21, rue d'Artois, F-75008 PARIS
http : //www.cigre.org

2016 CIGRE-IEC Colloquium
May 9-11, 2016
Montréal, QC, Canada

Optimal selection of insulation for NordLink ±525 kV DC transmission line in Norway

B. THORSTEINSSON, K. HALSAN
Statnett
Norway

I. GUTMAN, C. AHLHOLM
STRI
Sweden

SUMMARY

This paper presents a comprehensive study with the aim to obtain the best possible evaluation of the practical dimensioning of composite insulators for NordLink ±525 kV DC transmission line. This line is a part of the larger project NordLink which has as the main part a submarine HVDC power cable between Norway and Germany (Statnett and TenneT). Such connection is of great importance because for the first time it will interconnect the Norwegian and German electricity markets. From Norwegian side an overhead transmission line is planned for the length of about 50 km. This line will start close to the coast and then go inland. Due to the lack of IEC standards for DC pollution dimensioning, three available general approaches of IEC 60815-1 have been used:

- Dimensioning using "past experience" approach.
- Dimensioning using "measure and test" approach, which in turn covered the following sub-approaches to obtain design pollution stress ESDD:
    - Analysis of environment and climate in the area.
    - Analysis of existing service experience of overhead lines in the area.
    - Directional Dust Deposit Gauges measurements and analysis.
    - Application of models based on wind and precipitation parameters.
    - Final conversion of AC ESDD to DC ESDD.
- Dimensioning using "measure and design" approach.

The results of the evaluation of dimensioning are presented with comments on practical application for each of the approaches and sub-approaches. Composite insulators were decided as insulation option from the beginning. The study resulted in a solution where two different insulation lengths are recommended; one closer to the coast and another for more inland section of the line, however, longest variant of composite insulators were finally decided for the whole overhead line. The final recommendation on required specific creepage is considered as the average result from the different approaches, which is a conservative choice.

KEYWORDS

DC, Overhead line, Pollution, Insulation, Service experience, Composite insulators.

igor.gutman@stri.se

BACKGROUND AND GOAL

Norwegian TSO Statnett is going to build ±525 kV DC transmission line as a part of the larger interconnection project NordLink. The main part of this project will be a submarine HVDC power cable between Norway and Germany (Statnett and TenneT). Such cable is of great importance because it will for the first time connect the Norwegian and German electricity markets. In practical terms this means the following. When the wind blows and the sun shines from German side, this meteorological situation creates a surplus of renewable energy in Germany, which can lead to lower prices than in Norway. Norway can then import this excessive power and conserve it in its hydropower reservoirs. When there is little production of wind power and solar power in Germany the need for power increases and the prices will be higher than in Norway. During this meteorological situation Norway can in turn produce more hydropower and export it to Germany.

An overhead transmission line from Norwegian side is planned for the length of about 50 km. This line will start close to the sea coast and then goes inland. It was decided from the beginning that composite insulators will be the only option. Statnett made the first pre-design of tower and insulation based mostly on available service experience from Skagerrak projects. The goal of this paper was to obtain the best possible evaluation of the practical insulation selection and dimensioning for this ±525 kV DC transmission line and to verify the results of pre-design. More details on dimensioning of the same line also from ground clearances, electric field, audible noise, and corona point of view will be published in [1].

At present there is no published IEC standard for the selection of DC insulation in polluted environments, only CIGRE Guidelines are available [2]. It is believed that such normative document could be published in 2016 as a Technical Specification, at present it is still a working document under discussion [3]. Thus, all three basic approaches for insulation dimensioning according to the general part of IEC 60815-1 [4] has been decided (see Figure 1 adopted from IEC [4]). These included:

1. Dimensioning using “past experience” approach.
2. Dimensioning using “measure and test” approach.
3. Dimensioning using “measure and design” approach.

To make a comprehensive study, all three different general approaches for dimensioning of insulations with respect to pollution were investigated separately. They are then analyzed and converted into the final recommendation.

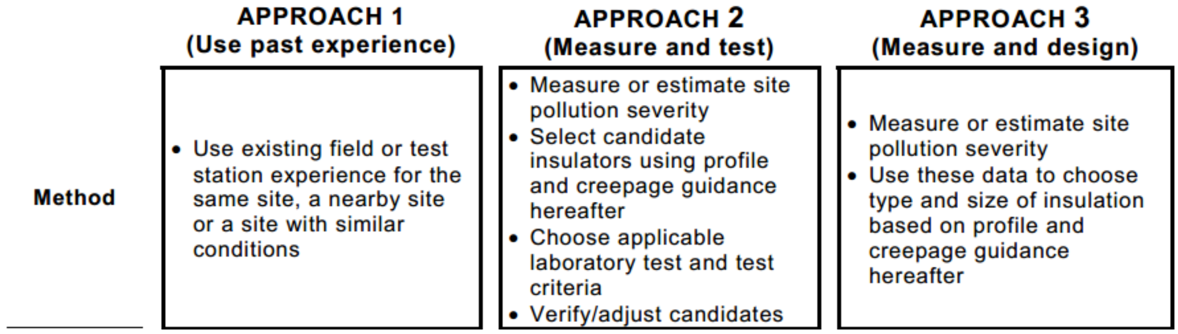

Figure 1 Three basic approaches to insulator selection and dimensioning (adopted from [4]).

DIMENSIONING USING “PAST EXPERIENCE” APPROACH

Service experience from overhead lines in *“similar geographical, topographical and climatic areas or environment”* will provide most reliable information regarding interaction between environmental stresses and insulator performance [4]. If this should be fully utilized for dimensioning of insulators of a new overhead line, service experience representative of the considered insulator type installed in a similar environment should be analysed. Unfortunately, the number of HVDC installations in the world is significantly lower than for HVAC, and thus data on actual pollution performance (especially for composite insulators) is rather limited. This means that it is typically not possible to use directly

service experience of the considered insulator type operating in the environment in question. Thus, such analysis in real life requires some assumptions and considerations.
To make a comparison with available service experience both world-wide and in Scandinavia (more related to the NordLink project), first another comprehensive program for the evaluation of design level of pollution stress, i.e. ESDD was performed and is described in detail in Section "Dimensioning using measure and test approach". Historically, this was done first and thus based on this program two sections of future DC line were preliminary defined as coastal (ESDD~0,07 mg/cm^2) and inland (ESDD~0,03 mg/cm^2). These estimations are used below for the evaluation of service experience in relevant environments, i.e. evaluation of service ESDD and corresponding specific creepage distance.

First, internationally available literature-based experience for composite insulators was analyzed. This included Cahora Bassa in South Africa, Itaipu in Brazil and Pacific Intertie in USA. All these DC lines are located in the areas with light pollution with estimated ESDD level of 0,03 mg/cm^2, thus similar to the inland part of the future NordLink line. The specific creepage for composite insulators was estimated to be 30-32 mm/kV. Secondly, the available experience in Nordic countries was analysed and evaluated. This included all three Skagerrak DC lines and some DC installations in Denmark, Finland and Sweden. The Skagerrak data analysis included earlier performed laboratory investigation of a few naturally aged composite insulators (pollution parameters, flashover performance, ageing performance including material analysis) and strings of glass insulators removed from the line [7]. Based mostly on Skagerrak data it was estimated that for the design level of ESDD about 0,02 mg/cm^2 (close to the inland part of future NordLink line) the specific creepage for composite insulators is about 30 mm/kV.

Finally, using the preliminary data obtained from service experience the best possible estimation of dimensioning using past experience was as follows. Based on pollution measurements (section "Measure and test") NordLink can be separated in two sections with different specific creepage distance requirements. The first section, referred to as "coastal" has been chosen to contain 52 insulators, while the second section referred to as "inland" contains 226 insulators per pole. The MTBF of these two sections were calculated using the Insulator Selection Tool (IST) program [5] for maximum operating voltage 525 kV DC, NSDD=0,1 mg/cm^2, 5 pollution events per year, and a set of different ESDD pollution levels. This part of the project was treated as a sensitivity analysis of estimated MTBF for different ESDD. The IST program follows the statistical approach for dimensioning of IEC 60815-1. This preliminary calculation was performed using only generic CIGRE pollution performance curve from [2]. The criterion was MTBF 40 years for each of the sections. By this calculation, the following specific creepage distance was estimated:

- 31,5 mm/kV for inland section
- 39,5 mm/kV for coastal section

The specific creepage distance of composite insulators earlier installed at DC Skagerrak project at Statnett is 30,2 mm/kV (5 years in operation at present). The recommended increase of required specific creepage from Skagerrak's 30,2 mm/kV to 31,5 mm/kV for inland and 39,5 mm/kV for coastal part of NordLink is due to:

- Increased level of maximum ESDD. The pollution level at the coastal part of Skagerrak is considered as equal to the inland part of NordLink (maximum ESDD at Skagerrak is 0,02 mg/cm^{2,} while is about 0,03 mg/cm^2 at NordLink). The coastal part for NordLink is estimated to be three times higher contaminated as the inland part (about 0,07 mg/cm^2).
- Increased number of insulators. The number of parallel insulators exposed to the same pollution event (storm from the sea) is larger for NordLink, leading to a larger risk of pollution flashover.

DIMENSIONING USING "MEASURE AND TEST" APPROACH

General

This approach formally corresponds to a procedure where at first the site pollution severity is measured and thereafter selected insulators are tested at the measured stress. Basically, knowing pollution stress and pollution performance one balances them depending on availability requirement in outage rate or Mean Time Between Flashover (MTBF). Taking into account the importance of the project, a comprehensive statistical method for insulation dimensioning according to IEC 60815-1 [4] has been decided. This method allows more accurate dimensioning than deterministic (simplified) method; however amount and quality of input data for this method should be high. The principles of statistical dimensioning are shown in Figure 2. The environmental stress f(γ) should be defined (normally described as soluble/non-soluble deposit density ESDD/NSDD, i.e. pollution parameters measured/estimated at the insulator). A cumulative distribution function P(γ) describing the strength of the insulation, should also be defined. These data normally come from laboratory tests, service experience or field tests. The two functions f(γ) and P(γ) are subsequently multiplied to give the probability density for flashover, and the area under this curve expresses the risk for flashover during a pollution event. Thus, based on required MTBF, the insulation length and the creepage distance of insulator in question can be calculated. The IST program follows this principle.

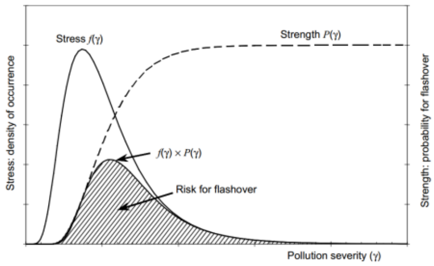

Figure 2 Principles of statistical dimensioning according to Annex G of IEC 60815-1 [4].

Estimation of pollution stress

It was decided to use best up-to-date knowledge to make estimation of the design ESDD, i.e. standard site severity parameter according to the IEC 60815-1. The following steps were used (in each step the ESDD was separately estimated, NSDD was defined as 0,1 mg/cm^2 based on earlier investigations):

1. Analysis of environment and climate in the area.
2. Analysis of existing service experience of AC overhead lines in the area.
3. DDDG measurements and analysis.
4. Application of weather models based on wind and precipitation parameters.
5. Conversion of AC ESDD to DC ESDD.
6. Based on data from 1-5 best possible estimation of DC design ESDD.

<u>1. Analysis of environment.</u> The route of future NordLink line is shown in Figure 3 (left). A figure from IEC 60815-1 representing the relationship between ESDD and NSDD and the site pollution severity classes for AC is shown in Figure 3 (right). This figure also presents typical environments (E1-E7) defined in the standard based on simple description. For example, environment "E2" corresponds to areas 10-50 km from the sea, similar to the right of way of NordLink line. However it was considered that during the storms the ESDD may reach higher levels. The resulting estimated ESDD level from this approach was thus decided as ESDD 0,024 mg/cm^2 (between E2 and E3).

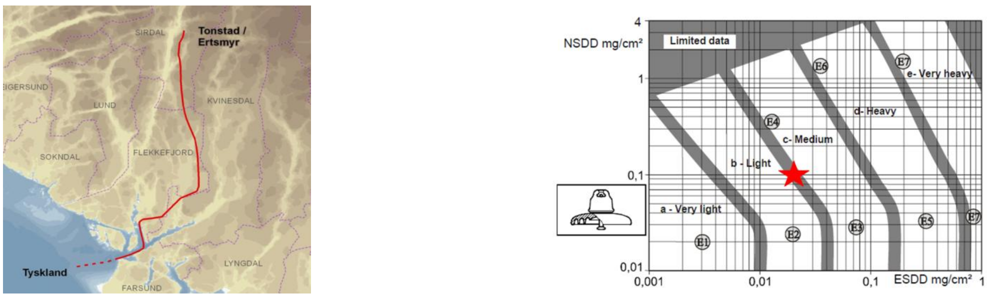

Figure 3 Left: Route of the NordLink line; Right: Relationship between ESDD and NSDD and environments E1-E7. The margin E2/E3 environment is marked by a red star.

2. Analysis of existing service experience of AC overhead lines in the area. Another approach to estimate the design ESDD is analysis of service experience of existing transmission or distribution lines together with meteorological data. In this case the IST program is used “backwards” to estimate the maximum (2 %) or design ESDD when knowing actual MTBF and generic pollution performance. There were six 300 kV AC lines in the area of interest which have been in service for approximately 40 years; their indicative positions are shown in Figure 4 (left). Three of them are placed more inland and the three others are placed rather close to the sea. The service experience for all of the lines of interest was analyzed to estimate the MTBF. Unfortunately, only three documented faults were defined as pollution flashovers by service personnel. These faults had occurred once on each of the overhead lines inland and coastal lines were completely fault-free. The resulting estimated ESDD levels for each of the existing AC lines are presented in Figure 4 (right). Due to absence of actual faults, the MTBF for coastal lines was considered equal to their service life (i.e. 44 years). Due to this consideration the estimated ESDD for the coastal lines is very conservative. The ESDD level for inland lines is considered as more realistic. Average ESDD for each of three lines (inland and coastal) from Figure 4 (right) was finally considered as an output from this approach.

Line	Maximum ESDD at NSDD = 0.1 mg/cm^2
Feda-Lista 1	<0,17
Feda-Lista 2	<0,17
Feda-Sira	<0,17
Feda-Tonstad 1	0,043
Feda-Tonstad 2	0,046
Lyse-Tonstad	0,041

Figure 4 Left: Existing 300 kV AC lines in the area of interest; Right: ESDD levels for AC lines calculated using IST program.

3. Analysis based on DDDG measurements. Standard Directional Dust Deposit Gauge (DDDG) device according to the IEC 60815-1 is measuring equipment for determining Site Pollution Severity (SPS). Using IEC 60815-1 the SPS can be converted into ESDD. The measurement equipment consists of four collection tubes with a jar mounted in the bottom placed on a support column at approximately 3 m height above ground; see Figure 5 (left). Each month the jars are collected, filled with de-ionized water up to maximum 500 ml and then the conductivity of the water (Pollution Index, PI, measured in µS/cm) is measured and normalized. From a 12-month measuring series of the PI the SPS can be determined and then converted into ESDD. The highest SPS class should be chosen from either the yearly average or the highest monthly value.

Statnett obtained positive experience with the first application of such devices [6]. The installation of the three DDDG’s was a joint mission by STRI and Statnett in May 2014, location of devices is presented in Figure 5 (middle). It was noticed at the time of the installation that DDDG 1-2 were placed at position possibly shielded from winds by nearby trees, but at that time no alternative open positions could be identified. The monthly measured values of the normalized conductivity are presented in Figure 5 (right). All three DDDG’s recorded their highest readings in January 2015 after typical winter storms. The highest value of conductivity was however recorded on DDDG 3 furthest away from the sea. Additional analysis of weather parameters at two nearby weather stations showed that during a major storm in January 2015 the wind came from the south. This indicated that DDDG 1 and DDDG 2 were not measuring the proper amount of salt coming from the sea since the wind did come from the south and theoretically should bring more salt on DDDG 1 and DDDG 2, than on DDDG 3. Thus, DDDG 1 and DDDG 2 were finally considered to be partially shielded by the trees even in this critical case. The location of DDDG should be carefully checked for the future from this perspective. However, no corrections were made for the measurement results and the final ESDD levels from this approach were considered as 0,02 mg/cm^2 (inland section) and 0,004 mg/cm^2 (coastal section).

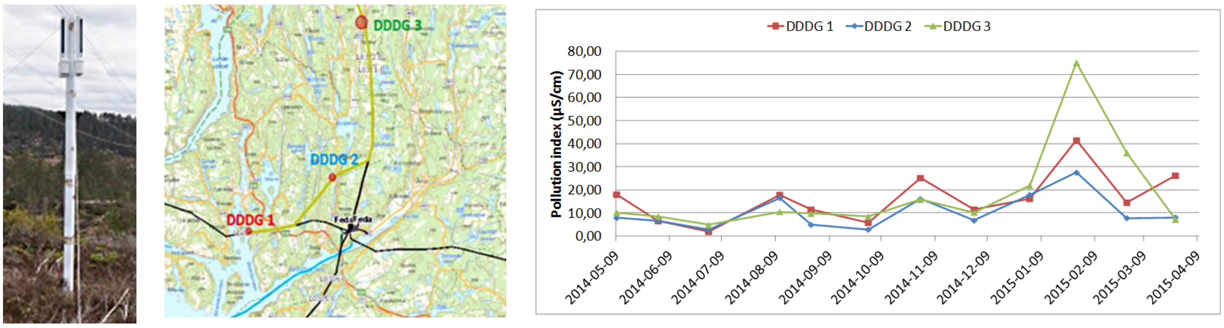

Figure 5 Left: Example of installed DDDG; Middle: Location of three DDDGs along the future route of NordLink; Right: Monthly measurements of DDDG Pollution index (1 year period).

4. Analysis based on wind modelling. Standard DDDG measurements are made on a monthly base and thus the amount of data is limited to twelve even after a year of measurements. Thus, it was proposed in [6] to combine DDDG measurements with ESDD modelling using wind and precipitation data. This approach worked well and was verified by a few case studies in Sweden, Norway and South Africa [6]. In this case the DDDG data is used for the calibration of the wind model and after this is done, the model is ready to predict the historical level of ESDD. Because standard weather parameters are registered rather often (can be once per hour) the massive data volume (thousands per year) became available for the prediction of maximum (in this case normally used 2% level) of ESDD, the example is shown in Figure 6. The specifics in our case was that it was assumed that in Norwegian environment the natural cleaning will only occur if the temperature during rainfall is above 0°C. Two different cases representing the coastal and inland areas of NordLink were analysed. The coastal area was using the DDDG results from the DDDG 1 closest to the coast and the weather data recorded at Lista, this resulted in ESDD 0,036 mg/cm^2. The inland part was using the DDDG results from DDDG 3 most inland and the weather data recorded at Eik-Hove, this resulted in ESDD 0,008 mg/cm^2.

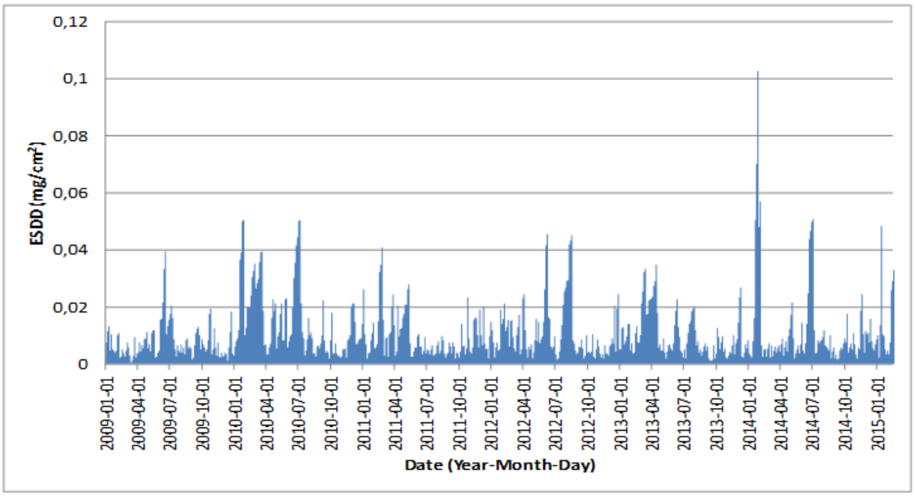

Figure 6 Historical variations of ESDD in the coastal area (results of weather modelling).

5. Conversion of AC ESDD to DC ESDD. All four approaches above provided estimations for AC ESDD. The procedure for estimating DC ESDD based on AC ESDD is described in [2] where the influence of the electrostatic field is described by the accumulation factor K_p. According to [2] the prediction of DC pollution levels from measurements on AC insulators is associated with significant uncertainty. However, the following general guidance is applied for the selection of K_p and at present it is included in the draft of the IEC for DC: *“K_p is typically 1,1, with a range of 1 to 1,2 in areas* *where maximum site severity conditions are reached in a short time following specific events. Typical cases are those where the wind speed is the dominant factor that determines the amount of pollution carried in the air or in areas where high wind speeds prevail."*[3]. For the present study, salt carried from the sea during storms with strong wind is considered to be the dominating factor. K_p is thus conservatively selected as 1,2 resulting in an estimation of the DC pollution level as DC ESDD = 1,2×AC ESDD.

6. Final estimation of design ESDD (pollution stress). The selected DC design ESDD obtained from the different approaches is presented in Table 1. The ESDD level estimated from service experience is conservative, and is the result of the long specific creepage used for the coastal AC lines around Feda and associated uncertainty in MTBF of the same lines (no actual faults registered). The DDDG results for the coastal section are however not too conservative and probably do not represent the maximum ESDD, since higher levels were measured further inland (possible influence of screening by nearby forest). The estimation obtained from the description of the environment (according to IEC 60815-1) already includes a great uncertainty by rough definition. The results of wind modelling showed that the DDDG measurements are relatively low for inland section when past years of wind and rain are taken into account. The results of the wind model however are probably the most accurate estimate of the actual maximum ESDD. Due to many uncertainties all four approaches are finally averaged in Table 1. However, if the mostly confident for coastal section is ESDD 0,043 mg/cm^2, it seems reasonable to use finally ESDD 0,069 mg/cm^2 which will be slightly conservative.

Table 1. Estimation of final design ESDD in inland and coastal areas.

	Estimation from environment (IEC 60815-1)	ESDD estimation based on AC service experience	ESDD estimation from DDDG measurements	ESDD based on wind model estimation
DC ESDD (mg/cm^2)	0,024	0,052	0,024	0,010
Final design ESDD	0,027 mg/cm^2 for inland section			
DC ESDD (mg/cm^2)	0,024	0,204	0,005	0,043
Final design ESDD	0,069 mg/cm^2 for coastal section			

Dimensioning using different pollution flashover performance curves

The required specific creepage distances of composite insulator types were calculated using the IST program and design ESDD presented in Table 1. The following parameters were used:

- DC voltage: -525 kV
- Number of insulators exposed to the same pollution/wetting event: 52 for coastal and 226 for inland section
- MTBF: 40 years.
- The number of pollution/wetting events per year: 5
- Insulator pollution performance curves represented "CIGRE composite" from [2] and insulator candidates previously installed for evaluation on Skagerrak [7], four different composite insulators in total.

The averaged available data from pollution tests of different insulators provided 31,3 kV/mm for inland section and 36,9 kV/mm for the coastal section of the NordLink.

DIMENSIONING USING "MEASURE AND DESIGN" APPROACH

The process of obtaining required insulator specific creepage using the "measure and design" is presented in Figure 7 [2]. The following values of correction factors were considered: $K_{CUR}=K_d=C_d=C_a=1$; $K_s=1,4$ (more than 100 insulators exposed to the same pollution event). The specific creepage distance is estimated as 36,2 mm/kV for coastal section and 28,7 mm/kV for inland section.

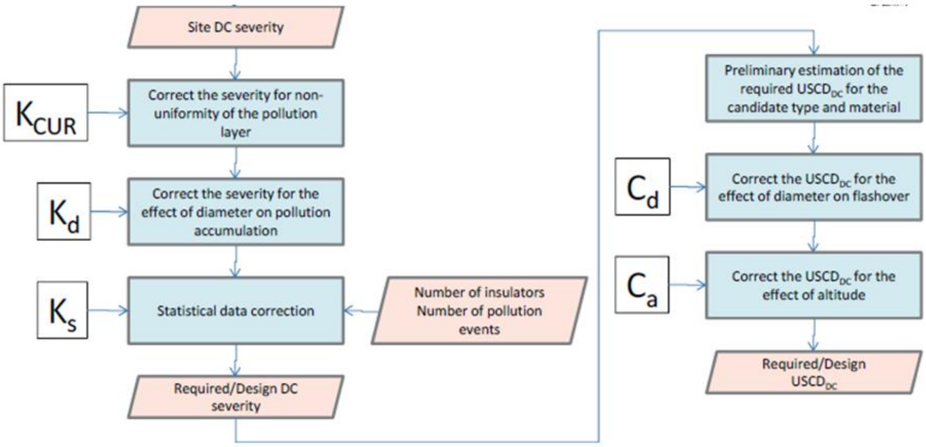

Figure 7 Simplified dimensioning process (measure and design) according to [2].

SUMMARY

In order to properly dimension the insulation of NordLink line with respect to pollution all three basic approaches of IEC 60815-1 were utilized for comprehensive estimation of the required specific creepage distances (respective insulation lengths). This is to verify the pre-design of insulator length made earlier by Statnett. Some of these approaches in turn consisted of a few sub-approaches. The results obtained from each approach are presented in Table 2. For the final recommendation the average result from the different approaches was utilized. This is of course a conservative approach. However, taking into account the specifics of the Norwegian environment for composite insulators (cold and humid) and for the project (VSC based HVDC system does not allow regulating the voltage during severe pollution events), such approach is considered as reasonable. The recommended specific creepage and corresponding insulation length (for specific creepage factor) are as follows: for coastal section 37,5 mm/kV (insulation length 5,3 m); for inland section 30,5 mm/kV (insulation length 4,3 m). The proposed length for the inland section was close to the Statnett's pre-design of 4,2 m [1].

Due to unification purposes (easier purchasing, installation and maintenance) Statnett decided to use only the longest insulator (composite insulator in a V-string configuration) for the whole line. For this insulator Statnett plans to perform pollution and ice testing to verify the results of design [1].

Table 2. Summary of specific creepage distance requirements obtained by different approaches

Area	Required specific creepage distance (mm/kV)			Average (mm/kV)
	Past experience	Measure and test	Measure and design	
Coastal	39,5	36,9	36,2	37,5
Inland	31,5	31,2	28,7	30,5

BIBLIOGRAPHY

[1] B. Thorsteinsson, K. Halsan, M. Abraha, W. Troppauer, C. Ahlholm, D. Loudon: "Design and engineering of a new 525 kV HVDC line in Norway", CIGRE Session 2016, B2-133 (to be published)

[2] CIGRE WG C4.303: "Outdoor insulation in polluted conditions: Guidelines for selection and dimensioning: Part 2: The DC case", Technical Brochure No. 518, December 2012

[3] IEC TS: "Selection and dimensioning of high-voltage insulators intended for use in polluted conditions – Part 4: Insulators for d.c. systems", IEC/TS 60815-4, committee draft 36/371/CD, 2015

[4] IEC TS: "Selection and dimensioning of high-voltage insulators intended for use in polluted conditions – Part 1: Definitions, information and general principles", IEC/TS 60815-1, First edition, 2008

[5] I. Gutman, J. Lundquist, "Optimization of AC and DC Insulation Using Software for Statistical Dimensioning", World Congress & Exhibition on Insulators, Arresters & Bushings, Seoul, Korea, 17-20 April 2011

[6] I. Gutman, C. Ahlholm, K. Halsan, R. Eide, L. Carlshem, W. L. Vosloo, J-F. Goffinet: "Application of weather models for the evaluation of design ESDD for harsh pollution conditions", CIGRE Session 2014, D1-212

[7] S. Berlijn, K. Halsan, I. Gutman, A. Dernfalk: "Assessing Ten Years of Service Experience with Composite Line Insulators at HVDC", World Congress & Exhibition on Insulators, Arresters & Bushings, Crete, 11-13 May 2009