Availability of Generator Breakers under Snow, Ice and Pollution during Connecting to a Line

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Abstract—Statistical or probabilistic approach for the dimensioning of insulators comprises the selection of the dielectric strength with respect to the voltage and environmental stresses to fulfill a specific performance requirement. Analysis of service experience at Statnett (Norway) revealed that the most critical scenario could be the synchronization of the generator breakers, when the stress on the insulation can be around 2 p.u. To perform the statistical dimensioning, both flashover performance in different environment and service environment were investigated. Environmental flashover performance curves for snow, ice and pollution conditions were obtained in the laboratory. Environmental parameters at area of interest were analyzed and dimensioning levels were identified. All earlier obtained flashover performance data under pollution, ice and snow conditions are used for the availability calculations and the results of the calculation are confirmed by service experience.

I. Introduction

A. Principles of statistical dimensioning

According to the revised IEC Standard IEC 60815, to be issued in 2008, *both deterministic and statistical design methods are available to design and select appropriate insulator solutions based on service environmental stress measurements and laboratory test results* [15]. The scope of the IEC 60815 is pollution dimensioning, however generally speaking the statistical dimensioning of insulators entails the selection of the dielectric strength of an insulator, with respect to *any* of environmental stresses and to the voltage (stress/strength concept), to fulfill a specific availability requirement. Application of this statistical method for the pollution dimensioning is illustrated in details in e.g. [1], and the same approach for ice conditions is illustrated in [3]. Independently of the environment in question, the basic concept of the stress/strength concept is shown in Fig. 1, adopted from [15].

With reference to Fig. 1, the risk for flashover can be calculated as follows (the wording is also mostly adopted from IEC 60815 [15]):

• The variation of the environmental stress (e.g. Equivalent Salt Deposit Density (ESDD) for pollution, or dripping water conductivity for ice or snow height and density for snow) at the site of interest is evaluated and represented by a suitable probability density function f(γ), expressed in terms of the site severity "γ" . These data normally come from direct service measurements; typically a lognormal distribution function is used.

• A cumulative distribution function P(γ) describing the strength of the insulation, i.e., the probability for flashover as a function of the same severity "γ" as used to describe the environmental stress (e.g. ESDD for pollution, dripping water conductivity for ice or snow height and density for snow) is obtained. These data normally originates from laboratory tests, service experience or field tests.

• The P(γ) function is then converted from a representation of a single insulator, to represent the performance of "m" insulators installed on an entire line (line section) or substation and exposed to the same number of environmental events.

• 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.

• If the number of pollution events per year is known (e.g. salt storms in coastal areas, or light rain or dew in inland areas or ice or snow storms in iced areas) the risk for flashover per year can be calculated.

This method requires an accurate determination of the statistical parameters that describe the site severity as well as those that describe the insulator flashover characteristics. The latter characteristic has to be determined for each insulator type by laboratory determination of U_{50} and standard deviation at several (at least two) pollution levels.

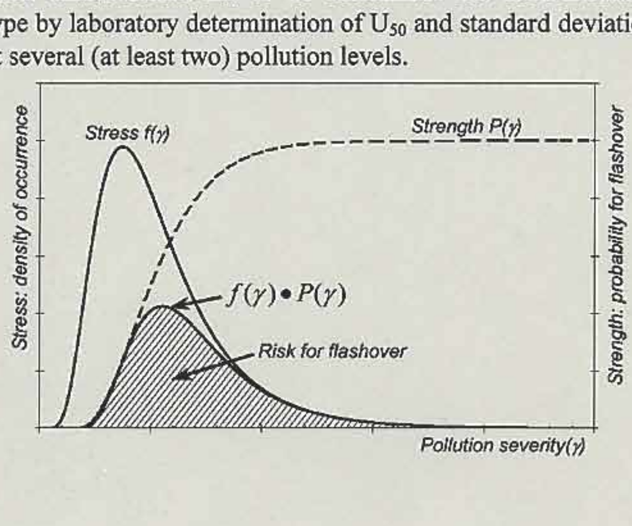

Fig. 1 The stress-strength concept for the calculation of the risk for flashover with respect to polluted conditions (figure adopted from [15])

B. Input in statistical dimensioning

Pollution and ice performance were earlier investigated for circuit breaker with horizontal insulators for different applications and were based on the different exposure times under voltage in service. The results were based on statistical dimensioning. It was found that pollution, not ice was dimensioning for the performance [10]. These investigations were based on pollution and ice conditions and on voltage stress 1 p.u. The flashover performance obtained for these calculations is used to create cumulative distribution functions P(γ) for pollution (Section IV) and ice (Section V) respectively. According to [1] the flashover performance with respect to pollution severity is typically given by:

$$\frac{U_{50}(\gamma)}{l} = A \cdot \gamma^{-\alpha} \qquad (1)$$

where U_{50} is the 50% flashover voltage; l is the axial length of the insulator; γ is the pollution severity; A and α are experimental constants.

After analysis of the service experience in Norway, it was identified that the most critical scenario could be the synchronization of the breakers under snow conditions, when the stress on the insulation can be about 2 p.u. Thus, the flashover performance under snow was obtained in [4]. This flashover performance is used to create cumulative distribution function P(γ) for snow (Section VI) .

The site distribution function f(γ) for pollution was estimated based on ESDD measurements in Norway and Sweden. The site distribution function f(γ) for ice was derived from service measurements in Norway [11]. Snow distribution was investigated for the south of Norway. However, it was not possible to get relevant snow distribution data of horizontal insulators from existing meteorological data. Instead, for a given performance the maximum snow height with given density could be calculated.

II. Service Experience

Flashovers due to pollution and ice for generator breakers are not known from Norway. However, snow-induced flashovers have occurred a number of times during connecting a generator to a line. The snow condition of a recent flashover on a breaker with parallel grading capacitors is illustrated in Fig. 2.

Fig. 2 Snow on breaker after heavy snowfall in the south of Norway

III. Test Objects

Three different circuit breakers for system voltage 400 kV were used in the tests and availability calculations:

- a conventional circuit breaker with porcelain insulators
- a conventional circuit breaker with porcelain insulators and grading capacitors
- a disconnecting circuit breaker with silicone rubber insulators.

Typical simplified drawing and a photo of the disconnecting circuit breaker are shown in Fig. 3.

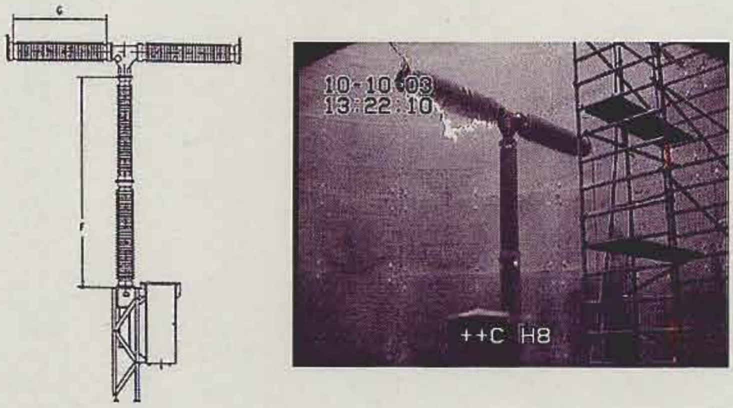

Fig. 3 Simplified drawing of the circuit breaker and a photograph during ice testing

IV. Pollution Investigations

A. Pollution flashover performance

The pollution tests were performed using the Quick Flashover Salt Fog test method (QFSF) described in [6]. The QFSF test consists of two phases: pre-conditioning and flashover.

<u>Pre-conditioning phase:</u>

- The initial level is a guess of 90% flashover voltage level, where the first test duration is 20 min.
- The voltage is raised then by steps +5% (ΔT=1 min.) until flashover
- The initial level after flashover is as from the beginning
- This is continued up to 5 flashovers
- An average flashover voltage (U_{FO}) is calculated

<u>Flashover phase:</u>

- The initial reference voltage is $0{,}9 x U_{FO}$
- The voltage is raised by steps +3% (ΔT=5 min.) until flashover
- This is continued maximum 7 times
- An average UFO is calculated and treated as U_{50}

The results for porcelain breakers are presented in Fig. 4 together with the results from [6] which were obtained on different porcelain horizontal and one vertical insulator. In case of the open position only horizontal flashovers occurred.

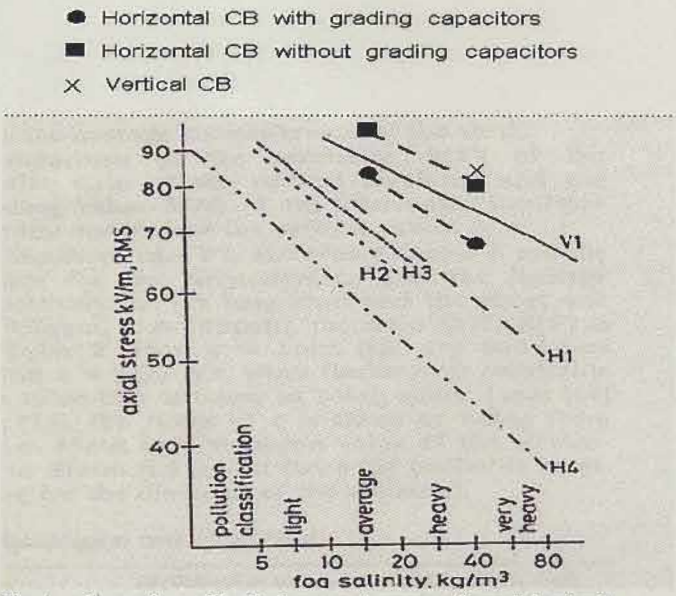

Fig. 4 Comparison of the flashover performance of porcelain circuit breakers with the results from [6]

The following indications can be made based on the results presented in Fig. 4.

- The inclinations of the flashover stress curves are similar for all presented results and this parameter is typically related to the test conditions (environment, in which dry-band arcs are burning). Thus, the results are reproducible.
- The results of the tests are completely in line with classical theoretical estimations:
    - The flashover stress of the breaker with grading capacitors is lower than for the breaker without capacitors. The explanation is that there is a continuous current through capacitors, however the maximum current through the pollution layer is much higher (up to 1 A), therefore the capacitors do not smooth the E-field distribution in pollution conditions. They create only additional path for the flashover, thus increasing the total risk for flashover for the breaker. This is in line with what happened during the tests.
    - The flashover stress of the vertical support insulator is higher than for the horizontal chamber. This can be explained by a larger diameter of the chamber.

The flashover stress for all tested insulators needed as an input in the statistical calculations is presented in Fig. 4. The results of regression are in the standard form according to equation (1). The normalized standard deviation is taken as an average from all test results and became 0.1. Note that composite breaker was tested in a very conservative mode with artificially reduced hydrophobicity of the surface before the test, however still had a superior to porcelain performance.

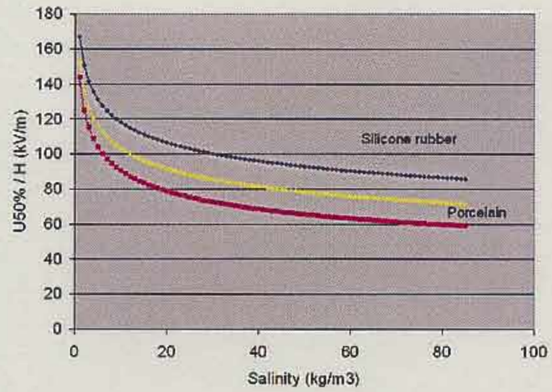

Fig. 5 Flashover performance of one silicone rubber circuit breaker and two porcelain breakers

B. Pollution severity stress

In the draft of the IEC Standard 60815 [15] it is suggested to define the "site pollution severity" as *The values are the maximum values that can be found from regular measurements taken over a minimum one year period.* For our calculations, based on previous experience the maximum ESDD level (statistical severity) in Norway is estimated as 0.1 mg/cm^2 [10]. Comparing then Fig. 6 and Fig. 7, both adopted from the IEC draft [15], we consider that flashover performance at the salinity "S" 40 kg/m^3 corresponds approximately to the defined ESDD 0.10 mg/cm^2 (typical NSDD 0.1 mg/cm^2), i.e. between "Heavy" and "Very heavy" site pollution severity.

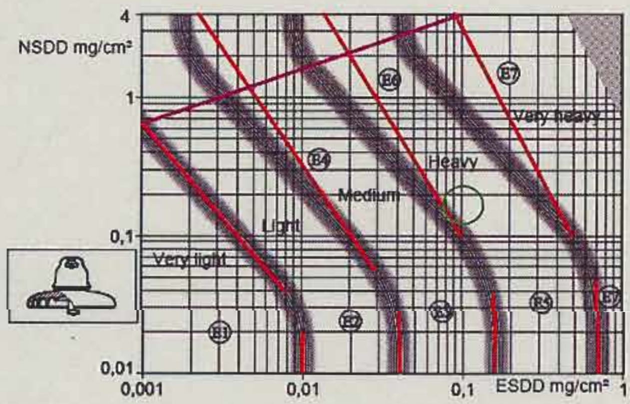

Fig. 6 Relation between ESDD/NSDD and "site pollution severity" (SPS) according to IEC [15]. Green circle corresponds to ESDD/NSDD = 0.1/0.1 mg/cm^2.

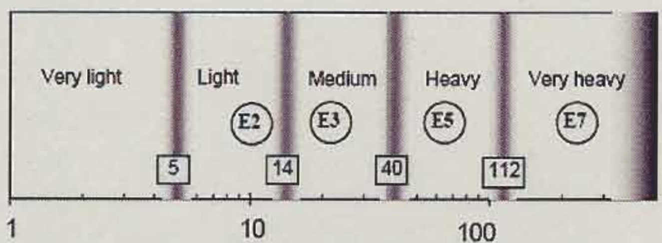

Fig. 7 Relation between "Site Equivalent Salinity" (SES) and "Site Pollution Severity" (SPS) according to IEC [15].

C. Pollution availability calculations

The availability calculations for pollution were made for three breaker types, DCB, CB+ and CB- at 2 p.u. during the synchronizing time. This voltage appears only over the horizontal breaking chambers. Therefore only horizontal flashover stress was used for the calculations. The insulator characteristics that were used in the availability calculations are presented in TABLE 1. The cumulative flashover probability P(γ) is shown in Fig. 8.

TABLE 1
PARAMETERS USED DURING POLLUTION AVAILABILITY CALCULATIONS

Parameter	DCB	CB+	CB-
Standard deviation of U	0.10	0.10	0.10
Truncation parameter, n	2.5		
Number of parallel insulators	3		
Maximum operation voltage, kV_{ph-ph}	840		
Statistical severity, ESDD (mg/cm^2)	0.10		
Standard deviation of ESDD	0.7		
Number of pollution events	5		

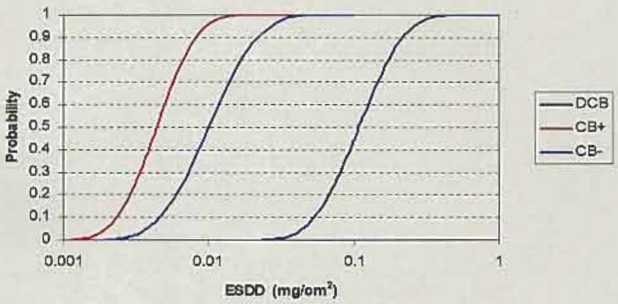

Fig. 8 Pollution flashover probability of circuit breakers with horizontal insulators

The exposure of the breaker under 2 p.u. is estimated as 60 seconds during one connection per day. However, the probability for a synchronizing to take place during a pollution event is also dependent of the duration of that event. Normally the pollution event takes from a few hours to 1 day, i.e. very conservatively during one-day pollution event a connection will take place. However, using laboratory simulation of the pollution event (IEC 60507) a flashover occurs only during the time when the layer conductance is above 90% of its maximum. This time is about 30 minutes (Fig. 9), while 2 p.u. exposure is limited to 1 min. Thus, it is reasonable to consider reduction of the flashover risk by 30 times.

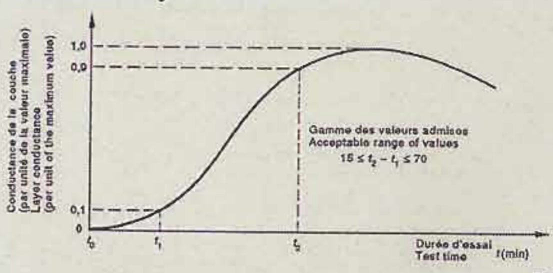

Fig. 9 Wetting cycle adopted from IEC 60507

The flashover risk with one synchronizing every day is therefore

$$R = \frac{N_p}{30} \cdot \int_{-\infty}^{+\infty} f(\gamma) \cdot P(\gamma) d\gamma \qquad (2)$$

where N_p is the number of pollution events.

The availability calculations for polluted insulators during connecting a generator to a line for the different breakers were performed in Insulator Selection Tool software program [13] and the results are presented in TABLE 2.

TABLE 2
NUMBER OF FLASHOVERS PER YEAR DURING CONNECTING A GENERATOR TO A LINE

DCB	CB+	CB-
0.015	0.17	0.16

V. ICE INVESTIGATIONS

A. Ice performance

The Ice Progressive Stress (IPS) procedure was used for the ice tests. The details on the procedure are summarized in [12], and a short description is as follows. As any of the ice test procedures the IPS procedure consists of two main phases:

- Ice deposition
- Flashover performance evaluation

The IPS ice deposition method is based on the wet ice accretion condition. The ice is applied by means of freezing water supplied by the nozzles. Maximum of 11 nozzles are used simultaneously to accrete ice on one T-formed breaker 400 kV.

After the ice accretion phase is finished, the voltage is increased at a constant rate of minimum 6 kV/s. This is quite in line with the IEEE recommendations. Because of the rather high rate, the basic ice conditions can be regarded as being constant within this period, which is an important demand to enable repeatability. The voltage was increased until a flashover was obtained and this ended the test. The flashover voltage level was noted. This procedure is repeated a few times and the output results in the U_{50} and the standard deviation. The conductivity of the dripping water is the main parameter that influences the flashover; therefore the U_{50} (or flashover stress in kV/m) is later presented as a function of dripping water conductivity.

The flashover stress 156 kV/m was defined over the horizontal insulators of the DCB. No useful results were obtained for other circuit breaker types. The flashovers that occurred over the support insulator indicated that there was no difference between the different breaker types. It was also not possible to find any influence of the dripping water conductivity on the flashover; this is most probably because the conductivity range was too small. Thus, for the statistical calculations it was assumed that there is the same type of relation between the flashover and the dripping water conductivity as is shown in equation (1). The "α" parameter is chosen as an average for pollution performance, i.e. 0.19.

B. Ice stress

The Norwegian Power Grid Company Statnett provided data about the conductivity of 122 ice samples taken from service, between 1987 to 1995 [11]. The probability density function of the conductivity of these melted-ice samples is shown in Fig. 10. These samples, mostly of rime ice, were taken from racks and towers close to the ground, which thus corresponds to applied water conductivity. The samples are more contaminated than snow on the ground, most probably due to the higher content of rime.

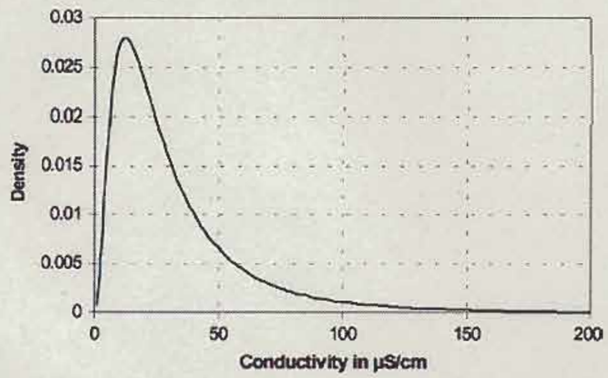

Fig. 10 Ice stress: density function of melted-ice conductivity (figure adopted from [3])

C. Ice availability calculations

The parameters used for ice availability calculations are shown in TABLE 3.

TABLE 3
PARAMETERS USED DURING ICE AVAILABILITY CALCULATIONS

Parameter	DCB
Standard deviation of U	0.10
Truncation parameter	2.5
Number of parallel insulators	3
Maximum voltage (kV_{ph-ph})	840
Statistical severity, dripping water conductivity (µS/cm)	120
Standard deviation of dripping water conductivity	0.7
Number of icing events	5

Number of flashovers per year during connecting DCB to a line was calculated as 0.01. It is most probable that it is also valid for other types of circuit breakers. However, lack of data calls for a sensitivity analysis of the constant α.

D. Sensitivity analysis

Because of the uncertainty of the ice pollution flashover data a sensitivity analysis is made by varying $\alpha \pm 50\%$ ($\alpha = 0.19 \pm 0.09$) while keeping $U_{50\%}$ as 156 kV/m. Constant A varies accordingly. The other parameters are as in TABLE 3. The result is presented in Fig. 11. The availability is not too sensitive to the changes of constant α.

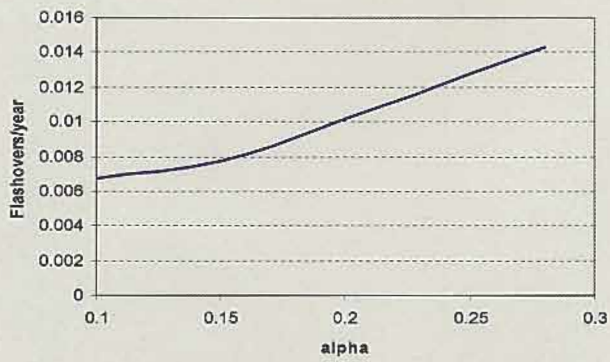

Fig. 11 Availability of ice covered breaker DCB as function of parameter alpha

VI. SNOW INVESTIGATIONS

A. Snow flashover performance

In order to make availability calculations of circuit breakers under snow conditions it is necessary to use some dimensioning snow parameter that has an influence on the flashover voltage and can be measured both in service and in the laboratory. The results for the breaker with porcelain insulators and grading capacitors (CB+) were based on laboratory snow flashover tests [14], [4]. In [14] the resistance of the snow on the horizontal insulator of the breaker was used as the main parameter governing the flashover. Unfortunately, such parameter cannot be obtained from service. Thus, this parameter was converted into snow height and snow density. In [7] the snow flashover process was investigated on horizontal string of insulators with snow height 40 cm as a function of the snow density. By rearranging the withstand voltage data in [7] it is possible to estimate the flashover relation of snow with different density on horizontal insulators. The equation has the form:

$$\frac{U_w}{l} = A_d \cdot d^{\alpha} \quad (3)$$

where α and A_d are experimental constants. The regression curve and the equation are shown in Fig. 12.

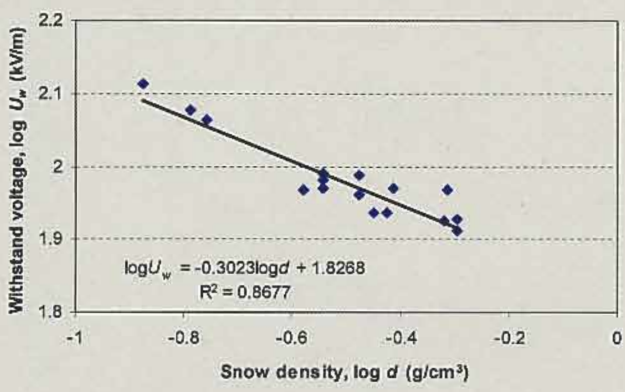

Fig. 12 Data from [7] showing the relation between snow density and withstand voltage with 40 cm snow on horizontal string insulators

The withstand voltage in [7] was also measured as a function of the snow height as illustrated in Fig. 13. It is thus also possible to estimate the withstand voltage for different snow heights and densities.

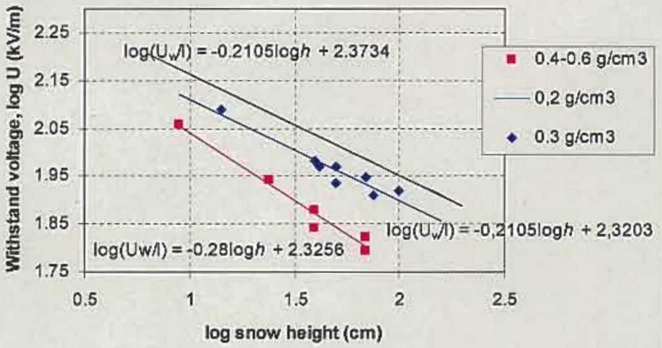

Fig. 13 Withstand voltage for different snow density as function of snow height on horizontal string insulators from [7]. The equation for snow density 0.2 g/cm^3 is calculated with the same α as for 0.3 g/cm^3

The best fit curves in Fig. 13 are in the form:

$$\frac{U_w}{l} = A_h \cdot h^{\alpha} \qquad (4)$$

i.e. the same form as for equation (3). The experimental constants α and A_h in equation (4) are then calculated from the snow flashover data for the disconnecting circuit breaker (DCB) and for the breaker with grading capacitors (CB+). For DCB the constants are calculated as follows. The constant α is assumed to be the same as in Fig. 14 (for the corresponding densities). U_{50}/l = 143,9 kV/m is taken from [4] at the time 60 seconds (as illustrated in Fig. 14) and this is the flashover stress at the maximum synchronizing time. Constant A_d is calculated from equation (3). The flashover voltage stress as a function of snow density then becomes:

$$\log\left(U_{50\%}/l\right) = -0.30\log d + \log 109.4 \qquad (5)$$

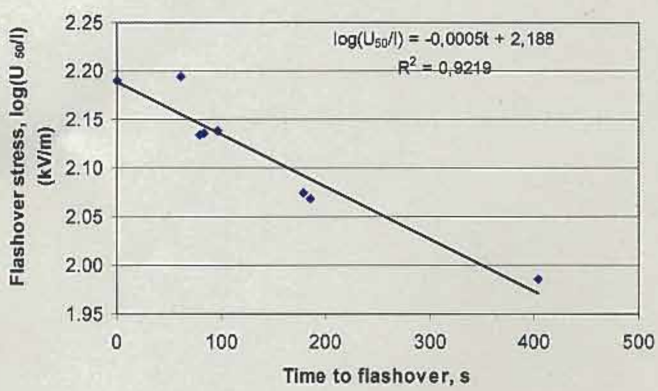

Fig. 14 Time to flashover of snow covered DCB versus flashover voltage stress from [4]

Using the equations in Fig. 13 the constant A_h is calculated for the different densities. A similar procedure is used for the calculation of the same constant for CB+. In this case U_{50} was taken as 420 kV for snow density 0.3 g/cm^3 and 360 kV for density 0.5 g/cm^3. These values are less accurate than for the DCB as only two flashovers were obtained for each density. The parameters used during snow availability calculations are presented in TABLE 4.

TABLE 4
PARAMETERS USED DURING SNOW AVAILABILITY CALCULATIONS

Parameter		DCB		CB+	
		α	A_h	α	A_h
Density	0.2	0.21	363	0.21	258
	0.3	0.21	323	0.21	228
	0.5	0.28	350	0.28	241
Normalized std dev of U		0.10		0.10	
Truncation parameter n		2.5		2.5	
Number of parallel insulators		3		3	
Max system voltage at synchronizing, kV_{ph-ph}		840		840	

A comparison the flashover stress of DCB and CB+ as a function of the snow height is illustrated in Fig. 15.

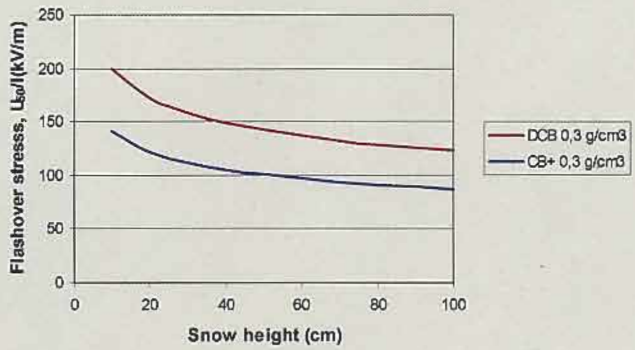

Fig. 15 Flashover stress of circuit breakers as function of snow height at density 0.3 g/cm^3

The risk for flashover (flashover probability) is presented for DCB and CB+ in Fig. 16.

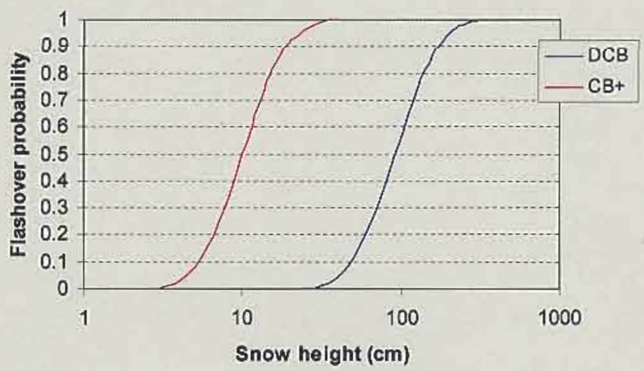

Fig. 16 Flashover probability for DCB and CB+ single breaker at density 0.3 g/cm^3

B. Snow severity stress

According to Statnett snow issues are mostly relevant for the South of Norway in an area to the south of latitude 60° N and to the west of longitude 10° E as illustrated in Fig. 17. The dimensioning values for snow density and snow depth are not yet available from the Norwegian Meteorological Institute.

Fig. 17 The area for snow statistics in Norway

As site stress data was not available it was not possible to calculate the availability for the breakers under snow stress. Thus, based on analysis of the available data from service and outdoor tests at STRI [14], it was assumed that the dimensioning snow height is 30 cm (snow height that is exceeded in 2% of the snow events) and the densities of the snow are 0.3 g/cm^3 or 0.5 g/cm^3. These parameters were used for the availability calculations.

C. Snow availability calculations

Using snow stress parameters from Section B above, the maximum permissible snow height at different snow densities was calculated as function of the number of flashovers per year for DCB and CB+ as presented in Fig. 18.

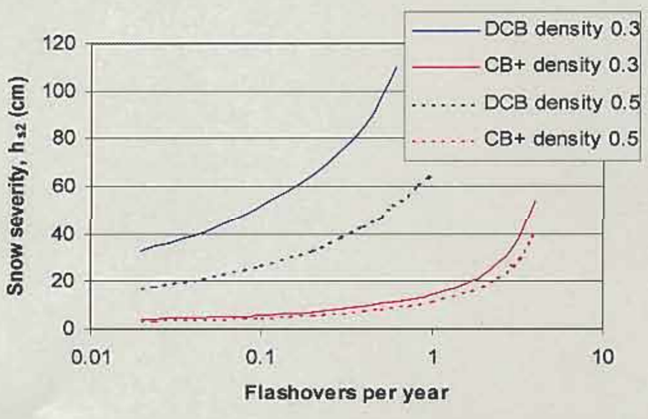

Fig. 18 Maximum snow height as function of the number of flashovers per year for snow with density 0.3 g/cm^3 and 0.5 g/cm^3. h_{s2} is expressed as the snow depth that is exceeded by 2% of the snow events.

VII. Discussion

A number of flashovers per year, while connecting a generator to a line (exposure under 2 p.u. voltage) is summarized for different environmental conditions in TABLE 5. The availability during snow is derived from Fig. 18 for the snow height 30 cm.

TABLE 5
NUMBER OF FLASHOVERS PER YEAR DURING CONNECTING A GENERATOR TO A LINE DURING DIFFERENT ENVIRONMENTAL STRESSES.

Type of pollution		Flashovers per year		
		DCB	CB+	CB-
Pollution		0.015	0.17	0.16
Ice		0.010	-	-
Snow, h_{s2} = 30 cm	density 0.3 g/cm^3	0.014	2.7	-
	density 0.5 g/cm^3	0.15	3.4	-

It is clear from TABLE 5 that in Norway snow environment is dimensioning for the availability of the breakers during the connection of a generator to a line. This is well correlated with the service experience (about 1 flashover per year).

The availability of the DCB in snow environment is better than for CB+. This is explained by follows:

- DCB has better flashover performance
- DCB has larger insulator length
- Snow bridging over the parallel grading capacitor insulator of CB+ increases the snow cross section and causes higher leakage currents

There is a lack of service data for snow environment. The already available data is only the frequency of snowfalls obtained from seven weather stations from the area of interest, as provided by the Norwegian Meteorological Institute (Met). From different investigations [7], [8] it was found that wet snow is the most critical for the flashover of snow-covered insulators. The snow height on the breaker depends on several factors, e.g. snow fall intensity, wind, temperature during and after the snowfall, snow melt and snow sliding. In a very conservative approach the snow depth on the ground could be used as the snow height on the breaker. In this case the accumulated snowfall and melting are considered but not snow sliding. Thus, it would be possible in the future to collect snow statistics in terms of snow height and density on the ground from existing meteorological data. Then, such data could be converted in snow height and density on the breaker. To make investigations on the real breaker using e.g. monitoring cameras would be even better possibility.

VIII. Conclusions

The following conclusions can be drawn from the investigation of the availability of circuit breakers during the connection of a generator to a line:

- Snow environment is the dimensioning parameter for the availability in Norway
- Availability calculations performed in Insulator Selection Tool program for pollution, ice and snow conditions correlate well with service experience
- The DCB type of breaker has better performance in snow environment than the breakers with porcelain insulators equipped by grading capacitors. This is valid for heavy snowstorms. The performance of the breaker equipped by grading capacitors would probably much better during light snowstorms, when snow does not bridge over the insulators.
- There is a lack of service data for snow environment. However, it would be possible in the future to collect

snow statistics in terms of snow height and density on the ground from existing meteorological data. Then, such data could be converted in snow height and density on the breaker. Using web-cameras for on-line snow monitoring on the breakers could also be an option [9].

IX. ACKNOWLEDGMENT

The authors wish to acknowledge the contributions and support from Statnett that made this work possible.

X. REFERENCES

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