004.

3 CABLE SYSTEM SHALLOW PART

The design of a submarine power cable includes much more than the determination of conductor size and insulation thickness. Not only thermal and dielectric conditions must be taken into account. The cable designer needs also to analyze the following aspects:

- marine environment (hydrographical, bathymetric, and geophysical conditions)
- protection needs
- permission requirements
- installation spread and methods
- operational requirements.

These conditions were varying along the cable route, hence calling for an adapted design for different sections. Only full consideration of all aspects can result in a successful project.
The generic design of the NorNed cable system (round conductor of profiled-wire copper, mass-impregnated paper-lapped insulation, lead sheath) is well-known from many previous projects. In the

shallow part of the NorNed project from the Dutch converter station to kp 420, the kilometre point 420 km from the Dutch shoreline, three different cable designs were installed.

Since the cable route crosses the busy ship traffic lane in the German Bight, authorities required to avoid possible deviation of magnetic compasses. Authorities also had quite some concerns regarding the potential impact from the magnetic field on different marine species. In this southern part of the cable route authority permissions were granted for a two-conductor design flat mass-impregnated (FMI) cable. The proximity of the conductors almost eliminates the resulting magnetic field. Figure 2 shows a cross section of the NorNed cable installed between the Dutch shore and kp 270.

The cable contains two complete fully insulated cable cores, each having a copper conductor, mass-impregnated paper insulation, a lead sheath and pressure reinforcement. As in all contemporary mass-impregnated cables the paper is high-density craft paper, impregnated with high-viscosity mineral-oil based compound. The very high viscosity accounts for the fact that no fluid emerges from the cable into the environment, even in the case of a severe damage.

A single wire layer armouring would provide enough tensional strength for cable laying in the shallow water (< 70 m). However, an analysis of all aspects showed that there was need for a stronger protection. First, the anchors of large merchant vessels can penetrate the seafloor down to a few meters and impose a threat to all cables. Second, tidal currents and storms can induce substantial seafloor movements in parts of the North Sea. Third, the envisaged trenching of the cable into 1-3 m depth may impose strong mechanical stresses.

The benefits of reducing the risk of cable damage, outage time and repair costs outweighed the extra costs of a second armour layer. As a result, the NorNed cables were equipped with a strong counter helical double-layer steel armouring. Soaking the galvanized armouring wires with bitumen provided additional corrosion protection. Tensional bending tests corresponding to 420 m water depth were carried out successfully on the torsion-balanced cable.

The manufacturing and installation of the two-core cable imposed considerable challenges as a “flat” cable can only be easily bent in one plane. Various bending and twisting tests were performed for a better understanding of the mechanical properties of the FMI cable. The cable gantries and cable traction systems in the factory and on the laying vessel were re-designed in order to handle the cable.

In the cable route between kp 270 and kp 420 two single-core MI cables with double-layer armouring were installed with a distance of approx. 50 m. The mutual distance of the cables avoided mutual heating and a slightly smaller conductor size compared to the FMI cable could be applied.
The short Dutch onshore route was covered by a pair of single-layer armoured underground MI cables.

For the thermal design of the NorNed cable a desk-top study was performed to assess the annual variations of the soil temperature for different route sectors. Soil thermal resistivity values were retrieved from in-situ measurements. It became clear that the slight differences in the thermal environment along the cable route would not justify the manufacturing of different cable cross-sections.

The Dutch land fall had to be given special attention. The cable had to cross the outer dike which is part of a vital floodwater protection system. Authorities posed very stringent requirements on the reinstatement of the dike after installation. Also the thermal environment of the dike crossing had to be investigated. The risk of drying-out of the soil near the cable could be ruled out as the cable surface temperature would not exceed 40ºC. It was decided to pull the submarine FMI cable from the open sea through an open cut at a level of 1.2 meter under the dike surface. The transition joint to the land cables could hence be placed safely on the sheltered side of the dike.

The extreme length of the cable route required several off-shore jointing operations. All applied joints are flexible with a diameter only slightly above the cable diameter. The generic joint design, used for all submarine and on-shore joints of the shallow NorNed part, comprises a flush-weld conductor joint. The joint insulation was produced using a semi-automatic paper-lapping machine inside a large purpose-built jointing container with controlled air temperature and humidity.

The variety of cables along the cable route required various transition joints. Different conductor sizes, insulation thickness, and armouring concepts were used along the cable route and needed to be connected. The two conductor sizes 700 and 790 mm^2 were jointed by the same welding method that was used for jointing of identical conductors. The transition between the slightly different conductor sizes was accomplished by careful tapering of the weld portion.

The semi-automatic paper-lapping machine allowed a smooth transition between 19 and 20 mm insulation thickness without compromising the dielectric stability.
The deep water cable had a flat-wire armouring while the shallow water cable had a round-wire armouring with a different number of wires. Standard wire-to-wire welding methods are not suitable when jointing different armour types. A purpose-designed welding sleeve featured tailor-made shoulders to each side of the joint providing a perfect welding base.

The design of the transition joint between the two-core and the single-core cable was a delicate challenge. The electric cores were jointed together in the traditional way when jointing two single-core cables. Afterwards a new section of armouring wires was applied over the transition. A “manifold” welding sleeve facilitated the connection of the armouring wires from both sides. The transition joint was tested to the same mechanical stresses as the cable itself for 100 m depth.

The FMI cable portion stretching out from the Dutch coast was equipped with a fibre-optical element in order to monitor the temperature along the cable. The Distributed Temperature Sensing (DTS) system was accommodated in the converter station and connected to the FMI optical element by means of a standard underground optical cable. The optical element in the FMI cable consisted of a 1.32 mm stainless steel tube holding two single-mode fibres. The stainless steel tube was covered with a polyamide sheath with 6 mm diameter. The sheath contributed to the tensional strength of the optical element and provided a tough system. In parts of the cable route the optical element was additionally equipped with an internal wire armouring. The experience is that the preference is to accommodate such fibre element somewhere inside the cable e.g. in the inner armour layer.

	Dutch underground	Shallow waters 1	Shallow waters 2
Route length	1.4 km	270 km	150 km
Conductor size	790 mm^2	790 mm^2	790 mm^2
Insulation	20 mm	20 mm	20 mm
Armouring	Single layer	Double-layer	Double-layer
Configuration	2 x single-core	Two-core (FMI)	2 x single-core

Figure 3 - Shallow part cable system

4 CABLE SYSTEM DEEP PART

The deep part cable system consisted of:

- 2x oil filled sealing end 450 kV
- 2x 1.5 km mass-impregnated tunnel cable -L 450 kV 1x760mm^2.
- 2x transition joint submarine to tunnel cable.
- 2x 156 km mass-impregnated submarine cable L 450 kV 1x700mm^2.

An overview of the system is shown in figure 4 and 5:

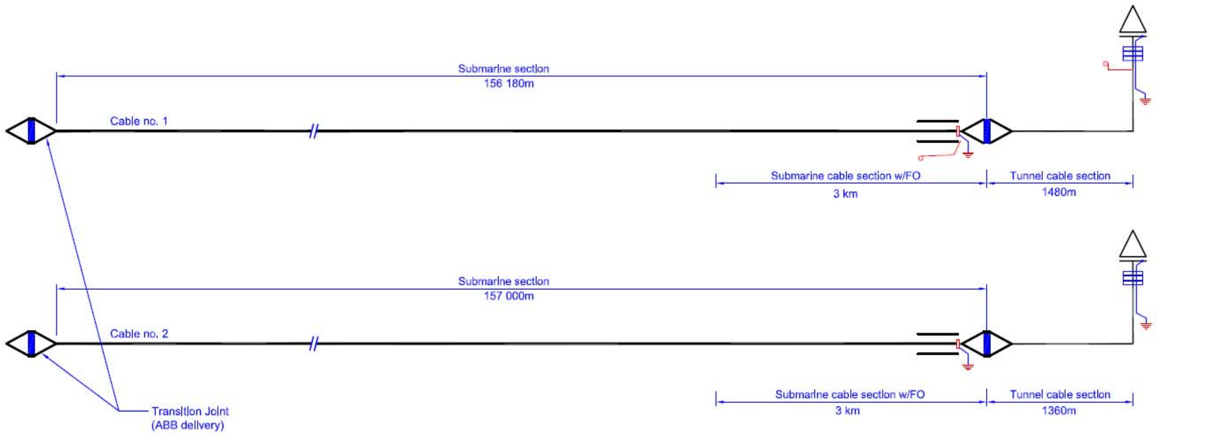

Figure 4 - Deep System Overview

	Land section ~100 m	Tunnel cable 1,4 km	Drill hole	Norwegian trench and Fedafjorden	Deep part Offshore route
Route length	0.1 km	1.4 km	0.15km	Approx. 12km	Approx. 144km
Conductor size	760 mm^2	760 mm^2	700 mm^2	700 mm^2	700 mm^2
Insulation	19 mm	19 mm	19 mm	19 mm	19 mm
FO element	Ø2,3mm	Ø2,3mm	Ø2,3mm	Ø2,3mm/3km/5km	
Armouring	Double-layer	Double-layer	Double-layer	Double-layer	Double-layer
Configuration	2 x single-core	2 x single-core	2 x single-core	2 x single-core	2 x single-core

Figure 5 - Main characteristics of the different sections

From the cable termination at Feda in Norway it first runs through a 1.4km long tunnel down to a jointing chamber. Here the cable was jointed to the submarine cable. From there on the cable runs through a 150m long micro tunnel down to the sea bed approx. 45m under sea level. Further on the cable is installed 156km out the Fedafjord and is jointed to the ABB single-core cable on the southern side of the Norwegian trench.

Figure 6 – The deep part of the NorNed cable route

Both the submarine and the tunnel cables are mass-impregnated (MI) cables.

The MI cable has been developed extensively in the last 15 years and it has been certified for transmission of 800 MW at 500 kV, according to Electra No. 72. The mechanical testing of this type of cable has been conducted for 500 m depth according to Electra No. 68. The resulting renewed knowledge was taken into use in the NorNed project.

In addition to the analyses mentioned in chapter 3 the design parameters of the MI cable were:

- power to be transmitted: 700 MW continuous (measured at receiving end)
- the given voltage level: ± 450 kV
- the transient voltage level: 2 x U_0
- the maximum allowable electrical stresses in no-load and full-load conditions (set by the manufacturers)
- in addition: maximum dimensioning current in this case: 824 A

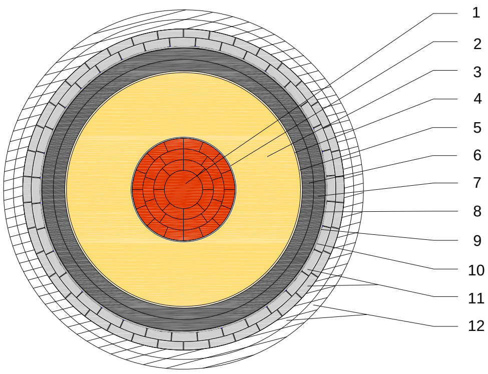

Figure 7 – Submarine cable

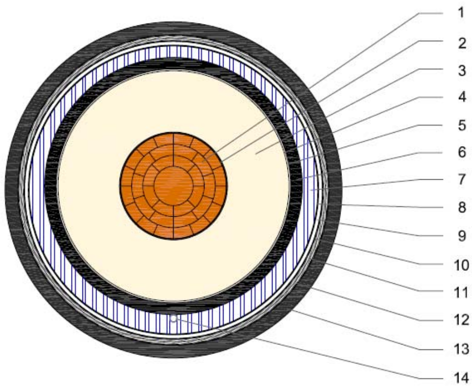

Figure 8 – Tunnel cable

The tunnel cable was delivered to Feda on 2 drums each with 1500m of cable. The installation was done by use of small caterpillars pulling the cable in the trough. Due to the steepness of the tunnel the cable had to be designed with longitudinal reinforcement. The longitudinal reinforcement was employed to take up some of the axial mechanical stresses the cable is subjected to during the installation process.

The tunnel cable had to have a slightly larger conductor, 760mm^{2,} than the submarine cable, 700mm^{2,} due to the thermal conditions. In addition the tunnel cable was installed in a concrete trough which was filled with a Weak mix concrete with the right thermal resistivity and mechanical strength. This solution together with the temperature measurement system should prevent overheating of the cable during service.

The submarine cable was designed to be laid across the Norwegian trench and the deepest part of 410m at the inlet of the Fedafjord. The armouring consists of 2 layers of counter helical flat 2,5 x 7,5mm wires giving a very compact design beneficial for use for larger depths. During the deep water installation there were 3 cable crossings where Uraduct tubes were used as separation layer.

At kp 576 the submarine cables were pulled through a 150m directional drilled rock hole with PE lining, were the inlet was at 45m below sea level and outlet in the tunnel a few metres above sea level. Installation of cable 1 started with 1st end pull-in at kp 576, but cable 2 was installed by 2nd end pull-in.

After the submarine cables were installed, a joint between the tunnel and the submarine cable was conducted in a tent at the bottom end of the cable tunnel. Also the fibre optical element was jointed. The cable armouring of the submarine cable was terminated in a hang of clamp system to secure the cable from being dragged/sliding out from the micro tunnel.

A fibre optical element was included in the inner plastic sheath above the lead sheath both in the tunnel cable and 3km/ 5km in the submarine cables. The steel-tube was 2,3mm and contained 4 multimode fibres which are used to read the temperature on the lead sheath along the cable route sections. The temperatures are then used in an algorithm to determine the possible ratings of the cable system.

5 SUBMARINE CABLE INSTALLATION

NorNed's handling of the submarine cable installation cannot easily be understood without some background explanation.

One important factor was the fact that Statnett, when NorNed was started, owned and controlled the cable lay vessel Skagerrak. It was therefore a given presumption that this vessel should be used for the laying of cable. The other most important driver was the fact that the agreed control estimate for the project did not contain sufficient cost for additional protection of the cables in the form of trenching or rock dumping. This lead to a separate submarine cable installation contract with C/S Skagerrak as Statnett/TenneT provided item.

Although Statnett/TenneT had been performing a thorough route survey already in 1997, the installation activities comprised pre-lay survey work in order to update and supplement the previous survey data.

The survey campaigns, which were performed both in 2005 and 2006 prior to corresponding laying campaigns, in addition to bathymetry, comprised sub-bottom profiling and side scanning. In some areas the conditions were also inspected by video camera. The pre-lay survey also had focus on removal of debris in order to remove hindrances for trenching.

Near shore the survey spread accommodated representatives from authorities looking for environmental and archaeological items such as valuable ship wrecks, coral reefs, etc.

The installation works detailed engineering process, besides establishing procedures for all work sequences, had much focus on route optimisation in order to maximise trenchability since trenching is a much more cost efficient protection method than rock dumping.

The NorNed cable laying consisted of eight planned laying campaigns, altogether 45000 tons of cable. Most of the campaigns comprised field jointing in addition to laying. All eight campaigns went remarkably well without very serious incidents or personnel injuries. In this respect the installation contractor Tideway was very well organised.

However, it is an important learning that the number of vessel days became much higher than anticipated due to several factors. The main contributor was of course the very rough North Sea weather and the tendency to see an increasing amount of extreme weather even in the summer season. However, some delay in the cable manufacturing also indirectly caused waiting on weather by bringing laying more towards the winter half year.

Figure 9 - Fully loaded lay vessel Skagerrak in Eemshaven

The weather concern also created quite some tension to the construction all risk insurers, who actually demanded a halt in the installation process until after a certain date. With the total NorNed cable workload such on and off insurance arrangement is not really acceptable and therefore constitutes an unresolved issue with respect to insurability of such a large operation.

The NorNed trenching experience is very varied. The main tool used was the Capjet trencher owned and operated by Nexans. This machine, most of the time operated from “Siem Louisa”, worked efficiently along major parts of the route.

What turned out to be a weak part of the trenching operation was the lack of accurate and expedient as-trenched survey work. This lead to a slow decision process regarding satisfactory protection. The consequence is a lot of extra shuttling of vessel and a large number of extra deployments.

But in the end the parties managed to conclude on the quantity of rock dumping and this programme was completed in time and has provided an all in all excellent protection of 270 km (two-core) + 2 x 306 km (single-core) = 882 km of cable, which represents a tremendous effort.

The real problematic part of the NorNed trenching experience is trenching of the first 40 km of two-core cable across Waddensea. The plan created by Tideway and their partner Bohlen & Doyen, was to use their jet sledge with U-shaped trenching swords acting as a cable depressor. The sledge was supposed to be towed from an anchored barge by a 50 t winch. The combination of quite some use of pulling force, lack of proper instrumentation and hard soil with unexpected stones created damage to the cable to a degree, which caused need for replacement of 10 km of cable.

In order to complete the Waddensea trenching the project employed several other trenching spreads such as Capjet (Nexans), Atlas and Otter (Global Marine) and a trencher owned by JD-Contractor. Over some stretches these machines did achieve adequate burial depth, but got into quite some problems in other sections. Consolidated peat created large problems in the inner part of the route. This is where the parties still have a challenge regarding achieving sufficient protection.

The rock dumping operations went without problems. This type of protection works turns out to be going according to very robust methods. The process can if necessary also without risk be performed on live cables. That, in addition to quite good weather limits, gives excellent construction flexibility.

The importance of consistent protection along the NorNed route has already been documented by inspection surveys. The picture figure 10 shows an example of trawl scars around 405 km from Eemshaven.

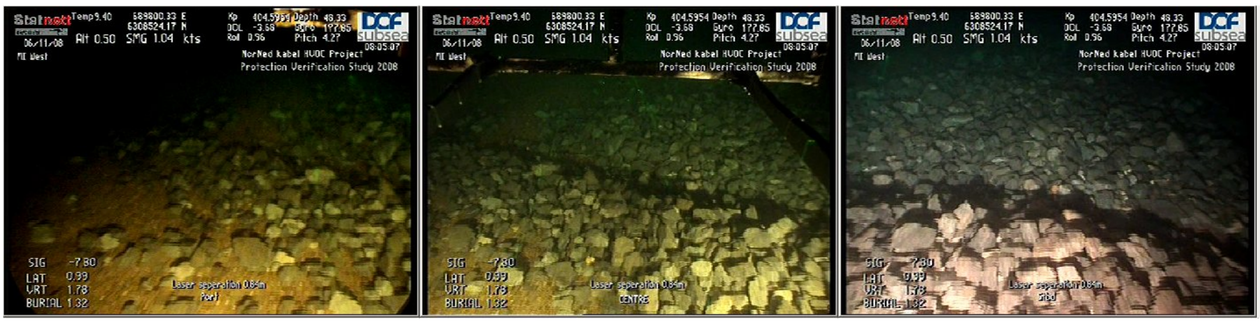

Figure 10 - Recently experienced trawl scars in dumped rock protection

As can be seen from the rock dump pictures, the trawl gear has penetrated the rock pile in quite a severe manner. For future projects it might be recommendable to study the stone grain size distribution once again. Perhaps even larger stones in an outer layer in the rock pile could be necessary.

When performing inspection surveys NorNed has tried to find a method, which can use the DC current normally floating in the cable conductor as the detection signal for finding the burial depth. For single-core cable this has turned out to be possible. For two-core cable no very good results have been achieved so far.

Statnett and TenneT keep close to 10 km of the different NorNed cable types in stock on a purposely made indoor turntable at quayside in Fedafjord in order to be prepared for repairs. The storage building also contains various jointing equipment and spare jointing kits.

However, due to the low frequency of repairs, TenneT and Statnett as operators cannot train their own jointers. An interdependency of the supplier regarding the repair jointing itself will remain. This should probably be organised as part of the supply contract already at an early stage.

When NorNed had to perform two cable repairs offshore before the HVDC link could be put into operation, the value of prepared and immediate access to skilled jointers from the supplier was experienced. The failure causes are as usual not easy to find and the incidents are still being evaluated and discussed.

Also in 2009 the link experienced operational problems which are still being investigated. First one DC cable failure was experienced close to the converter station in Eemshaven and not long after an extensive fire which started in a 420 kV AC cable (Prysmian delivery) connecting the converter station to the TenneT grid caused a 10 weeks outage.

6 CONCLUDING REMARKS

The overall assessment is that the NorNed implementation was successful and that the link functions as presumed contributing to reliability and sustainability of power supply.

NorNed is proving that power transmission over 580 km distance is feasible and without causing unacceptable power loss. The NorNed transmission loss at full load 700 MW (receiving end) is 4.2% only.

The NorNed project encourages even more research work within the field of extra high voltage DC cables in order to better define the real limits regarding installation parameters (bending, tension, temperature, etc). It also seems to be a need for improved test technology. It can be seen from the fact that NorNed experienced two cable failures after successful after installation test as recommended by CIGRE.

BIBLIOGRAPHY

[1] J.E. Skog et al. The NorNed HVDC cable link B1 Colloquium, Bergen, June 2009

[2] J.E. Skog et al. The NorNed cable link. A power transmission highway between Norway and the Netherlands, Stavanger 2006.