

New Fenno-Skan 2 HVDC pole with an upgrade of the existing Fenno-Skan 1 pole

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SUMMARY

Fenno-Skan 2 is an extension of the existing Fenno-Skan 1 scheme commissioned in 1989. Fenno-Skan 2 is 800 megawatt and 500 kilovolt HVDC interconnector between Finland and Sweden. The total length of the transmission link is approximately 300 kilometres, of which the actual submarine cable will account for some 200 kilometres. Fenno-Skan 2 increases the electricity transmission capacity between Finland and Sweden by approximately 40 per cent, integrating the Nordic electricity market even more closely together. In practice, the inter-connector will reduce temporary differences in the price of electricity between the various countries within the electricity market. The Fenno-Skan 2 scheme also reduces losses in the Nordic transmission grids and improves power system security.

The project consists of several subprojects: converter stations at Rauma and Finnböle, including upgrade and retrofit at Dannebo, greenfield HVDC overhead line Dannebo-Finnböle, subsea cable across the Gulf of Bothnia, upgrade of the existing HVDC overhead line Rihtniemi-Rauma and finally the upgrade of the sea electrode.

The practical implications of brown field installation and interfaces are elaborated such as semi-distributed location of the converter stations and new neutral circuit arrangements. One pole of the 20 years old HVDC overhead line Rihtniemi - Rauma was upgraded from 400 kVdc level to 500 kVdc.

Different studies were conducted and conclusions are discussed. AC filter interactions between the poles as well as electrode line unbalance supervision are briefly covered. The 20 years old electrode replacement with new titanium mesh and applied design parameters are discussed. Finally, the power market implications during the transmission testing and mitigation methods are discussed.

KEYWORDS

HVDC, Interconnector, Transmission, Fenno-Skan, Electrode, HVDC overhead line upgr

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1 INTERFACES IN THE EXISTING CONVERTER STATIONS IN RAUMA AND DANNEBO

On the Finnish side the existing converter station in Rauma was expanded with new valve hall and new outdoor AC and DC switchgears, including extension of the existing AC substation and connection to the existing DC neutral circuit to the sea electrode. The secondary and auxiliary equipment were fitted in the existing control building with number of interfaces to the existing systems.

On the Swedish side the existing converter station in Dannebo has two-folded role. It was upgraded to serve as the connection point for new 500 kV circuit between Finnböle and Rauma and as the connection point for common DC neutral circuit to the sea electrode.



Figure 1 Fenno-Skan station locations

On the Swedish side the poles are situated in two different locations. The reason for that is AC network congestions with too much power in one location in the grid. The first pole, Fenno-Skan 1 (FS1), was built 20 years ago close to one nuclear power station. During the time nuclear power station was upgraded creating a need for having new connection point in another location on the Swedish grid. This configuration also enables internal transmission inside Sweden by exporting in one pole and importing in the other, i.e. DC loop flow. This possibility was also used during the high power transmission testing to reduce the total test power and market implications.

The existing electrode on Swedish side was not changed in any way because it was already made of titanium net and can be used both as cathode and anode. Normally the return current will be low by a current balancing function unless the transmission network situation urges for a special operation.

The EPC, Emergency Power Control function will also be on Pole level because of the distance between the stations on the Swedish side. The subsea cables for both Fenno-Skan 2 (FS2) and FS1 start in Dannebo. FS2 subsea cable is terminated at Dannebo and connected to an 500 kV DC overhead line Dannebo - Finnböle.



Figure 2 Finnböle Station, Sweden.

In order to make the current balancing simple and make it possible to operate the scheme from one “local” spot together with the fact that the control system is 20 years old in FS1, the control system will be upgraded to the same type and generation as in FS2. The limit for changes of the control is the Valve Base Electronics (VBE) cubicles, which is the interface towards the valve, and the switchyard interfaces towards the primary AC and DC sides. This means that the mimic boards and quite a lot of other cubicles will disappear or host new equipment. The outage time is planned to be four weeks for the FS1 pole when the control system is changed.

The electrode line for FS2 is an overhead line from Finnböle to Dannebo where it is connected to the FS1 neutral side. The existing small electrode switchyard was expanded with neutral bus switches and neutral bus grounding switch to take care of fault clearance when there is a fault in one of the poles. This arrangement helps to avoid a bipolar trip which may cause severe adverse effects in the Swedish and Finnish grids subject to the transmission situation.

2 HVDC LINE IN PARALLEL WITH THE EXISTING AC LINE

In Sweden HVDC overhead line runs in parallel with the existing 400 kV overhead line from Dannebo to Finnböle, totalling almost 70 kilometres of which 53 kilometres is in parallel.

Studies have been made how the influence of induced current in normal operation from the 400 kV AC overhead line will interfere with the DC scheme. Based on the study it was concluded that with 2000 A loading in 400 kV overhead line the DC current in the valve side winding has a substantial margin up to the design limit [1].

Studies have also been made how the influence of fault current between the two lines could lead to unselective tripping of the AC line [6].

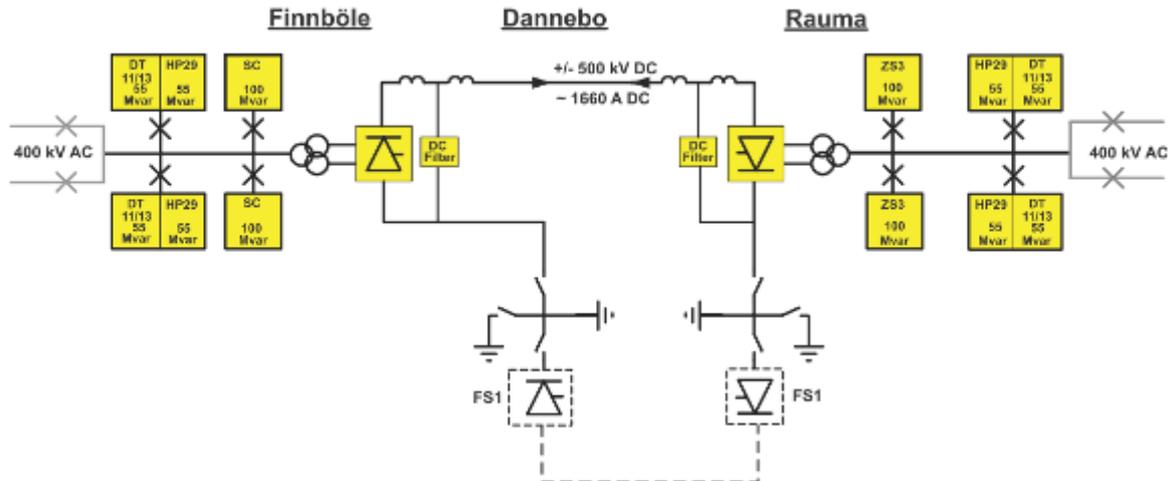


Figure 3 Fenno-Skan scheme, pole 2

3 UPGRADE OF HVDC OVERHEAD LINE IN FINLAND DURING OPERATION OF FENNO-SKAN 1

3.1 Existing overhead line structure

The original HVDC overhead line (OHL) Rihtniemi - Rauma consisted of 95 free-standing towers. It was originally designed for 400 kV (actually the basis for design was 350 kV) DC. The length of the line is 33 km. The OHL consists of two circuits coupled in parallel and two ground wires. Each circuit bundle has three (3) sub-conductors, and the ground wire has two sub-conductors, as illustrated in the following picture. Lower v-strings are two pole circuits, 2*3*Finch; two upper lines are neutral wires with 2*2*Finch (circuits * number of sub-conductor * conductor type). All the following aspects were considered when the upgrade was decided.

3.2 Flash over performance of the insulators

In order to expose 500 kV operating voltage to FS2 circuit, the actual pollution flashover performance of the existing insulators was examined in the laboratory at STRI [2]. Several naturally polluted insulators were dismantled from the overhead line and made available for laboratory testing.

The key conclusions of this report were as follows:

- Detailed investigation of naturally polluted insulators from the 400 kV HVDC OHL Rihtniemi - Rauma showed that with a conservative approach and high availability requirements of Mean Time Between Failures, MTBF 100 years, the insulation strings should be expanded by two units. The applied HVDC voltage was in range 505-515 kV.
- If lower availability (i.e. MTBF 50 years) can be considered, the line may be used even after pole 2 with the original insulator structure, i.e. 24 units in the insulator string.

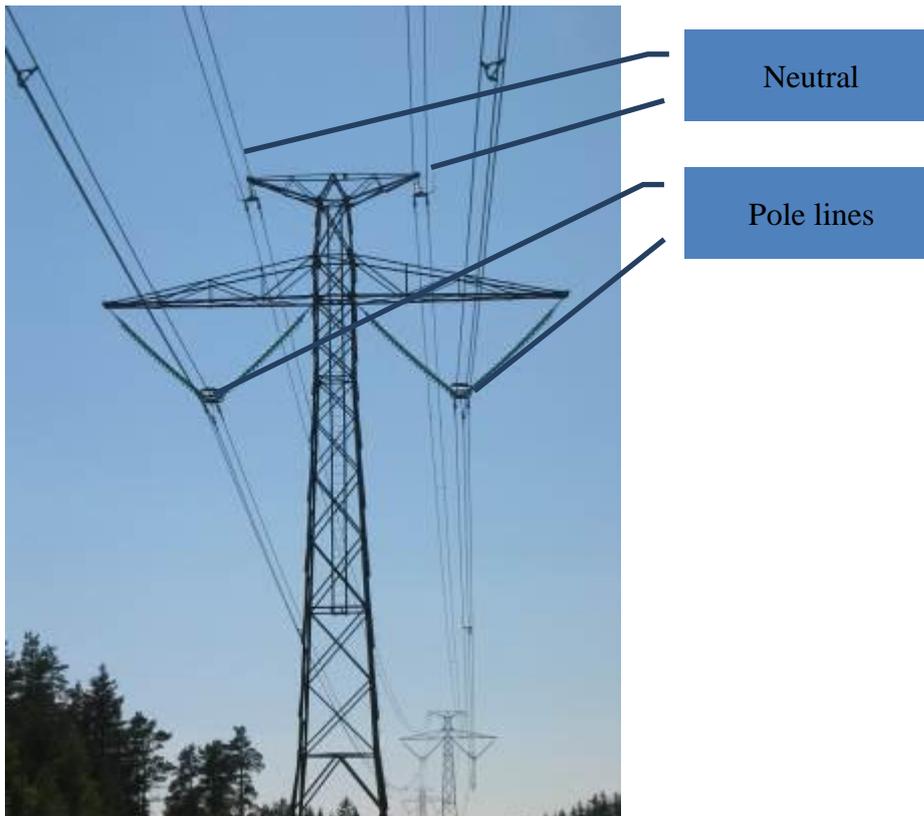


Figure 4 Rihtniemi - Rauma 400 kV DC overhead line before upgrade

3.3 Surface gradient - corona losses causing radio interferences, audible noise and ozone content contribution

The expected electrical performance with different conductor selections was studied with FACE² calculations conducted at Manitoba Hydro [3]. If the existing physical structure (conductor type, number of sub-conductors, clearance between the poles, spacing, tower height) was maintained with no further changes, the voltage gradient E_{max} would be in range of 28...29 kV/cm in bipolar scheme. Based on the information available, that would be the highest number among the HVDC schemes in use today. The higher the surface gradient, the bigger are corona losses, radio interferences, audible noise and ozone contribution respectively.

The following options were pondered in order to reduce voltage gradient:

- to expand the clearance between the poles (which was in range of 9 meters)
- to increase the number of sub-conductors in the conductor bundle
- to change conductors

3.4 DC electric fields - static and enhanced

There are no legitimate exposure limit values for DC electric fields but for static magnetic fields ICNIRP has in 2009 recommended exposure limits 0,4 T in case of general public (exposure of any part of the body) whereas the corresponding values in occupational exposure are 2 T for head and trunk and 8 T for limbs. Values are so high that they hardly become a limit in HVDC power transmission.

² Field and Corona Effects Program

Practical experiences have shown that annoying feelings will start when field strength exceeds about 30 kV/m [7]. The ambient weather conditions affect the value and therefore even lower values can be annoying. And beyond that, the levels are very subjective, i.e. they varies from person to person. The field strength at DC is very much affected by space charges, especially in bipolar operation. Based on the FACE calculations at Rihtniemi - Rauma OHL with 415/515 kV voltage levels the maximum static electric field at 1.5 m height is about 16 kV/m, but the space charge taken into account may increase the field to near 40 kV/m. This value is very extreme, but may occur for some time. Normally wind stirs the charges and +/- charges will neutralize each other.

During the 20 years monopole operation of existing line one complaint has been received. That day weather was very calm and dry. Company representative visited the concerning place under the OHL and verified that some annoying effects was clearly present. The same person visited the same place some days later when weather was windy and found no annoying effects at all. In monopole operation the static field is about 20 kV/m and due to space charge it may rise over 30 kV/m.

3.5 Ion-current flow and ozone content

Ion current flow of 200 nA/m² has been estimated in worst conditions. This is far below what is allowed to flow inside human body. For that respect this should not be a problem. For ozone content 120 µg/m³ limit value has established in Finland. The ozone will be created at conductor surface area and is dependent on surface gradient.

3.6 Mechanical strength of the towers

Practical possibilities to change tower structure and/or conductor bundle composition (as listed in 3.3 above) were examined in several studies conducted by Eltel Networks [4] and Finnmast [5].

It was concluded from the studies that in practice it was not possible to expand the clearance between the poles without major changes or replacements in cross-arms / towers. One option studied was the solution to replace the existing V-strings by I-strings and fix the attachment point at different distances to gain wider clearance between the poles.

Based on the screening made by Fingrid, it was found out that conductor trade name "AeroZ" with smooth circular surface has favorable effect on surface gradient. The existing 3-Finch conductor bundle in Fenno-Skan 2 pole could be replaced by 4-AeroZ. Detailed mechanical study of towers was performed by Finnmast.

3.7 Environmental aspects

The following aspects were considered assuming the conductors will be replaced in Fenno-Skan 2 circuit.

- Ozone content: Limit value exists in Finland. Not likely to be exceeded and cause any problem.
- Ion-current flow: No limit value exists. Current density in human body has limit value, but this will not be exceeded.
- DC electric field: No limit value exists. Current density in human body has limit value, not likely to be exceeded. DC electric field varies due to ambient conditions e.g. wind, humidity etc. This may cause some occasional claims.
- Radio interference: Not likely to cause any claims.
- Audible noise: Not likely to cause any claims.

3.8 The executed solution and outcome

Several studies were made in order to upgrade the existing Rihtniemi - Rauma 400 kV DC overhead line to 500 kV level. These studies included inter alia flashover performance study, FACE calculation studies and mechanical reinforcement studies. It was decided to change the existing conductor in Fenno-Skan 2 circuit to a special type of conductor to mitigate adverse electrical effects (DC electrical strengths at conductor surfaces, radio interference and audible noise). Also two insulator units were added to insulator strings and composite insulators were used in sharp corners to gain minimum clearance of three meters. The results will be verified with field measurements later on.

4 ELECTRODE LINE UNBALANCE SUPERVISION FOR ELECTRODE LINE WITH OVERHEAD LINE AND CABLES

When the new configuration is running in bipolar mode in most cases the DC current in the electrode is practically zero. At full power there is a net DC current flowing in the electrode line to the sea electrode.

On the Finnish side the existing electrode line supervision system is based on DC current measurements in the two electrode line conductors. The DC Current Transducer (DCCT) is of open core design where the two line conductors protrude the center in opposite directions giving a zero net current through the DCCT. A new system is introduced where a short time temporary unbalance in DC current is created once a day to be able to indicate any fault on the electrode line.

On the Swedish side the existing electrode supervision system for the common line for both FS1 and FS2 is unchanged and based on injecting high frequency AC voltages between two blocking filters and measuring the impedance of the electrode line. The neutral line between Finnböle and Dannebo is protected by a new protection based on differential current measurement.

5 AC FILTER INTERACTION FENNO-SKAN 1 AND 2 IN RAUMA

The AC filters for Pole 1 and 2 are connected to the same 400 kV AC bus at Rauma. Different requirements on reactive power from the two poles resulted in different sizes of AC filters for the poles. Further the design for Pole 2 had to consider different AC network harmonic impedance compared with the design for Pole 1. Due to different filter impedance characteristics from increased requirement on reactive power compensation comprehensive studies were performed to cope with filter component rating of the existing and new filter components and harmonic filtering performance.

6 MATCHING OF AC ARRESTERS IN RAUMA

The AC bus arresters in Rauma for Pole 1 and 2 are connected to the same AC bus. Due to the sharp U/I characteristics of arresters the sharing of energy from transient overvoltages need to be considered. As the AC arrester stresses increase with larger amount of AC filters and shunt banks the AC bus arresters in Pole 1 were replaced and matched with the new arresters for Pole 2 to share discharge energies for different AC transient overvoltages.

7 SUB-SYNCHRONOUS TORSIONAL INTERACTION, SSTI, WITH MANY FREQUENCIES IN NEARBY NUCLEAR POWER PLANTS OLKILUOTO AND FORSMARK

A generator includes inertial masses coupled by steel shafts. The mechanical system described has several well-defined modes of torsional oscillation below synchronous operating frequency. The physical explanation of the oscillatory modes is the interaction between the mechanical torque placed on turbines and the opposite electrical torque produced by the power system.

In Fenno-Skan 2 both stations are located close to nuclear power plants, Olkiluoto and Forsmark. Consequently verification of positive damping for the torsional mode oscillations of the turbine generator shafts was one of the most important tests, both in the FST, factory system test, as well as verification during system testing at site.

The set up during FST was a challenge due to the complexity of machine models, total four turbine generators, Olkiluoto 1/2-3 in Finland and Forsmark 1/2-3 in Sweden. The generators were represented as one-mass models as well as multi-mass models. The one mass models were used for verification of the generator damping in the frequency domain and the multi-mass models were used for verification of the generator damping in the time domain.

During system tests at site, both in Finland and in Sweden, the SSTI was monitored by use of the existing SSTI supervision. Oscillations at the torsional mode frequencies were measured at the converter stations by the SSTI supervision based on deviation in period time of the AC-voltage.

Two different test methods were used for verification of the torsional interaction:

- Step in current order, 0,1 pu
- Simulated DC-line faults, with re-start of the DC-link.

The simulated DC-line faults were executed close to nominal power level, starting with tests at minimum and 50% power. The DC-line faults at high power were chosen in order to get enough power changes in the network to initiate SSTI. However, the disturbance caused by this method was too moderate to initiate any significant SSTI since the network configurations during the system tests were fairly strong, and the corresponding Sub-synchronous Damping Controller (SSDC) was activated. It has also to be kept in mind that the damping of the shaft contains both a mechanical part and an electrical part where the mechanical is the most important component and the surrounding network configuration contributes to the electrical part.

The SSTI tests concluded that the link with its SSTI regulator did not deteriorate the damping of the torsional frequencies.

8 EMERGENCY POWER CONTROL SOLUTION ON BIPOLAR/MONOPOLE LEVELS IN FINLAND/SWEDEN

Due to the semi-distributed location of converter stations of Fenno-Skan 1 and 2 the demands and strategies for the Emergency Power Control (EPC) differ between the ends in Sweden and Finland. While connected in two separate spots in the Swedish main grid, the two poles in

Dannebo and Finnböle have their own EPC logic based mainly on local criteria. The EPC functionality is used to reduce risks for overload of AC lines or other network weaknesses. The criteria used are for example voltages and AC switchyard configuration so unnecessary action is avoided. In the Finnish main grid both poles have connection to a single common spot, and the EPC logic is also common.

9 SEA ELECTRODES FOR BOTH ANODE AND CATHODE OPERATION

The Figure 5 depicts Finnish end of the replaced electrode circuit. The existing copper loop cathode at Finnish shore in Laitakari was not designed to operate in anode mode. During the original installation back in late 80's a test cathode net similar to Swedish end was installed at Laitakari. It was removed and inspected at manufacturer's facility with the following conclusions. Most part of the titanium mesh has a white deposit attached. The mechanical structure was deemed to be intact except for two points visible in Figure 6 where small parts of the mesh are missing. The reason for missing parts is the test samples cut out in 1996 and 1998.

New design of the electrode is similar to Swedish end, utilizing 40 pieces of meshed titanium nets. The design criteria applied were as follows: maximum continuous current 1700 A at ambient temperature 0° C, voltage gradient $E_{max} < 2,0$ V/m, step voltage $< 1,25$ V/m and ability to operate with 50% of the nets, i.e. 30 pieces. Different shapes of the electrode were studied and finally the arc shape was selected because it gives good current sharing and is relatively resistant in small deformation of shape or electrode breakdowns. It also gives room to possible expansion in the future. Other shapes, e.g. circle, would not be as easily to expand and misplacement or breakdown of electrodes would easily lead to exceeded step voltages.

The electrode is covered with 200 mm of gravel in order to mitigate step voltages, increase physical protection of the nets, hinder unauthorized access to the nets and finally mitigate environmental impacts.

10 CHALLENGES FOR TRANSMISSION TESTING INSIDE COMMON ELECTRICITY MARKET

Finland and Sweden are located inside the common electricity market area and interconnected with AC overhead lines and HVDC interconnectors. Before Fenno-Skan 2 commissioning the transmission capacity between the countries was 2000 MW from Sweden to Finland and 1600 MW from Finland to Sweden respectively. Since the power is traded in a day-ahead market, capacity allocation including the possible constrains is done a day before.

In order to meet all stringent market rules the following ground rules were established between TSOs and ABB prior to the transmission tests. ABB delivered weekly request plan of test power on previous week's Tuesday. The daily transmission request plan was delivered on a previous day by 8 am CET time for the approval. The smooth information flow was secured by applying single point of contact principle, i.e. Finnish Power System Control Centre and ABB's commissioning manager.

The daily operation plan for both poles was completed after approval of the daily request plan and after the information of the allocated capacities between Sweden and Finland for the next day were available.

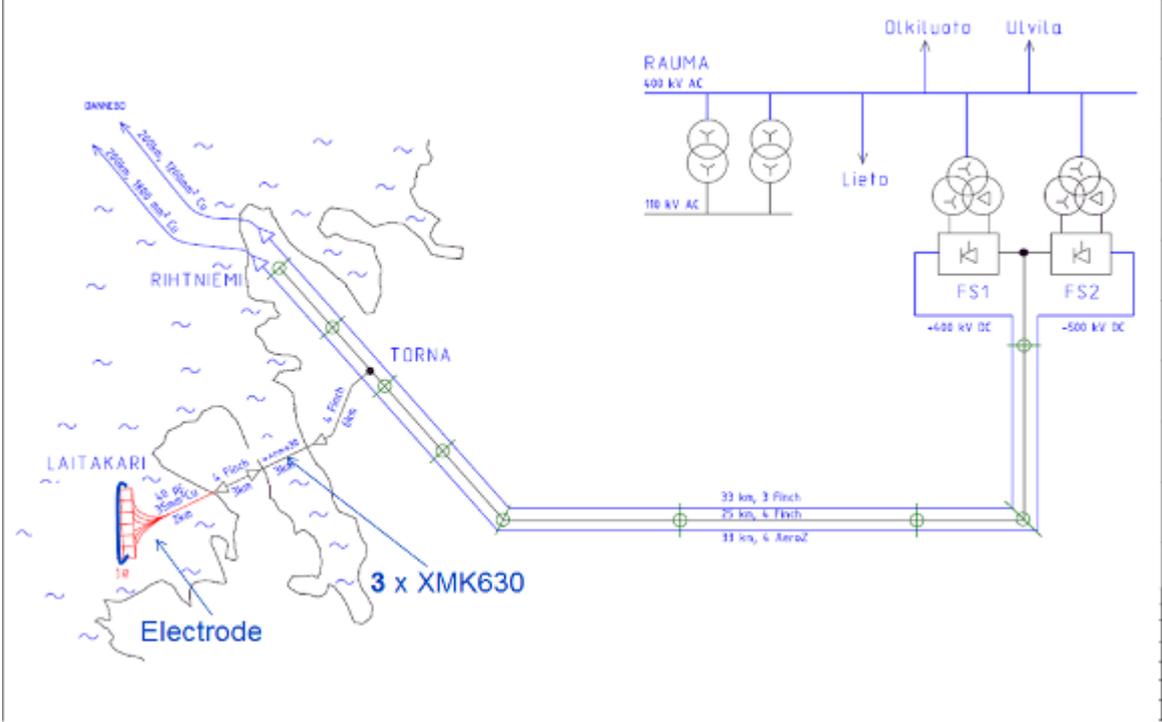


Figure 5 Fenno-Skan scheme electrode circuit



Figure 6 Test electrode titanium net after 20 years operation in cathode mode

With the minimum power transmission test (40 MW) flow between the countries was not a problem at all. Since Fenno-Skan 2 increases significantly the cross-border capacity, the challenges occur when the test power was over the capacity of the existing pole (>500 MW) or when the transmission direction was against the intrinsic direction of the market. During the transmission testing there were a lot of inexpensive Nordic hydropower available. The area price in Sweden ranged between 10 and 15 €/MWh and in Finland between 30 and 40 €/MWh. Almost all tests with Sweden as rectifier were carried out already and the outstanding test plan required transmission direction from Finland to Sweden, so we had to run 800 MW against the intrinsic transmission direction of the market. In order to mitigate unexpected market implication all the following remedies were employed. Firstly, Fenno-Skan 1 compensated net flow by 500 MW to 300 MW, secondly, in same rare occasions TSOs reduced the cross-border capacity temporarily and finally as last resort also counter trade was applied.

11 CONCLUSIONS

The Fenno-Skan 2 projects with interfaces and upgrades were completed successfully and the link is in commercial operation since December 15, 2011 according to original time schedule. From the very start the link has proven to be an important, valuable asset in the the Nordic transmission system.

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