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Paper 304 Cigré SC B4 2009 Bergen Colloquium

The Cobra Cable - A feasibility study regarding an HVDC submarine cable inter connector between the Netherlands and Denmark

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SUMMARY

The TSO's TenneT TSO B.V. and Energinet.dk have performed a feasibility study of a 600 MW HVDC submarine cable connection, named the Cobra Cable, between the Netherlands and Denmark. This paper describes the process of assessing the different cable routings and connection points, the expected utilisation of the cable and the possibility of providing ancillary services. The annual transmission losses for different HVDC technologies and DC voltages are estimated based on the expected utilisation of the cable. From the study it is concluded that it is feasible to build an HVDC connection between Denmark and the Netherlands.

KEYWORDS

LCC HVDC, VSC HVDC, transmission losses, ancillary services, feasibility study.

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1. Introduction

After a successful start of the HVDC NorNed link between Norway and the Netherlands in 2008, the transmission system operators of Denmark (Energinet.dk) and the Netherlands (TenneT TSO B.V.) have started a feasibility study to an HVDC inter connector between Denmark and the Netherlands, with the intention to strengthen both systems. Furthermore this study is also started from the perspective that it can attribute to the intentions of the Dutch and Danish governments to increase the amount of wind generated power.

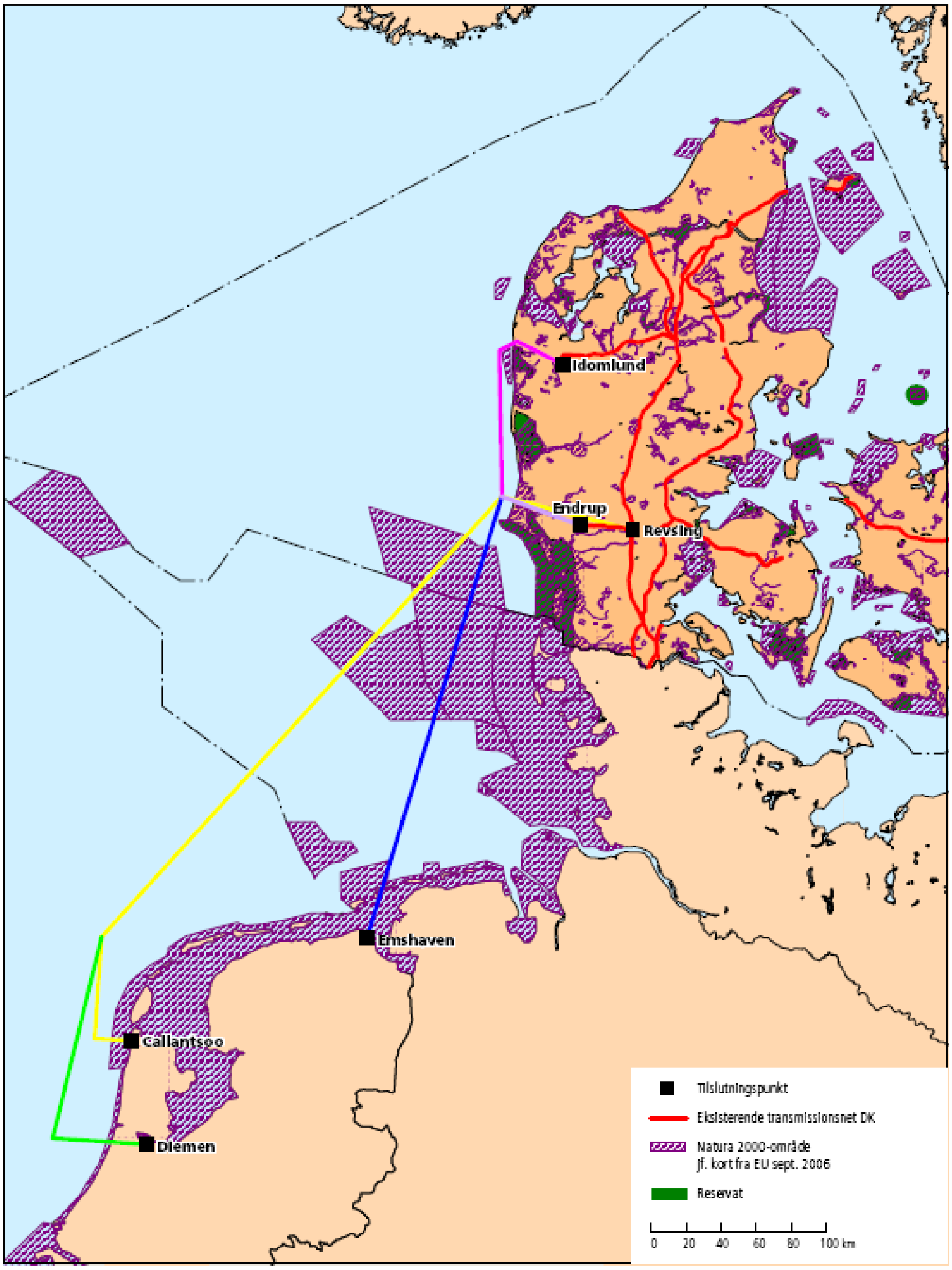

Figure 1: Map of possible routings and connection point for the Cobra Cable. Some very large marine Natura 2000 sites are located off the cost of Germany and at the possible cable landings and connecting point in the Netherlands and Denmark

2. The electricity transmission system in the Netherlands

The Dutch electricity transmission system is owned and operated by TenneT TSO B.V. The Dutch transmission system consists of a 380 and a 220 kV network and is part of the UCTE network. Present, there are five high voltage overhead line inter connectors with Germany and Belgium. The transmission system has also two international HVDC connections, one already in operation and one under construction. Since 2008 the 700 MW HVDC connection with Norway (NorNed) is successfully in full operation. The 1000 MW HVDC connection with Great Britain (BritNed) will become in operation at the end of 2010.

The Dutch 380 kV network is based on a centralised ring structure (double circuit), with some single branches towards production locations. Because of the announced increment of installed production capacity and the forecasted increment of the load, several 380 kV grid reinforcements are planned or already under construction.

The power production in the Netherlands is at the moment mainly based on gas and coal fired power plants, partly concentrated in north and in the west of the Netherlands. The total amount of installed production capacity is approximately 21000 MW (year 2008), including the wind generation already in operation. The load is concentrated in the south-west part of the Netherlands.

3. The electricity transmission system in Denmark

The transmission system in Denmark is owned and operated by Energinet.dk, the Danish TSO. The Energinet.dk system is divided into two electrical separated systems, the Eastern system and the Western system. The Western system is synchronous with the European UCTE system via 400 kV and 220 kV AC transmission overhead lines. The Eastern system is synchronous with the Nordic system NORDEL via 400 kV and 132 kV AC submarine cables.

The Danish power system is characterised by a high penetration of distributed power sources, i.e. wind power and CHP (Combined Heat and Power) plants. In the Western system, the wind power penetration is 200%, which is calculated as maximum wind power production divided by minimum consumer loading, while in the Eastern system wind power penetration is 85%. Where CHP is concerned, the penetration is 136% in the Western system and 74% in the Eastern system.

The following HVDC links with a total capacity of 3120 MW are expected to be in operation in the Western system in 2016:

- Konti-Skan 1, 380 MW (1965, new converters in 2005)
- Konti-Skan 2, 360 MW (1988)
- Skagerrak 1, 250 MW (1976, new control system in 2007)
- Skagerrak 2, 250 MW (1978, new control system in 2007)
- Skagerrak 3, 500 MW (1993)
- Skagerrak 4, 640 MW (planned as bipole with Skagerrak 3 in 2014)
- Storebælt 1, 600 MW (2010, under construction)
- Cobra Cable, 600 MW (2016, under planning, transmission capacity and connection point not yet decided).

4. DC cable routing and location of the HVDC stations

4.1 Introduction

The feasibility of getting the necessary permits and the legal approval is examined for the new converter stations in the Netherlands and Denmark respectively and for the land route and the offshore route of the Cobra Cable which will pass German territory, see figure 1. TenneT and Energinet.dk have examined the project for appropriate knockout criteria in their own country. In particular, approximations to spatial planning and environmental aspects have been considered.

4.2 Dutch location

TenneT has investigated five options at four locations where the Cobra DC cable could land to the Dutch coast, where the converter station could be located and where the connection to the 380 kV AC grid could be made. The investigated locations are spread over the Netherlands, locations in the North and the Western part of the Netherlands have been surveyed. The performed assessment is in particular based on the nearby availability of a 380 kV AC substation, the possibility to obtain building land for the converter station, the length of the submarine cable, the length of the land cable and a thorough review of the expected licensing procedure. Also the risk of congestion for the transport of the electrical power of the cable in the Dutch transmission system has been investigated. Based on the fact that the shortest submarine cable will have an important positive effect on the business case, the location Eemshaven, which did anyhow met the most important demands, is selected as the preferred location.

4.3 Danish location

Energinet.dk has investigated three options where the Cobra DC cable could land to the west coast of Jutland, where the converter station could be located and where the connection to the 400 kV AC grid could be made. Based on an comparable assessment as in the Netherlands, the preferred location in Denmark is Endrup, although the DC submarine cable shall have to be extended onshore by approximately 40 km.

5. Utilisation of the Cobra Cable

5.1 Introduction

In order to obtain the revenues of the Cobra Cable, the effect of the Cable on the operation and market structure in both countries and the economics of the cable has been investigated.

5.2 Economic services

With respect to the economics of the Cable, three different scenario's (reference scenario, wind scenario and a fossil scenario) are investigated by means of a power market simulation tool. This work has been performed by Econ Pöyry, supported by TenneT and Energinet.dk.
The load duration curve, presented in figure 2, is based on the wind scenario because this scenario is best in line with the ambitions of both Denmark and the Netherlands to increase the amount of installed wind generation in favour of fossil generated power. According to the wind scenario as presented in figure 2, 77 % of the yearly energy transmission capacity (5.3 TWh) of the Cobra Cable will be used, with 4700 equivalent full load hours of transmission from Denmark to the Netherlands and 2000 equivalent full load hours from the Netherlands to Denmark. The results from the load duration curve are used to calculate the yearly transmission losses for technical and economic evaluation of the Cobra Cable and to estimate the yearly revenues by assessing the future market developments.

5.3 Revenues related to ancillary services

Besides revenues from economic services, the Cobra Cable can also attribute to the operation of the transmission systems in both countries. The possibilities for exchange of ancillary services of the Cobra Cable were investigated. The following benefits that could be obtained with the Cobra Cable have been identified and will be briefly discussed:

5.3.1 Wind Power

It is investigated whether imperfect forecasts in wind generation leads to additional benefits with are not included in the economical assessment. It is concluded that this creates opportunities for both TSO's to exchange ancillary services by mutual cancellation of system imbalances or by using the most efficient reserve.

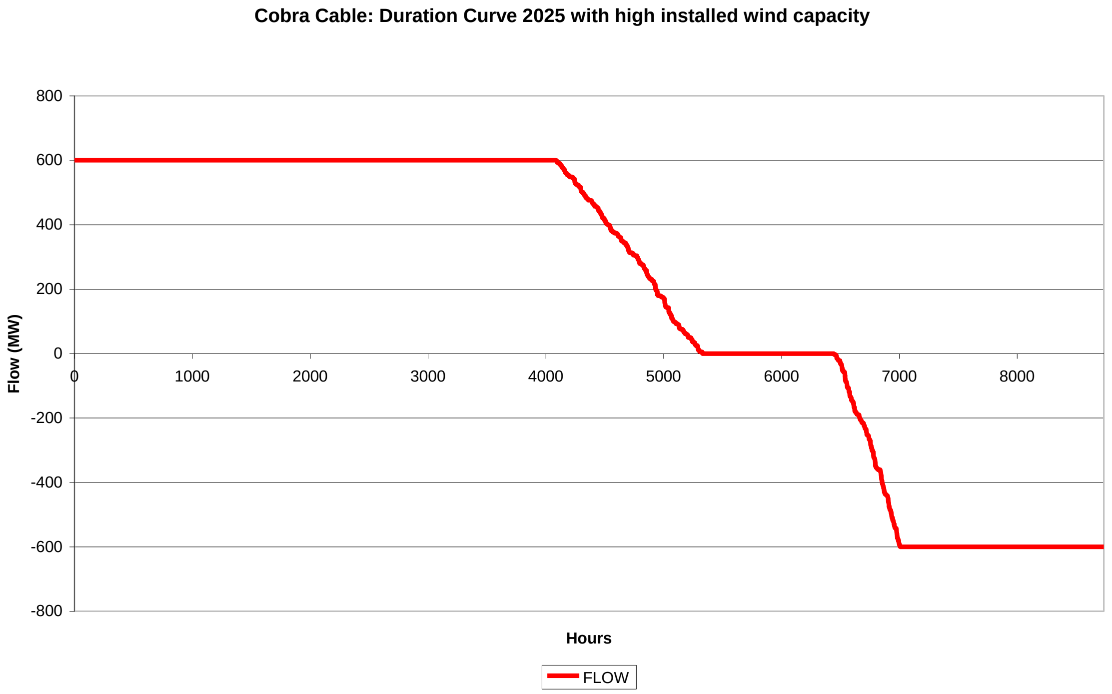

Figure 2: Load curve for Cobra (77 % utilisation). + MW is power direction from Denmark to the Netherlands and - MW is power direction from the Netherlands to Denmark.

5.3.2 Sharing reserves

Sharing reserves could reduce the total amount of reserves needed for both area's. If the two markets for reserve power are merged this could lead to lower expenses for both TSO's.

5.3.3 Common bid ladder for ancillary services in Denmark and the Netherlands

If bids for ancillary services are shared between the TSO's this could presumably lead to a reduction of the costs.

5.3.4 Extension of procurement area for primary and secondary reserves

One way of getting advantage of cooperation between Energinet.dk and TenneT is to exchange imbalances within the hour between the two systems, and thereby reducing the total sum of imbalances, although the Cobra Cable is not the stringent condition for that.

5.3.5 Black start capability

If the VSC technology is used, the Cobra Cable will potentially be able to deliver black start capabilities in both areas. This will be profitable, especially in Denmark, although it can not replace all existing black start capacity.

Today the black start capability in Western Denmark is available from two emergency diesel sets. A 25 MW emergency diesel at the power plant 'Nordjyllandsværket' and a 14 MW emergency diesel at the power plant 'Studstrupsværket'. The Cobra Cable can also provide black start capabilities with its full capacity if it is realised with VSC HVDC technology. If the Cobra Cable is used in regular daily operation, it will immediate be ready for black start without relying on black start capabilities from other parties.

Also in the Netherlands utilisation of the Cobra Cable for replacement of one of the contracted black start power plants may be possible.

5.3.6 Short circuit capability

Because the short circuit power in Denmark must be kept sufficiently high, the Cobra cable could attribute to the total available amount of short circuit power in Denmark. This prevents the forced operation of a conventional large power plant. However, this is only in the case that VSC technology is used, and it will particularly be profitable for Denmark, because of the already strong grid in the Netherlands.

5.3.6.1 Inertia and short circuit power in Western Denmark

The inertia of the large rotational masses of the turbine generators prevents the power system from collapse and the inertia ensures that the system frequency is maintained during system faults. The frequency deviations as a percentage of the nominal frequency at a reduction of the power in-feed in Western Denmark have been calculated based on the system inertia. The system inertia has been calculated for minimum short circuit power (5 GVA) with 2 and 1 Central Generation (CG) power plant in operation in Western Denmark.

The largest reduction in power in-feed can occur at sympathetic commutation failure on all LCC inverters feeding into the Danish power system [1]. If the Cobra cable is build with VSC technology, the converters will not experience commutation failure and the reduction in power in-feed will be less. The frequency deviation is calculated for a fault clearing time of 200 ms and in all cases the calculated frequency deviation is less than 5 %, except for the situation with only one Central Generation power plant in operation (frequency variation 8.2 %). It is therefore concluded the system inertia is sufficient with two CG power plants in operation in Western Denmark.

5.3.6.2 Inertia and short circuit power in the Netherlands

The preferred location of the converter station in the Netherlands will be Eemshaven, next to the location of several large generation power plants with a total installed generation capacity of 2400 MW (future extension to 5000 MW). These generation capacity is sufficiently strong to keep the system frequency within the limits in case of a short circuit fault. Therefore an HVDC converter based on VSC technology does not attribute significantly from that perspective. However, because the NorNed converter station, which is based on conventional LCC technology, is also located in Eemshaven, there can be a strong influence between both HVDC converters if the Cobra Cable will also be a LCC converter. A commutation failure in one system will then unarguably trip the other system, which could lead to a maximum loss of 1300 MW of imported power. With a Cobra Cable based on a VSC converter this common cause failure can be prevented.

6. Transmission capacity for the Cobra Cable

In general, the most economically transmission capacity is determined by the largest size for which no additional power reserves and the additional costs are required in the terminating AC grids. In Denmark the largest power plant has a capacity of 600 MW for which 600 MW reserve capacity is required as back up in case of a trip of this power plant. To be able to keep this power plant as reserve for the Cobra Cable, the maximum transmitted power is limited to 600 MW in the direction from the Netherlands to Denmark. In the other direction there are no economic limitations with respect to the maximum transmitted power

Depending on the costs and revenues of ancillary services provided by the Cobra Cable it may be an advantage to increase the rating of the Cobra Cable above 600 MW to supply reserve capacity, but this must always be considered in perspective with the above mentioned limitation.

7. Transmission losses

The AC/DC conversion losses are in general higher for VSC than for LCC technology [2]. In order to be able to compare the economy of the different technologies, the losses are calculated for a Cobra Cable HVDC link between Eemshaven (the Netherlands) and Revsing (Denmark). There are five different technical options considered:

- LCC, monopole technology, DC voltage of 450 kV
- LCC, balanced monopole technology, DC voltage of +/– 450 kV
- VSC, 2-3 level PWM converter technology, DC voltage of +/– 320 kV
- VSC, 2-3 level PWM converter technology, DC voltage of +/– 200 kV
- VSC, multilevel PWM converter technology, DC voltage of +/– 300 kV

For each technical option a DC cable with the appropriate cross section is assumed. The considered DC cable has a total length of 70 km onshore and 275 km offshore.

The transmission losses are calculated as AC/DC conversion losses in the converters and as resistive losses in the DC cables. The losses are calculated for 8760 hours (one year) using the loss functions specified below and the load profile in figure 2.
The LCC AC/DC conversion losses are approximately 0.7 % per converter at full load whereas the VSC AC/DC conversion losses are approximately 1.4% - 1.6% per converter dependent on the VSC technology. The DC cable loss function is calculated as the resistive losses in the DC cable. The following loss functions, based on experiences, are used to calculate the converter losses and the DC cable losses. The parameter A_{cab} represents the losses at maximum DC current as a percentage of the rated power of the HVDC link.

LCC HVDC loss function: $$\frac{P_{loss}}{P_N} = 0.11\% + 0.18\% \cdot \frac{P_{tr}}{P_N} + 0.41\% \cdot \left(\frac{P_{tr}}{P_N}\right)^2$$

VSC HVDC loss function $$\frac{P_{loss}}{P_N} = 0.2\% + (0.8\% \ldots 1.0\%) \cdot \frac{P_{tr}}{P_N} + 0.4\% \cdot \left(\frac{P_{tr}}{P_N}\right)^2$$

(dependent on the chosen VSC technology)

DC cable loss function: $$\frac{P_{cable,loss}}{P_N} = 0.2\% + A_{cab} \cdot \left(\frac{P_{tr}}{P_N}\right)^2 \quad \text{where} \quad A_{cab} = \frac{R_{dc} \cdot I_{dc,\max}^2}{P_N}$$

The calculated losses of the AC/DC converters and the DC cables for the five different technical solutions are depicted in figure 3.

8. Planning

As part of the feasibility study, a preliminary planning has been made. First the licensing period has been considered, which can take 3 to 4 years. During this period the technical specifications will also be written, so that at the end of the licensing period the requests for quotation could be send out. Next the engineering, production and construction phases of the equipment and buildings are considered, for which also 3 to 4 years are incorporated including two laying seasons for the submarine DC cable. Overall, it is expected that if the next phase of the project, the licensing preparations, can proceed mid 2009, the Cobra Cable could be in operation in 2016.

9. Conclusion

From the study it is concluded that it is feasible to build an HVDC connection between Denmark and the Netherlands. The preferred locations for the converter stations are Endrup in Denmark and Eemshaven in the Netherlands. The length of the DC submarine cable is the shortest between these locations.

From a study performed by licensing experts, it appeared that the licensing route requires a lot of effort and accuracy. Overall the procedure can take up to 3-4 years. Special attention has to be paid the licensing procedure in German offshore territory.

Both the conventional HVDC LCC technology and the VSC technology have been considered, but from technical point of view there are no decisive arguments at the moment to choose a specific solution. It should however be kept in mind that a high DC voltage of the transmission system contributes better to the feasibility of the project due to lower losses. Presently there is no practical experience with DC cables with extruded polymeric insulating material, used for the VSC, for voltages higher than 150 kV DC.

The VSC transmission losses are significant compared with a balanced bipole conventional HVDC solution. Due to lack of practical experiences with VSC transmission at higher power ratings and DC voltages, assessment of risks and minimisation of the VSC transmission losses, either by increasing the DC voltage and/or increasing the cross section of the DC cable, are very important parameters of the business cases for the Cobra Cable. An important advantage of VSC compared with LCC is that it may be possible, at a later stage, to connect offshore wind farms in the North Sea to the DC cable, if it is required in the future. Although the present assessment results are slightly in favour of a conventional LCC HVDC system, both Energinet.dk and TenneT do also see the advantages of supporting an innovative development to build the Cobra Cable with VSC technology.

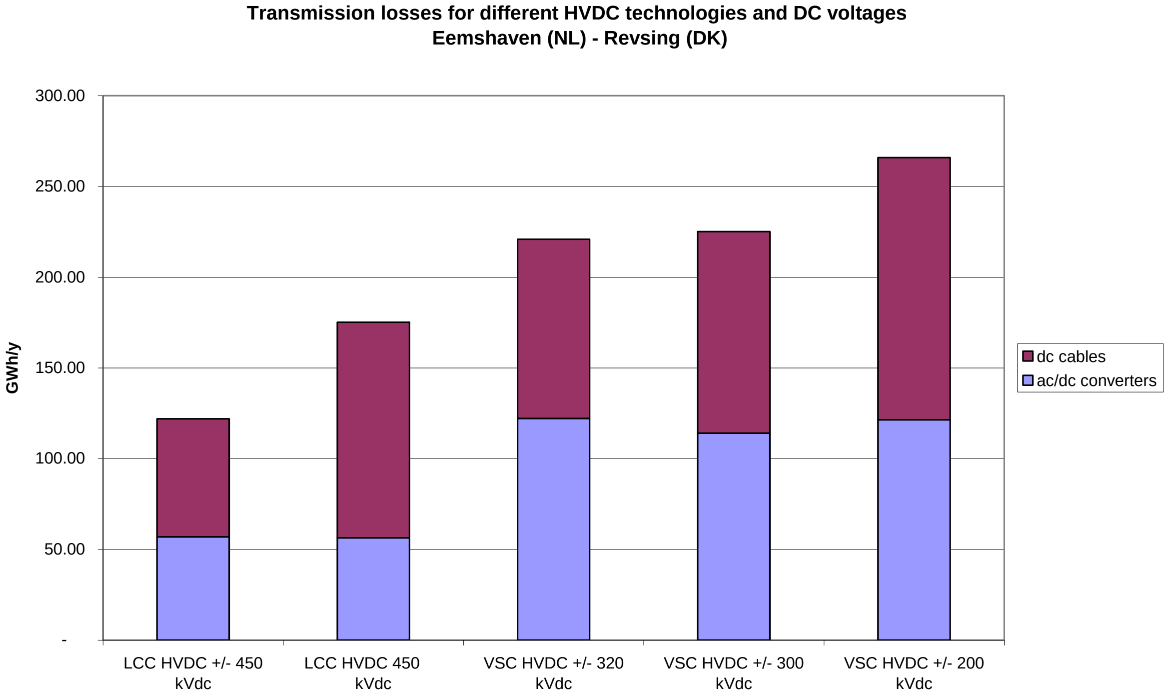

Figure 3: Bar chart of transmission losses (AC/DC conversion + DC cable losses) for Eemshaven -Revsing, corresponding to the duration curve in figure 2

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