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The Storebælt HVDC Project in Denmark

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SUMMARY

Denmark has two power transmission systems: one for eastern Denmark and one for western Denmark. Eastern Denmark is synchronous with the Nordel system, whereas western Denmark is synchronous with the UCTE system.

The construction of the Storebælt (Great Belt) HVDC interconnection between eastern and western Denmark has now been approved after many years of discussion. The Danish power system has changed considerably over the past few years, due to the high penetration of renewable energy sources and due to the decommissioning of several old power stations. These changes have made the HVDC interconnection technically and economically advantageous.

On Funen, the existing 400 kV AC transformer station has been expanded, and on Zealand a completely new transformer station will be built under an existing overhead line.

As a consequence, the authorities have stipulated new legal requirements regarding incorporation of the landscape. Additionally, requirements for special acoustic noise are made.

A contract for the Storebælt HVDC Project with a rating of 600 MW was signed in May 2007, and the interconnection was originally planned to go into commercial operation in April 2010. Due to delays of the authorities' processing of the new substation in Zealand, the substation will only come into commercial operation in the autumn of 2010.

There is a description of what has to be done to make the visual impact of the new substation as low as possible.

Also there is a description of emergency power, frequency control, and runback which are normally used in Denmark.

KEYWORDS

LCC HVDC, Light Triggered Thyristors, Acoustic Noise, Visual Impact

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1 THE DANISH POWER SYSTEM

The transmission system in Denmark is owned and operated by Energinet.dk, the Danish transmission system operator (TSO). The system is divided into two electrically separated systems, the eastern system and the western system.

The western system is synchronous with the European system, UCTE, 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 western system has two HVDC interconnections to Sweden, Konti-Skan pole 1 (380 MW) and pole 2 (360 MW), and three HVDC interconnections to Norway, Skagerrak pole 1 (250 MW), pole 2 (250 MW) and pole 3 (500 MW).

The eastern system has one HVDC interconnection to Germany, Kontek (600 MW).

Table 1-1: Overview of the installed production capacities

Synchronous area	**Western system UCTE**	**Eastern system Nordel**
Central power stations	3400 MW	3800 MW
Local CHP plants	1700 MW	650 MW
Wind power plants	2400 MW	750 MW

In order to provide sufficient short-circuit capacity and inertia in the power system, at least three central power stations must be in operation at any time in the western and the eastern systems, respectively.

2 THE NORDIC POWER MARKET

The Danish power market is a part of the Nordic power market, and Denmark is a member of the Nordic power exchange (Nord Pool [1]), which is jointly owned by the Nordic TSOs.

The Storebælt (Great Belt) power interconnection is one of five electricity transmission projects that were recommended by Nordel [2] in 2004, and which are now in the process of being realised. The other projects that were recommended are; a new HVDC link, Fenno-Skan2, between Finland and Sweden, a new HVDC interconnection, Skagerrak 4, between Denmark and Norway, a new line between central Norway and central Sweden, and, finally, a line between north and south Sweden.

The new Storebælt HVDC Project was decided by Energinet.dk because it will yield economic benefits as a result of better **utilisation of the power system**, **sharing of power reserves** across the Storebælt HVDC interconnection, **synergies in a common regulating power market** and **better market performance** due to more competition in the market. The Storebælt HVDC interconnection was planned to be ready for commercial operation in April 2010.

Exchange of power on the Storebælt HVDC interconnection
The expected exchange of power on the Storebælt interconnection has been estimated on the basis of energy balances in the Nordic system using historical hydro- and wind-power time series, and on the assumption that the production at local and central power stations is optimised.

The equivalent full-load hours for the Storebælt HVDC interconnection are 4,362 h/year, and the loss hours are 3,551 h/year, while operating hours amount to 7,237 h/year.

Technology and rating
Classic HVDC with line-commutated converters and VSC (voltage-sourced converters) were considered.

In order to find the most economical solution, various ratings and technologies were considered as shown in Figure 2-1.

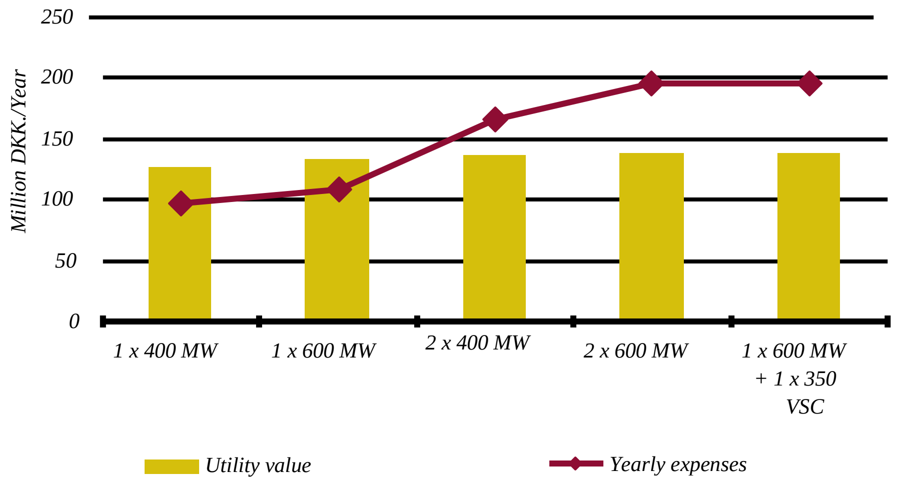

Figure 2-1: Utility value and expenses per year for the Storebælt HVDC interconnection

Because of the higher utilisation rate and the relatively higher losses in connection with VSC transmission, LCC HVDC turned out to be the most economical solution.

3 HVDC CONTROLS

Emergency power
There are eight inputs for traditional emergency power and two for droop-effect.

The traditional emergency power has different priorities, directions ΔMW or MW and load gradient. A higher priority takes over the control from a lower. They also have different possibilities of activation: manually, frequency, voltage, current or a combination of all.

The two droop-emergency effects must be activated by frequency and resembles frequency control. They can be active at both substations.

Frequency control
There is an automatic frequency control which can only be active in one substation at a time. It is used for power frequency control and it, normally, only controls few MWs.

Runback and grid protection
There are five digital inputs to activate a runback to a predefined MW power. They can be used in case a failure occurs in the AC net, which does not allow for more than a certain amount of MW being transmitted.

4 HVDC CONVERTERS

The HVDC Project

The tenders were invited for a 600 MW monopolar LCC HVDC cable system with metallic return cable, which can, subsequently, be expanded to a bipolar system, if required.

The Project is split up into different subprojects and subcontracts for HVDC converters, submarine cables, land cables, AC substations and civil works, respectively. The contract for the LCC HVDC converters and the DC cables was signed on May 2007, and the contractual date for handover and commercial operation of the interconnection is April 2010.

HVDC ratings

The ratings of the monopolar Storebælt HVDC system is 600 MW, 400 kV DC and 1500 A DC. The HVDC converter stations located at Fraugde and Herslev are designed to transmit rated power in either direction.

The DC cable transmission system consists of 26 km (16 on Funen and 10 on Zealand) land pole and returns cables and 32 km sea pole and return cables.

A single-line diagram of the Storebælt HVDC Interconnection is shown in Figure 4-1.

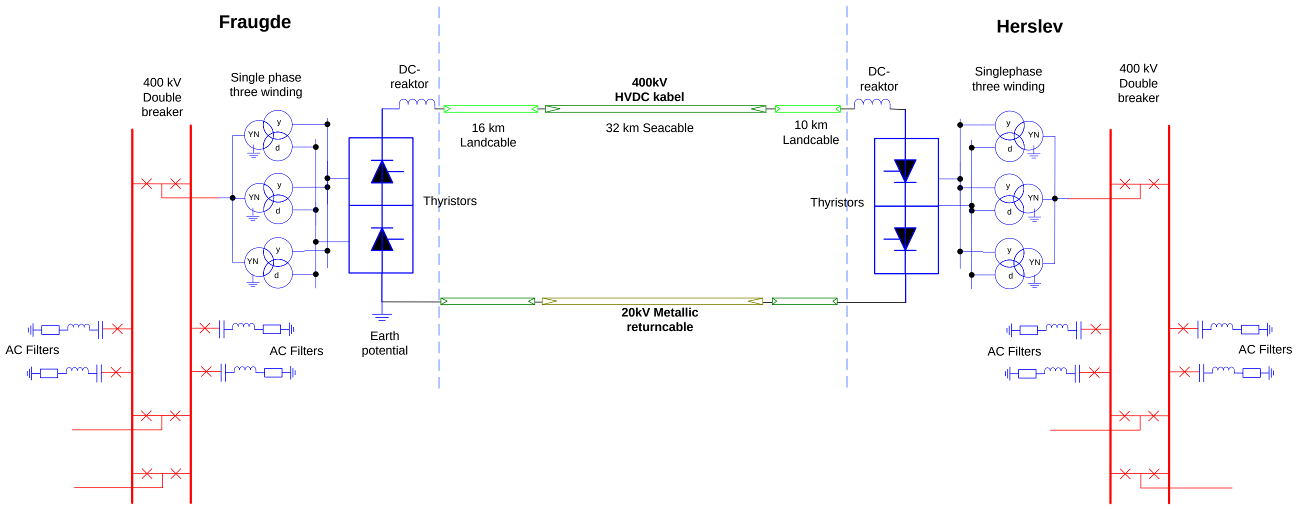

Figure 4-1: Schematic single-line diagram

Main circuit parameters

The continuous rating is 600 MW without a redundant cooling system in service. With redundant cooling, a continuous overload of 105% of rated load is achievable. Additionally, the DC transmission permits a 2-hour overload of 1.05 p.u. rated power without redundant cooling and up to 1.1 p.u. with redundant cooling in operation. Furthermore, a 3-second overload of 1.35 p.u. is available for use up to maximum ambient temperature and for the maximum 2-hour overload as previous operating condition.

Reactive power and AC harmonic filters

In order to balance the reactive power demand of the DC converter at 600 MW, a total reactive compensation of nearly 340 MVA Mvar of shunt capacitors is required per converter station. The compensation is subdivided into four filter sub-banks of 87 Mvar rating, each to comply with the limitation on AC voltage change due to filter switching at 420 kV AC system voltage.

The design of the triple tuned AC filters has been chosen to satisfy harmonic performance requirements over the whole range of operation, as well as a high degree of flexibility and filter redundancy.

Using a special control mode with increased firing/extinction angles, the reactive power consumption of the DC converter can be increased in order to limit the reactive power flow into the AC systems during light DC loads without additional shunt reactors.

Converter transformer
The converter transformer configuration comprises three single-phase three-winding transformers for each 12-pulse group. One spare converter transformer will be installed at Fraugde station.

The leakage impedances were determined by taking several factors into consideration such as the permissible short-circuit current of the thyristor used and optimised ratio between rating and construction cost, etc. The selection of a load tap-changer range was adapted to the requirements of AC voltage variation range and valve capability of operating at high firing angles [6].

All the secondary bushings of the transformer will protrude directly into the valve hall. Both star and delta connections are made inside the valve hall, thereby eliminating the need for wall bushings and avoiding lightning surge stresses of the valves caused by direct strokes.

The thyristor valves
The converters of the Storebælt Project are based on 4-inch direct light-triggered thyristor (LTT) technology. The thyristor valves are arranged in three towers per 12-pulse bridge, each representing one phase. Every tower consists of eight modular units, each of which includes 30 series-connected thyristor levels with auxiliary components, eg snubber circuit, voltage monitoring electronics and saturable valve reactors.

The valve towers are suspended from the valve hall roof, and all joints between modules such as suspension insulators, bus work and piping are flexibly designed to allow maximum deflection. Cooling water and fibre optics are supplied from the top. All non-metallic materials used were selected in order to minimise the risk of severe fires. Capacitors are filled with insulating gases and oil is eliminated. Plastic materials for tubing and insulation have flame retardant self-extinguishing characteristics.

Smoothing reactor
The smoothing reactor to be installed outdoor is of the air-core dry-type design. Considering the metallic return DC circuit configuration, the calculations indicated that a 300 mH smoothing reactor per station is an adequate size to avoid resonance at low order harmonics. This size of the smoothing reactor ensures fulfilment of further tasks as well, eg limiting the transient over-currents caused by DC side faults or commutation failures, avoiding discontinuous current operation at low DC currents, especially at operation with high firing angles at minimum load operation. The smoothing reactors are installed at the 400 kV DC busbar.

6 RELIABILITY

The energy availability (EA) for both Storebælt converter stations together is guaranteed to be more than 98.5%, with a forced outage rate (FOR) of less than five outages per year.

Fault-tolerant control systems, an intelligent redundancy and spare-parts philosophy combined with stringent quality standards ensure high component and system reliability. Additionally, intensive off-site tests are performed on the HVDC control and protection system (eg functional performance tests), to enhance the reliability, availability and quality to the highest possible level.

The spare-parts philosophy requires only one spare part for each main component (transformer, filter components, etc.) stored at Fraugde converter station for the use at both converter stations. The sensitive station elements are designed with redundant capacity or as dual systems (valve cooling system, auxiliary power system, control and protection systems, etc.).

7 HVDC CABELS

The 400 kV HVDC pole cables are mass impregnated (MI), and the metallic return is a polymeric cable.

There is a 16 km long land cable on Funen, and on Zealand there is a 10 km land cable, and the submarine cable is 32 km long.

As the Great Belt is not that deep, the submarine cable has one layer of armouring. Due to gas pipes crossing the Great Belt in the vicinity of the cable crossings, there is a return cable all the way. They are 100 m apart. They are submerged all the way across the Great Belt, but due to the hard sea bed they are buried with a specially designed digging wheel. The trench is dug beforehand, and the cable is placed in it.

The land cables are buried in the same trench 70 cm apart. There are four parallel return cables with aluminium conductors on land, closely packed. The two fibre optics that are there, could be used for communication and distributed temperature readings.

Cable data

	Land cable		Submarine cable	
	HVDC pole	Return	HVDC pole	Return
Cable length	16 + 10 km	16 + 10 km	32 km	32 km
Rated voltage	400 kV	24 kV	400 kV	24 kV
Rated current	1500 A	1500 A	1500 A	1500 A
LIWL	800 kV		800 kV	
SIWL	800 kV		800 kV	
Cross section	2000 mm^2 Cu	4*800 mm^2 Al	1700 mm^2 Cu Except the nearest 300 m to shore, 2000 mm^2	1200

8 DESIGNING A DOUBLE BREAKER STATION

Existing 400 kV AC station on Funen

The existing double breaker 400 kV station Fraugde on Funen will be expanded with an extra bay for HVDC pole. The four AC filters have each their circuit breaker thus enabling the use of the filters regardless of the HVDC pole being on line or not.

The buildings, on each side of the link, look alike and comprise a valve hall (720 m2) and a control building (350 m2 in 2 floors).

If there is a fault in one busbar only, at the most, two AC filters will be lost; all four are dimensioned to run full effect without the two filters.

A new HVDC station on Zealand
A new double breaker 400 kV station was to be built under an existing overhead line.

It has been a long process due to some problems regarding sanctions to build the new station on Zealand. A municipality reform has taken place at 1 January 2007 and as a consequence, one local council became a part of another local council. We had to start applying for the authorities' approval all over again.

In order to keep the visual impact as low as possible, the earth wires were not pulled down into the station.

The council investigated if they could find a new location for the HVDC station next to an oil refinery. As this was not feasible, the council decided to go back to the original location and instead demand extra requirements for the visual impact.

Finally it was decided to accept that the whole area should be lowered approx. by 2 m. Thus, 350.000 m2 soil had to be removed from the area and formed into hills sloping naturally into the landscaping.

Acoustic noise and magnetic field
The requirements for acoustic noise is dB(A) during the day, 45 dB(A) in the evening and 40 dB(A) at night. The new transformer station complies with 35 dB(A), round the clock, as additional 5 dB(A) is supplied.

The impulsive noise from the filter breakers will cause a problem as they are switched several times a day, whenever there is a big variation in the effect.

The magnetic field is larger near the components inside the fenced area, but along the fence there is no difference.

9 CONCLUSION

The new 600 MW Storebælt HVDC interconnection is one of five electricity transmission projects recommended by Nordel, the body for cooperation between the Nordic TSOs. The HVDC interconnection will interconnect eastern and western Denmark, and it will improve the Nordic electricity power market in general and the Danish market in particular. The benefit will be gained by increased trade in the Nordic power market and by a more optimised utilisation of the Nordic power generation system. Additional gains will be achieved by improvement of the market performance.

LCC HVDC and VSC HVDC technology for the Storebælt Project was evaluated. Due to the expected high utilisation of the Storebælt HVDC interconnection and, consequently, the relatively high capitalisation of transmission losses for VSC HVDC, it was decided to realise the Project based on classic LCC HVDC technology with a rating of 600 MW.

The Project started May 2007 and the Storebælt HVDC interconnection was planned to go into operation April 2010, but due to delays of the authorities' processing of one substation on Zealand, the substation will only come into commercial operation in the autumn of 2010.

New methods have been used to get the new substation on Zealand to fade naturally into the countryside. Thus, 350.000m3 soil has to be moved in order to give a general depression of the terrain.

Like other HVDC connections in Denmark, there are emergency effects, frequency controls and runbacks.

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