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HVDC Multiinfeed Considerations in Norway and Denmark

J.B. Davies, I.T. Fernando, K.L. Kent
Manitoba Hydro
Canada

Bård Ek
STATNETT
Norway

K.H. Søbrink
Energinet.dk
Denmark

SUMMARY

This paper summarizes salient features of the multiinfeed HVdc systems being planned for both Denmark and Norway. The paper starts with a description of basic HVdc multiinfeed concepts, with an emphasis on technical issues most relevant in the development of the Norwegian and Danish systems.

Over the years, much experience has been garnered in the study and operation of the multiinfeed situation in Denmark. This situation, already one of the more complex multiinfeed HVdc environments in the world, will be expanded with the possible developments of the Storebælt and Cobra cable projects. The paper describes important technical conclusions related to these developments.

The Norwegian power grid is dominated by hydro electric resources. Under conditions of drought, energy is imported from neighbouring countries over HVdc links and this situation is especially onerous given the lack of strength with machines not being connected. The paper gives further insight into the challenges presented.

KEYWORDS

HVdc, multiinfeed, MIIF, MIESCR, commutation failure

Email: jbdavies@hydro.mb.ca

1.0 **INTRODUCTION**

In 2008, CIGRE WG B4-41 published a brochure which provides utilities basic planning guidance for systems with multiple HVdc infeeds. Integral to that brochure were contributions from Norway and Denmark which have and are continuing to develop significant multiinfeed HVdc systems. This paper will expand on recent work completed in those countries.

But first, a refresher on salient features of multiinfeed planning is in order.

2.0 BASIC FACTORS

A line commutated inverter is dependent upon the ac system voltage present at its terminals (called the commutating voltage) and indeed the real and reactive power injected by an inverter does in turn affect the commutating voltage. The commutating voltage is the single most important quantity which both determines and reflects the MVA power injection from the associated HVdc link. It stands to reason therefore that interactive effects between inverters would most accurately be captured by the relative change in the remote inverter commutating voltage for a fixed change in the local commutating voltage. This is the essence of the Multi Infeed Interaction Factor and can be described mathematically as:

$$MIIF_{e,n} = \frac{\Delta V_e}{\Delta V_n} \qquad (1)$$

This formula can be extended to the general problem through the matrix form:

MIIF Table		**Relative Inverter ac Voltage Change**		
		Inverter1	**Inverter 2**	**Inverter3**
Bus at which fixed reduction is applied	**Inv. 1**	$MIIF_{1,1} = \frac{\Delta V_1}{\Delta V_1}$	$MIIF_{2,1} = \frac{\Delta V_2}{\Delta V_1}$	$MIIF_{3,1} = \frac{\Delta V_3}{\Delta V_1}$
	Inv. 2	$MIIF_{1,2} = \frac{\Delta V_1}{\Delta V_2}$	$MIIF_{2,2} = \frac{\Delta V_2}{\Delta V_2}$	$MIIF_{3,2} = \frac{\Delta V_3}{\Delta V_2}$
	Inv. 3	$MIIF_{1,3} = \frac{\Delta V_1}{\Delta V_3}$	$MIIF_{2,3} = \frac{\Delta V_2}{\Delta V_3}$	$MIIF_{3,3} = \frac{\Delta V_3}{\Delta V_3}$

Infinitely apart busses would have MIIF values of zero; busses electrically approaching each other would be leading to a unity MIIF. The MIIF provides a very intuitive feel for the electrical closeness amongst inverter busses.

The above table is sufficient if the HVdc power injections at each inverter bus are similar, but if a wide disparity exists, then a more accurate assessment requires weighting by HVdc power ratings.

MIIF Table		P_{DC}	Megawatt Weighted Relative Inverter ac Voltage Change		
			Inverter 1	**Inverter 2**	**Inverter 3**
Bus at which fixed reduction is applied	**Inv. 1**	P_{DC1}	P_{DC1}	$MIIF_{2,1}$ x P_{DC2}	$MIIF_{3,1}$ x P_{DC3}
	Inv. 2	P_{DC2}	$MIIF_{1,2}$ x P_{DC1}	P_{DC2}	$MIIF_{3,2}$ x P_{DC3}
	Inv. 3	P_{DC2}	$MIIF_{1,3}$ x P_{DC1}	$MIIF_{2,3}$ x P_{DC2}	P_{DC3}

Links that have a weighted product of 15% or more of the reference links rating are starting to influence the reference links performance.

The knowledge of which links to include in a multiinfeed sphere allows an important HVdc planning parameter to be calculated, namely the MIESCR (Multiinfeed Interactive Effective Short Circuit Ratio).

$$MIESCR_i = \frac{(SCC_i - Qf_i)}{Pdc_i + \sum_j (MIIF_{j,i} \times Pdc_j)} \qquad (2)$$

The MIESCR is an extension of the well known HVdc planning parameter ESCR but extended into a multiinfeed context. Conversely, MIESCR collapses into a classic ESCR definition for a single infeed situation.

The essence of this formula is that the short circuit capability in any particular multiinfeed system must be shared amongst competing inverters and that the multiinfeed dynamic may be significantly weaker than what a single infeed calculation might imply. MIESCR inverter values below 2 would be considered undesirable for the integration of an HVdc link into a major ac system.

Evaluating MIIF and MIESCR parameters provides a basic understanding of the nature of the multiinfeed situation under consideration. The technical brochure provides many more insights into specific interaction phenomena and the reader is encouraged to pursue the brochure for more details.

3.0 Norway

3.1 Introduction to the Norwegian System

Hydropower accounts for about 97% of the total generation in the Norwegian power system. The annual generation of electricity is therefore strongly dependent on precipitation and inflow to the hydro power reservoirs. A so-called dry year may require an annual import of 35 TWh, whereas a wet year may require an export of 25 TWh. Thus, the Norwegian system needs substantial transmission capacity to neighbouring power systems in order to handle these hydrological variations.

The power system in Norway, Sweden, Finland and eastern Denmark is synchronous with a common frequency. This heavily integrated synchronous system is supplied by a mix of hydro-, thermal- and wind power generation with strong internal interconnections. Both the UCTE system and the UK system are mainly supplied by thermal power generation, but have also significantly wind power generation. It is therefore favorable to utilize Scandinavian fast-acting hydro power to compensate for variations in the daily load and wind power generation in these systems. For this reason, it can be attractive to establish new dc links from Norway to countries like Denmark, Germany, the Netherlands and the UK.

Today, there are two existing dc connections from Norway with a combined dc capacity of 1740 MW: Skagerrak (1040 MW) and Norned (700 MW). Skagerrak consists of three dc connections between Norway and western Denmark, Skagerrak 1, 2 and 3. Norned is a simplified bipolar link between Norway and the Netherlands, which came into commercial operation in June 2008. These links are connected to Kristiansand (Skagerrak 1-3) and Feda (Norned) substations, which are located in close electrical proximity to each other (63 km apart by 300 kV OH line) in southern Norway.

The Norwegian and Danish TSOs, Statnett and Energinet.dk, have started the licencing process for a 4th Skagerrak link (SK4). Presently, there are large amounts of both onshore and offshore wind power generation under planning in Norway. If implemented, this will increase the need for new dc capacity to neighboring countries.

3.2 System study

Statnett has performed system studies to identify necessary grid reinforcement for up to three new classical dc links (including SK4), using the MIIF (Multi Infeed Interaction Factor) and MIESCR (Multiinfeed Interactive ESCR) methodology.

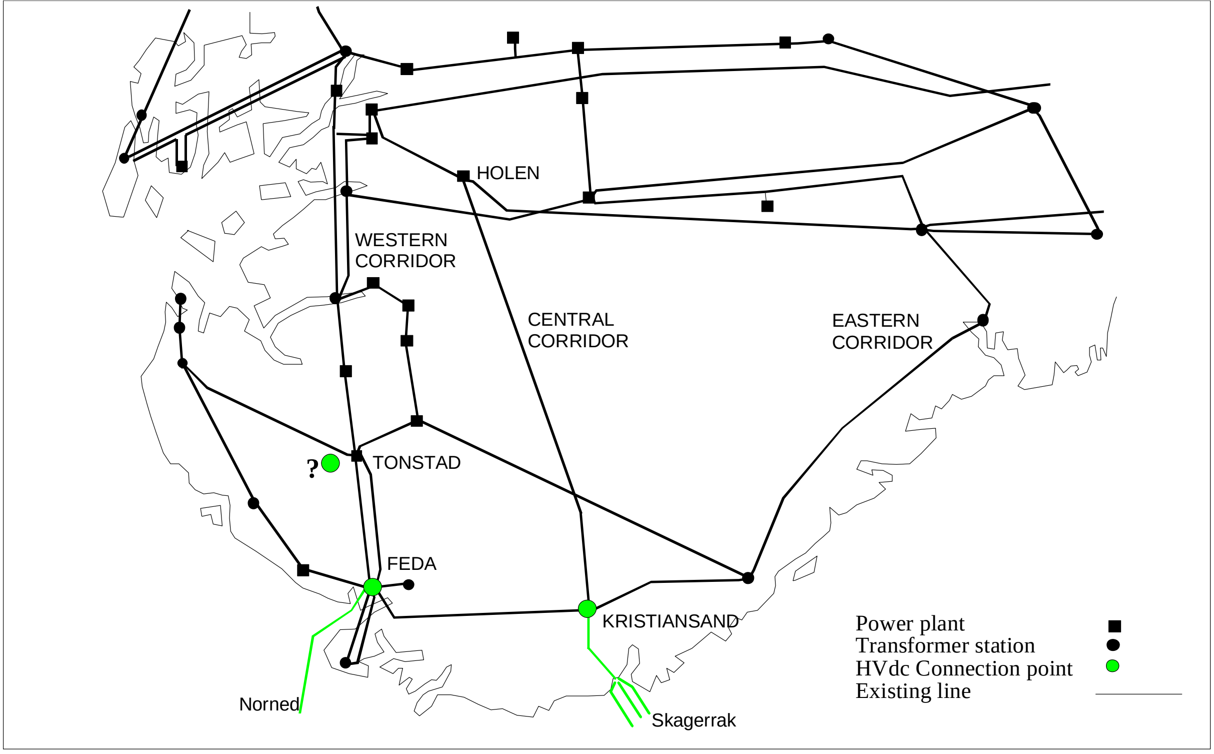


Figure 1 South Norwegian transmission system

The critical situation is the maximum import scenario. During power import, most of the local hydropower plants are stopped, resulting in a weak grid with low short circuit power (SCP). The following scenarios have been analysed:

- Basecase scenario with existing 1740 MW dc capacity. Skagerrak 1-3, Norned and 420 kV OH line Holen-Kr.sand.
- New link SK4 with 700 MW new dc capacity, eastern corridor voltage upgraded from 300 to 420 kV.
- New links SK4 and Norned 2 (NN2) with 1400 MW new dc capacity, eastern and western corridors voltage upgraded to 420kV
    - With and without 400 MVA synchronous condenser (SC) at Feda.
- Maximum scenario with 2100 MW new dc capacity. New links SK4 and Tonstad 1400 MW, eastern and western corridors upgraded to 420 kV.
    - With and without 400 MVA SC at Feda and 400 MVA SC at Kr.sand

The study is based on post fault conditions after the limiting n-1 transmission line contingency. Statnett has experienced several common mode line contingencies at the parallel lines between Tonstad and Feda. Therefore, Statnett has defined this as an n-1 contingency in this study. All new dc links are modelled with the same rating and data as Norned in order to simplify the study, The new 1400 MW dc link from Tonstad is thus modelled as two 700 MW units in the maximum scenario.

	P_{DC}	Filters
Skagerrak 1-3	1 040	340
NorNed	700	485

Table 1 Main data for existing HVdc links

Below the results of the base case scenario and the maximum scenario are presented:

Basecase - MIIF		
	Kr.sand	**Feda**
Kr.sand	1,0000	0,7010
Feda	0,7578	1,0000

	SCP	P_{DC}	ESCR	Σ $MIIF_{ji} \times P_{DCj}$	MIESCR
Kr.sand	4 282	1 040	3,8	1 530	2,6
Feda	4 690	700	6,0	1 490	2,8
One eq. Link	4 282	1 740	2,0	-	-

Table 2 MIIF and MIESCR for basecase scenario

The results from the base case scenario with existing 1740 MW total dc capacity, show a strong interaction between the Skagerrak links and Norned. Table 2 shows MIIF values of 0.76 and 0.70 between the Skagerrak converter station at Kr.sand and the Norned converter station at Feda.

	MIIF - Without Sync Condensers			MIIF - With 800 MVA Sync Cond.		
	Kr.sand	**Feda**	**Tonstad**	**Kr.sand**	**Feda**	**Tonstad**
Kr.sand	1,0000	0,9122	0,5270	1,0000	0,8529	0,5000
Feda	0,7206	1,0000	0,4191	0,6486	1,0000	0,3874
Tonstad	0,5043	0,4872	1,0000	0,3805	0,3717	1,0000

Table 3 MIIF for maximum scenario with 2100 MW new dc link capacity.

		Without Sync Condensers				With 800 MVA Sync Condensers			
	P_{DC}	SCP	ESCR	$\Sigma\ \text{MIIF}_{j,i} \times P_{DCj}$	MIESCR	SCP	ESCR	$\Sigma\ \text{MIIF}_{j,i} \times P_{DCj}$	MIESCR
Kr.sand	1 740	6 450	3,2	3 120	1,8	7 960	4,1	3 040	2,3
Feda	700	4 720	6,0	2 540	1,7	5 970	7,8	2 370	2,3
Tonstad	1 400	5 990	3,6	2 620	1,9	6 200	3,7	2 320	2,3
One eq. Link	3 840	6 450	1,2	-	-	7 960	1,6	-	-

Table 4 MIESCR for maximum scenario with 2100 MW new dc link capacity

The maximum scenario with 2100 MW new dc capacity has been analysed both without and with combined 800 MVA in new SCs. The results shown in Table 3 and 4 confirm the strong interaction between Kr. sand and Feda, although the MIIF values decrease from 0.91 (without SCs) to 0.85 (with SCs). Hence, it can be seen that the interaction decreases with increased short circuit power caused by the addition of new SCs.

The interaction varies because each scenario has different grid reinforcements and different limiting transmission line contingencies.

The interaction between Tonstad and Feda is significantly weaker although the physical distance between the substations is only 42 km. This can be explained by the fact that the limiting contingency is failure of both transmission lines between Tonstad and Feda resulting in a long electrical distance between the substations. During pre-fault conditions, the interaction factors would be substantially higher.

The ‘one equivalent link approach’, where all links are considered as one large lumped dc link, is included in the MIESCR result tables. One of the major challenges of this method is to choose the suitable short circuit power. The calculations above are based on choosing the lowest SCP level of the considered grid connection points, i.e. Kr. sand for basecase and Feda for the maximum scenario. This approach is very conservative compared to the MIESCR methodology. However, if the calculated ESCR in the equivalent link approach exceeds 2.0, this will indicate a strong system suitable for multiinfeed operation.

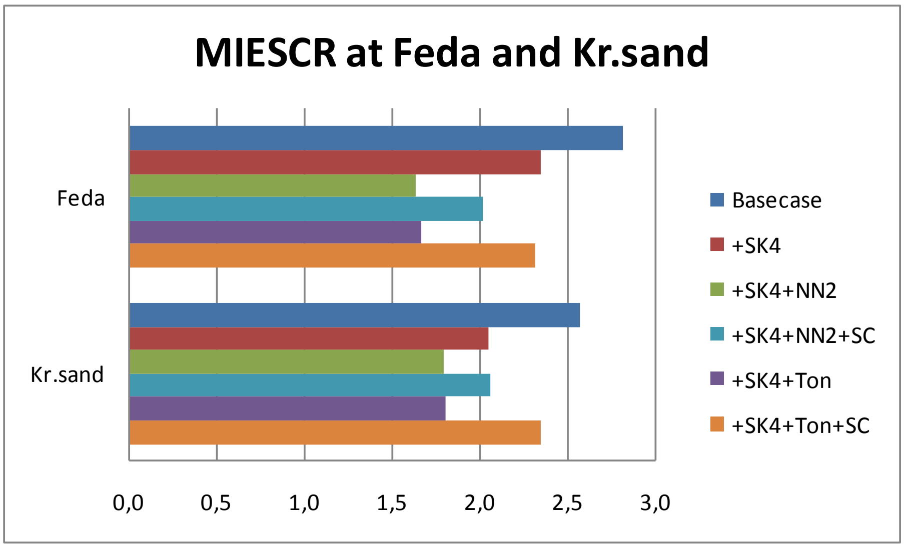


Figure 2 MIESCR results of the scenarios.

The Temporary Over Voltage (TOV) calculations are based on the same scenarios as the MIIF calculations. All dc links are blocked and the instantaneous 50 Hz rms voltage after the blocking is registered as the TOV value.

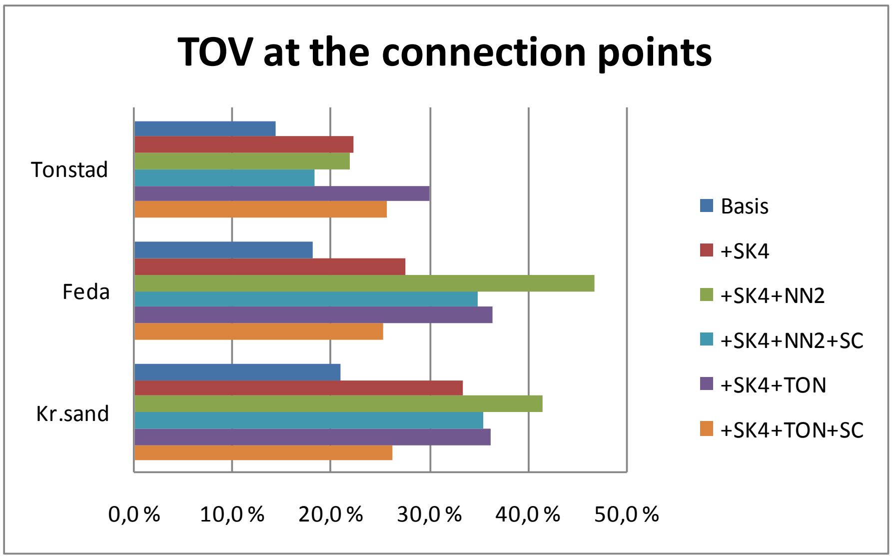


Figure 3 TOV results of the scenarios

The TOV results mirror the MIESCR results; scenarios with low MIESCR have high TOV. Both MIESCR and TOV results confirm the main challenge of adding new dc links within Southern Norway. By introducing new dc links, the operation conditions of existing links are affected. Although the ac grid is reinforced and the short circuit power in each connection point increases, the margins in system operation are still reduced.

The scenario with SK4 and NN2, with one additional 700 MW dc link in each of the stations Feda and Kr.sand, represents the scenario with highest concentration of dc links. The results show a lowest MIESCR (1.6) and highest TOV (47%) without 400 MVA SC at Feda.

The maximum scenario, one additional 700 MW link at Kr.sand and a 1400 MW bipole at Tonstad, shows improved performance compared to scenario ‘SK4 and NN2’ even though the new dc capacity has been increased from 1400 to 2100 MW. The results show a MIESCR of 1.7 and TOV of 36%. The main explanation for the improved performance is the relocation of the second link from Feda to Tonstad represents a reduction of the dc link concentration.

3.3 Summary

The study shows that when adding more than one new dc link to the Norwegian system, the proposed ac grid reinforcements do not provide sufficient voltage support. Synchronous condensers are required to strengthen the system voltage and ensure proper dc link performance.

At MIESCR levels above 2.0, dynamic simulations of limiting transmission line contingencies show system recoveries without repetitive commutation failures. This finding supports the MIESCR factor as a proper indicator of HVdc multiinfeed performance.

4.0 HVDC Multiinfeed in West Denmark

4.1 The Danish AC and DC system

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 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 Danish power system is characterised by a high penetration of distributed power sources, ie wind power and CHP (combined heat and power) plants. In the Western system, 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, penetration is 136% in the Western system and 74% in the Eastern system.

The installed production capacities are shown in the table below.

Synchronous area	**Western Denmark**	**Eastern Denmark**
	UCTE	**Nordel**
Central power stations	3400 MW	3800 MW
Local CHP plants	1700 MW	650 MW
Wind power plants	2400 MW	750 MW
Wind power penetration	65-200%	30-85%
Combined heat and power penetration	46-136%	25-74%

CHP and wind power production is determined by the weather conditions, with CHP production being high in cold weather when the need for domestic heating is high, and wind power production being high at high wind velocities.

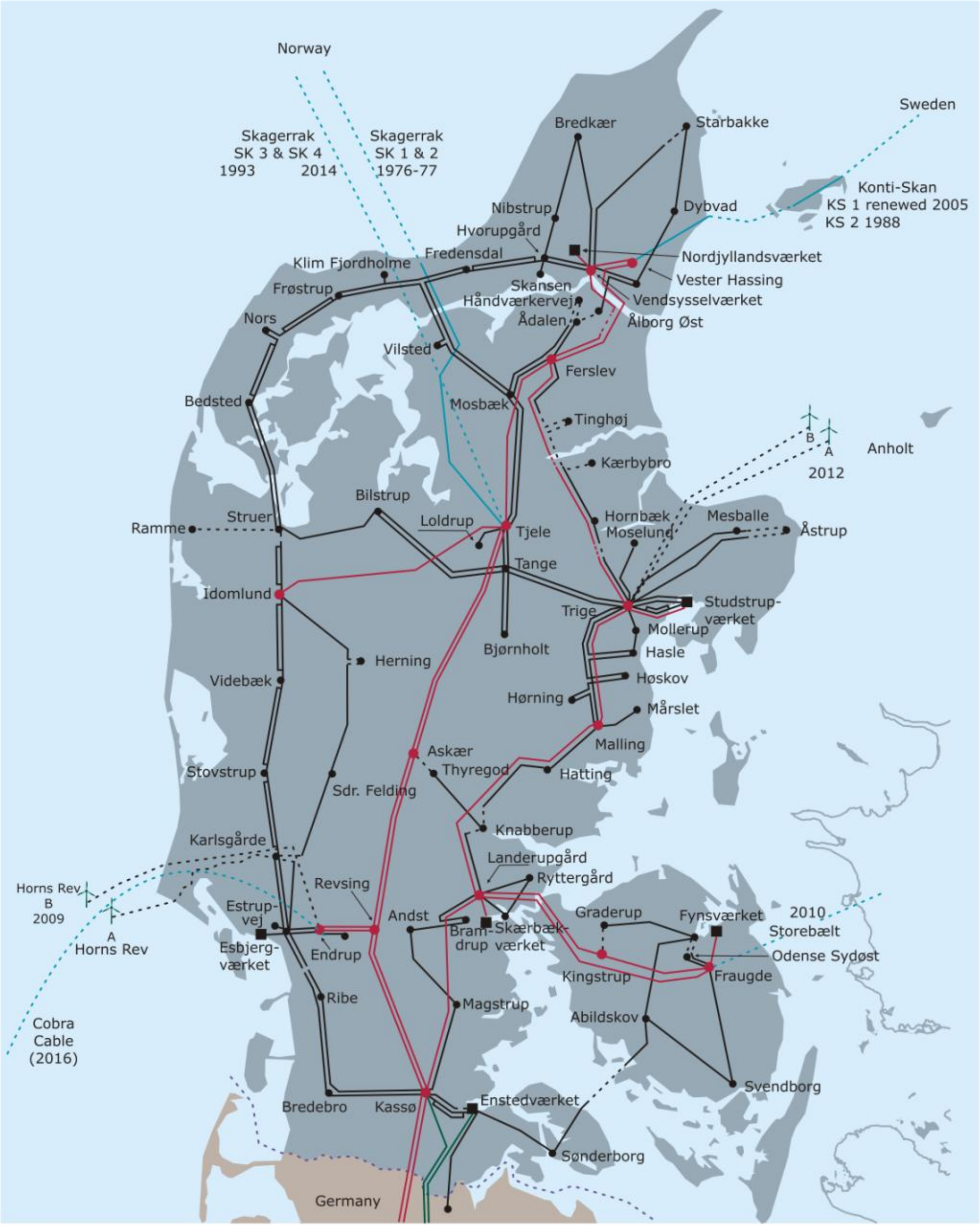
In order to provide sufficient short-circuit capacity and inertia in the power system, at least three central power stations must be in operation at any time in the Western and the Eastern systems, respectively.

The following HVdc links are expected to be in operation in Western system in 2016:

- Konti-Skan, Vester Hassing (DK, 400 kV ac substation) to Lindome (S, 400 kV ac substation):
    - Konti-Skan 1, 380 MW (1965, new converters in 2005)
    - Konti_Skan 2, 360 MW (1988)
- Skagerrak 1 & 2, Tjele, (DK, 150 kV ac substation) to Kristiansand, (N, 400 kV ac substation):

  - Skagerrak 1, 270 MW (1976, new control system in 2007)
  - Skagerrak 2, 270 MW (1978, new control system in 2007)
- Skagerrak 3 & 4, Tjele, (DK, 400 kV ac substation) to (N, 400 kV ac substation):
  - Skagerrak 3, 500 MW (1993)
  - Skagerrak 4, 640 MW (planned as bipole with Skagerrak 3 in 2014)
- Storebælt, Fraugde (DK, 400 kV ac substation) to Herslev (DK, 400 kV ac substation):
  - Storebælt 1, 600 MW (2010, under construction)
- Cobra Cable, Endrup (DK, 400 kV ac substation) to Eemshaven (NL, 400 kV ac substation):
  - Cobra Cable 1, 600 - 700 MW (2016, under planning, transmission capacity and connection point not yet decided).

4.2 Expansion of the Transmission System



The following expansion of the Western system is assumed to be implemented before 2016:

- The Horns Rev 2 offshore wind farm (200 MW) is under construction and will be connected to the Endrup 400 kV substation in 2009.
- The Storebælt HVDC link (+/- 600 MW) is under construction and will be connected to the Fraugde 400 kV substation in 2010.
- The Anholt offshore wind farm (400 MW) is under licensing and will be connected to the Trige 400 kV substation in 2012.
- The ac transmission capacity to Germany will be upgraded to 1500/-2000 MW by installation of phase shifter transformers in Kassø 400 kV substation and Ensted 220 kV substation in 2013.
- The 400 kV transmission systems will be upgraded with systems of 400 kV overhead lines between the 400 kV substations Kassø and Tjele and with a new 400 kV substation in Revsing in 2013.
- A second 400 kV overhead line between Endrup and Revsing installed in 2014.

4.3 MIIF Approximation Using a Short Circuit Calculation

The interaction between multiple HVdc inverters in a power system is mainly due to impedances between busses in an AC grid. The mutual coupling between busses, say bus A and bus B, is the off-diagonal elements Z_{AB} and Z_{BA} in the $\underline{Z}$ (= $1/\underline{Y}$) impedance matrix for the grid. By way of initially estimating the MIIF between busses in a grid, a load-flow calculation followed by short-circuit calculations can be used without dynamic simulation models being required. If the initial estimation of the MIIF indicates a potential risk of interaction, then a supplementary new MIIF calculation in accordance with the definition may be required.

The estimation of the MIIF based on short-circuit calculations does not take account of any dynamic interaction, only impedances in the grid are used in the estimation.

As an example, the MIIF between the new Storebælt and the new Cobra Cable HVdc inverters is determined by using short-circuit calculations.

First, a three-phase short circuit is applied to the Storebælt HVdc inverter AC bus. The bus voltage at the Storebælt HVDC inverter before and after the short circuit is applied is observed as follows: The bus voltage at the Storebælt HVdc inverter before the short circuit is applied is V_{e0} = 413.4 kV, and afterwards the bus voltage is V_{e0+} = 0 kV, which means that the relative voltage change at the Storebælt HVdc inverter bus is $(V_{e0} - V_{e0+})/ V_{e0}$, which is (413.3 - 0) / 413.3 = 1 pu. Similarly, if the bus voltage at the Cobra Cable HVdc inverter before the short circuit is applied is V_{n0} = 410.7 kV, and after the short circuit is applied, the bus voltage is V_{n0+} = 310.4 kV, then the relative voltage change is (410.7 - 310.4) / 410.7 = 0.2442, which is equal to the estimated MIIF (= 0.2442/1) for the minimum scenario.

Secondly, a short circuit is applied to the Cobra Cable inverter AC bus, and the bus voltages before and after the short circuit are applied is observed and the relative voltage changes calculated.

The following two scenarios are investigated, by the use of the short circuit calculation method described above:

1. A maximum scenario with all wind power, all CHP units and all central power plants in operation and with complete grid equivalents for the German, Norwegian and Swedish grids represented in the model.
2. A minimum scenario with all wind power, all CHP units out of operation and with only three central power plants in operation and with minimum short circuit power in the grid equivalent for Germany.

In both scenarios it is stipulated that all lines are in service

The estimated Multi Infeed Interaction Factors (MIIF) and the Effective Short Circuit Ratio (ESCR) for the HVDC inverter ac busses in the Western system are shown in the tables below:

MIIF		Cobra Cable	Storebælt	Skagerrak 3+4	Skagerrak 1+2	Konti-Skan 1+2
Maximum scenario		Endrup	Fraugde	Tjele	Tjele	Vester Hassing
Pdc	MW	600	600	1140	540	740
Sk"	MVA	10041	8489	10572	7129	9259
AC filters	Mvar	300	340	580	80	310
ESCR	MVA/MW	16.2	13.6	9.3	12.8	12.1

							MIESCR
Cobra Cable	Endrup	1.0000	0.2345	0.5147	0.1831	0.2871	6.1
Storebælt	Fraugde	0.2673	1.0000	0.2384	0.1105	0.1938	6.7
Skagerrak 3+4	Tjele	0.5079	0.2179	1.0000	0.3392	0.5228	4.8
Skagerrak 1+2	Tjele	0.7146	0.6672	0.8033	1.0000	0.7551	2.5
Konti_Skan 1+2	Vester Hassinge	0.3024	0.1780	0.5646	0.2652	1.0000	5.0

In the maximum scenario, the ESCR at each inverter bus is high as well as the MIESCR, with the Skagerrak1+2 ac buses having the lowest MIESCR.

MIIF		Cobra Cable	Storebælt	Skagerrak 3+4	Skagerrak 1+2	Konti-Skan 1+2
Minimum scenario		Endrup	Fraugde	Tjele	Tjele	Vester Hassinge
Pdc	MW	600	600	1140	540	740
Sk"	MVA	5351	3925	4689	3126	3807
AC filters	Mvar	300	340	580	80	317
ESCR	MVA/MW	8.4	6.0	3.8	5.5	4.5

							MIESCR
Cobra Cable	Endrup	1.0000	0.4431	0.6628	0.4032	0.4841	2.3
Storebælt	Fraugde	0.6219	1.0000	0.5836	0.4020	0.4480	1.6
Skagerrak 3+4	Tjele	0.7645	0.4643	1.0000	0.5766	0.6959	1.5
Skagerrak 1+2	Tjele	0.8707	0.7838	0.9576	1.0000	0.8948	0.9
Konti_Skan 1+2	Vester Hassinge	0.6805	0.4770	0.9036	0.6214	1.0000	1.2

In the minimum scenario, the MIESCR is low indicating that a significant interaction between the inverters may exist. This situation occur at large import at the HVDC Links, large export to Germany and at minimum generation and low short circuit power in the system.

In general, no serious operational problems have been experienced with the existing HVdc links. However, due to the high penetration of distributed renewable generation - wind power and CHP plants - one of the planner's concerns has been to assess whether additional remedies are required in order to provide sufficient short-circuit power for the operation of existing HVdc links and the future HVdc links.

Harmonics and power/voltage stability have not caused operational problems in the existing system, whereas fault recovery after sympathetic commutation failures has been dealt with by appropriately tuning the HVdc controls and coordinating dc recovery times.

Operational experiences in the Western power system indicate that commutation failure at one of the HVdc inverters occasionally may cause sympathetic commutation failures at other HVdc inverters.

The experiences are that the Western system is stable at peak load (maximum scenario). At low load with large distributed generation (minimum scenario) the Western system is more oscillatory and fault recovery is slower. The MIESCR calculation above indicates that this should be more pronounced with a new Skagerrak 4, a new Storebælt and a new Cobra Cable in operation, which needs to be studied in more detail by the use of dynamic simulations.

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