Flashover performance of line composite insulators with different profiles intended for ice & snow environment

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Abstract—Accretion of ice and/or snow polluted by salty seawater on the insulators is a concern for users in Scandinavia and Japan as it will alter the insulation performance. In order to investigate the impact of profile on ice performance, laboratory tests were performed on three specially selected composite line insulators with different profiles: standard, alternating and so-called "ice-breaker" profile. The last profile was created utilizing an insulator with alternating profile omitting sets of sheds at 1/3 and 2/3 of the insulator length, creating two rather long gaps intended to prevent bridging by icicles in these parts of the insulator. However, based on results obtained from Ice Progressive Stress (IPS) tests no general and clear trend indicating which insulator profile provides the highest performance under simulation of severe and light ice storms could be identified. Further, no advantages in performance were found for the "ice-breaker" design compared to insulators with alternating and standard profile.

I. Introduction

A. Background

Japanese and Scandinavian power utilities have very much in common regarding environment due to periodical accretion on the insulators ice and/or snow polluted by salty seawater. Based on discussions with utilities from both countries the following was concluded:

- Line composite insulators are of interest for future applications as such insulators are believed to perform well in both pollution and ice & snow environments.
- The environmental pollution is generally similar for Scandinavia and Japan, because the pollution originates from salt storms. However, levels of ESDD and NSDD may be different.
- The ice environment can also be generally similar for Scandinavia and Japan and ice performance will be a dimensioning parameter for vertically installed insulators (suspension and jumper support)
- The snow environment can be generally similar for Scandinavia and Japan, even if the conductivity of the snow may be different. Snow performance will be in general a primarily dimensioning parameter for horizontal and inclined insulators (V-strings, tension strings, line posts). However, wet and conductive snow may create problems even for vertically installed insulators.

The intention of the joint project presented in this paper was thus to find trends for optimization of insulator profile and to make a recommendation for the design of composite insulators, which should withstand a combination of pollution and ice events. Further, because Japan and Scandinavia have similar types of environments, but different levels of pollution and ice stresses, it was decided to combine the efforts to obtain complete design curves for ice stress, characterised by dripping water (melted ice) conductivity.

II. Test objects

Three different insulator profiles were chosen for laboratory tests: a standard profile, an alternating profile and a so-called "ice-breaker" profile. The latter profile was designed based on some discussions with composite insulator manufacturers and was created utilizing an insulator with alternating profile, omitting sheds at 1/3 and 2/3 of the insulator length. This design created two rather long inter-shed gaps, intended for the prevention of bridging of sheds by icicles in this region.

The basic geometrical parameters of the insulator types are presented in TABLE II-1. All insulators were intentionally manufactured with almost the same creepage and arcing distances allowing for a direct comparison. For the "ice-breaker" design, the gap between the groups of the sheds was 260 mm.

TABLE II-1
GEOMETRICAL PARAMETERS OF TESTED INSULATORS

Profile	Standard	Alternating	"Ice-breaker"
Connecting length (mm)	3700	3700	3700
Arcing distance (mm)	3400	3395	3395
Creepage distance (mm)	8430	8600	8600
Shed type 1 diameter (mm)	195	195	195
Shed type 2 diameter (mm)	-	163	163
Shed type 3 diameter (mm)	-	128	128
Shed spacing	97	73	65

III. TEST PROCEDURES

A. *General*

Experiences with accretion of snow and ice on insulators in service reported from Norway and Japan were summarized with the aim to identify a representative test method. The analysis of service cases, based on [1]-[11], showed that "pollution" events comprise of either icing or wet-snow accretions. The first one can be simulated by the "freezing rain" mode of the Ice Progressive Stress (IPS) test method [5]. The wet-snow accretion observed in service can on the other hand at present not be directly simulated in the laboratory. However, wet-snow accretion can be described by snow accretion after which the snow is first frozen into rime ice and then melted again. Thus, conditions can be simulated by the "sun-rise" mode [5] of the IPS test method.

For the current tests, the parameters for the conductivity of applied water were derived from the service data available and were considered as:

- Conductivity in the range of about 100-200 µS/cm for the simulation of the "freezing rain"
- Conductivity of about 200 µS/cm for the simulation of the "sun-rise"

B. *Freezing rain simulation*

In each test, three insulators of different types were subjected to an ice accretion phase at maximum operating voltage (243 kVAC) followed by a flashover test.

Tests were performed applying two different ice accretion times, 5 hours and 2,5-3 hours respectively. The longer period of ice accretion was chosen to achieve a close to complete briging of the insulator length by ice, corresponding to a worst-case scenario. This simulated rather severe ice storms. The shorter accretion period was chosen since less bridging was expected to increase the influence of profiles. This simulated light ice storms.

Further, all insulators were tested using water with two different conductivities, 110 µS/cm and 230 µS/cm. This approach gave three flashover values per insulator type, average dripping water conductivity and ice accretion time. However, for water conductivity 110 µS/cm and 3 hours of ice accretion, only two tests were performed.

Practically, all but one insulator was disconnected after the accretion phase, and thereafter the voltage was applied again, but now rapidly increased (rate about 35 kV/s) until flashover. Once the insulator flashed over, the next insulator was connected and tested. By this approach, the insulators experienced slightly different periods of exposure to water before tested. However, the difference of typically less than 5 minutes is considered as insignificant compared to the total accretion time of at least 2,5 hours.

In the beginning of each test, the temperature in the test hall was about –10 °C. Application of water to the insulators increased the temperature in the hall approximately 2-3 degrees during the following 2 hours before temperature leveling off. The temperature in the hall was kept below – 6 °C in all cases. The test setup is presented in Figure 1.

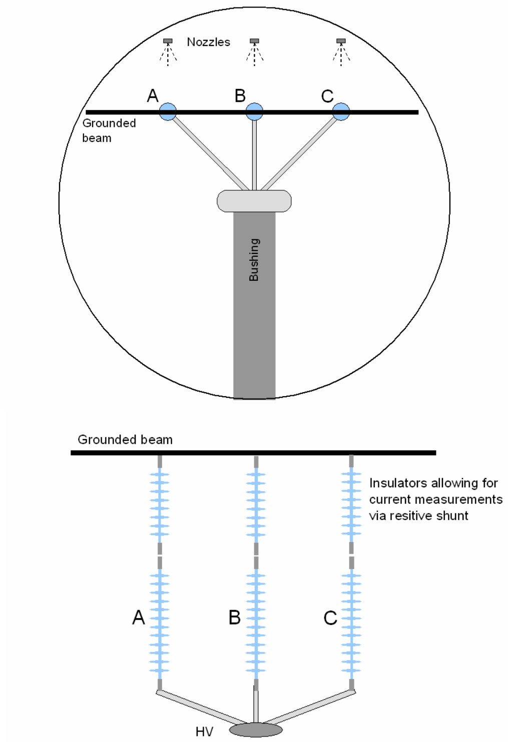


Figure 1 Schematic drawing showing insulators under test (A-C) hanging vertically in front of the spray nozzles in the cylindrical climate hall (top). Voltage is applied at the bottom side, and additional insulators allow for leakage current measurements utilizing resistive shunts.

C. *Sun-rise simulation*

The so-called sun-rise tests were performed as follows. Three insulators of different profile were subjected to ice accretion phase according to the procedure utilized in the freezing rain tests described above. The applied water had a conductivity of approximately 230 µS/cm. After completion of 5 hours accretion, the voltage was disconnected and the water spraying system was turned off. The insulators were left non-energized in the cold climate hall for approximately 1 hour, allowing for free water on the insulator/ice surfaces to freeze completely.

Thereafter, insulators were moved to the high voltage hall where tested. In order to avoid breaking/removing ice, insulators were transported in hanging position. The time between removal from the cold climate hall and voltage application in the high voltage hall was typically 10-12 minutes. The higher temperature in the high voltage hall (about 20 °C), caused the ice to start melting, creating a wet ice surface. Once mounted, the voltage was applied and quickly ramped to flashover.

IV. RESULTS

A. Freezing rain simulation

Examples of photographs of insulators with ice after freezing rain tests are shown in Figure 2 (3 hours of ice accretion) and in Figure 7 (5 hours of ice accretion). As expected, the longer accretion time resulted in a more dense coverage by icicles.

Recorded flashover voltage values from each test are presented in TABLE IV-1 to TABLE IV-4. The $U_{50\%}$ (approximated by average flashover voltages) of each insulator profile and ice condition are shown in Table IV-5. In order to allow for comparison with data obtained from standard up-and-down tests, the values presented in this table have been corrected by a factor 0,92 [6].

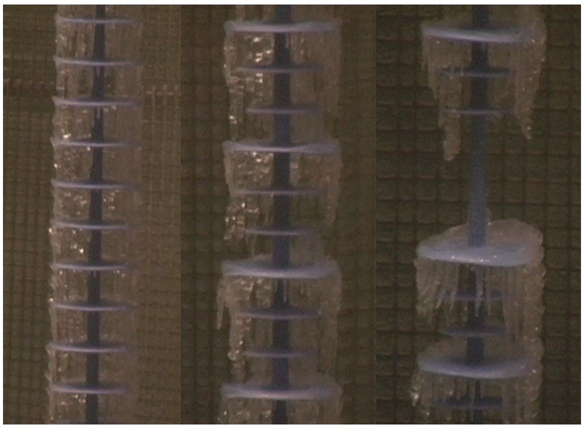


Figure 2 Detail of mid portion of insulators with ice after 5 hours of ice accretion, i.e. exposure to water spraying (from left to right: standard, alternating and ice-breaker profile).

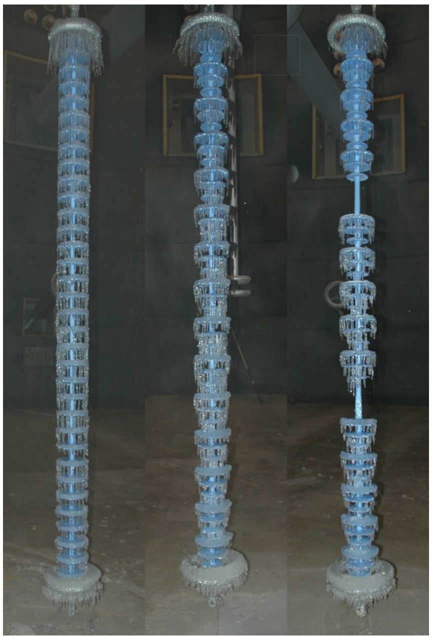


Figure 3 Insulators after test with 3 hours of ice accretion time. From left to right: standard profile, alternating profile and ice-breaker profile.

TABLE IV-1
RECORDED FLASHOVER VOLTAGE VALUES DURING FREEZING RAIN TESTS AT TARGET 110 µS/CM AFTER 5 HOURS OF ICE ACCRETION

Test Nr	Flashover voltage (kV)		
	Standard	Alternating	"Ice-breaker"
#1	468	>512[a]	456
#2	537	519	480
#3	532	568	494
#4	539	554	494

[a] No FO during three voltage applications up to 512 kV, a level at which the used transformer tripped due to overvoltage. Due to this, the setup was changed, and an extra test was performed

TABLE IV-2
RECORDED FLASHOVER VOLTAGE VALUES DURING FREEZING RAIN TESTS AT TARGET 230 µS/CM AFTER 5 HOURS OF ICE ACCRETION

Test Nr	Flashover voltage (kV)		
	Standard	Alternating	"Ice-breaker"
#1	350	385	359
#2	382	380	372
#3	429	430	403
#4	408	436	410

TABLE IV-3
RECORDED FLASHOVER VOLTAGE VALUES DURING FREEZING RAIN TESTS AT TARGET 110 µS/CM AFTER 3 HOURS OF ICE ACCRETION

Test Nr	Flashover voltage (kV)		
	Standard	Alternating	"Ice-breaker"
#1	609	603	596
#2	615	583	631

TABLE IV-4
RECORDED FLASHOVER VOLTAGE VALUES DURING FREEZING RAIN TESTS AT TARGET 230 µS/CM AFTER 3 HOURS OF ICE ACCRETION

Test Nr	Flashover voltage (kV)		
	Standard	Alternating	"Ice-breaker"
#1	524	550	520
#2	559	530	538
#3	522	497	472

TABLE IV-5
U50%-VALUES AND STANDARD DEVIATIONS AFTER CORRECTION

Ice accretion time	Dripping water cond. (µS/cm)	Parameter	$U_{50\%}$ (kV)		
			Standard	Alterna-ting	"Ice-breaker"
5h	140	Average FOV (kV)	477	503	443
		Standard deviation	7 %	5 %	4 %
	303	Average FOV (kV)	361	375	355
		Standard deviation	9 %	7 %	6 %
3h	133	Average FOV (kV)[a]	563	546	565
		Standard deviation[a]	1 %	2 %	4 %
	300	Average FOV (kV)	492	484	469
		Standard deviation	4 %	5 %	7 %

[a] Based on two tests only

B. Sun-rise simulation

Recorded flashover voltage values are presented in TABLE IV-6. The corrected $U_{50\%}$ (approximated by average flashover voltages) of each insulator profile are given in Table IV-7.

TABLE IV-6
RECORDED FLASHOVER VOLTAGE VALUES DURING SUN-RISE TESTS AT TARGET 230 µS/CM AFTER 5 HOURS OF ICE ACCRETION

Test Nr	Flashover voltage (kV)		
	Standard	Alternating	"Ice-breaker"
#1	>243[a]	517	484
#2	396	446	439
#3	468	512	505
#4	477	481	434
#5	459	510	455

[a] 30 minutes withstand test without FO.

TABLE IV-7
U50%-VALUES AND STANDARD DEVIATIONS AFTER CORRECTION

Ice accretion time	Dripping water cond. (µS/cm)	Parameter	$U_{50\%}$ (kV)		
			Standard	Alterna-ting	"Ice-breaker"
5h		Average FOV (kV)	414	454	426
		Standard deviation	8 %	6 %	7 %

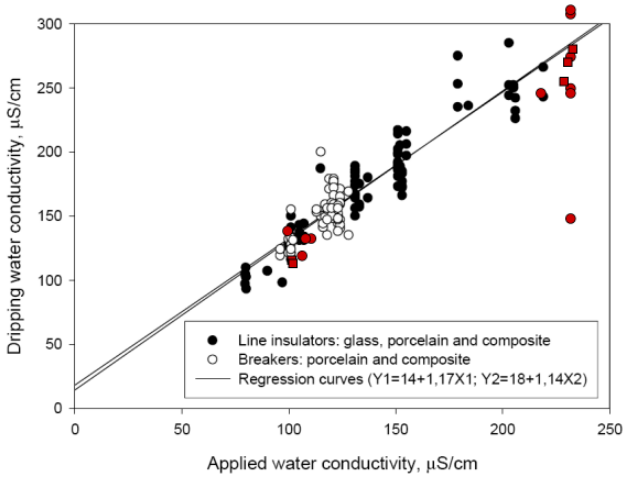
V. REPEATABILITY OF TESTS

The repeatability of a test procedure is a measure of how well the tests can be repeated on the same test objects in the same laboratory giving the same results. A reasonable repeatability is thus an important and generally applied demand on any test method. Results can be flashover conditions and/or flashover results obtained in different tests. A typical measure for the repeatability is the variation or standard deviation of the flashover value obtained from several tests on the same test object.

The repeatability of the applied IPS procedure can be verified via comparison of results previously obtained for line insulators and circuit breakers. Such evaluation may include the variation in test parameters such as e.g.:

- Factor between dripping and applied water conductivities
- Ice density
- Standard deviation of flashover voltage

The graphs shown in Figure 4-Figure 5, clearly indicate that the repeatability of the IPS method is excellent taking into account the results from all performed tests, i.e. for different time of the year and different accretion time.



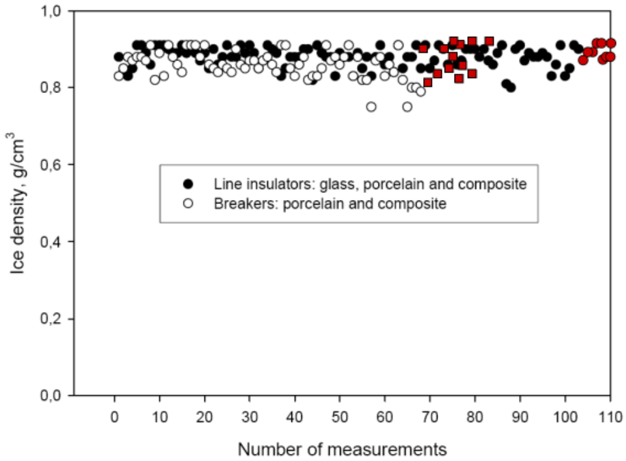


Figure 4 Relation between dripping- and applied water conductivities (top) and recorded ice densities of about 0,90 g/cm^3 (bottom) [7]. Red circles and squares indicate results of measurements made within this project (5 and 3 hours of ice accretion respectively).

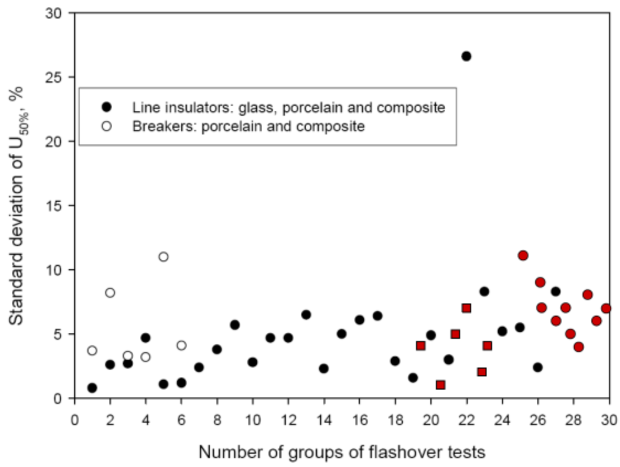


Figure 5 Standard deviations of flashover voltages generally below 10% [7]. Red circles and squares indicate results of measurements made within this project (5 and 3 hours of ice accretion respectively).

VI. DISCUSSION

A. Ranking based on freezing rain simulation

Insulators can be preliminary ranked with respect to flashover performance in ice conditions via direct comparison of only $U_{50\%}$ values presented in Table IV-5. For the longer period of ice accretion (5 hours), yielding approximately 90-95% ice bridging, the insulator with alternating profile appears to have the best performance, followed by the insulator with standard profile and thereafter the "ice-breaker".

However, from comparison of both $U_{50\%}$-values and corresponding standard deviations, as illustrated in Figure 6, it is evident that there is actually weak support for any ranking. From the presented diagrams, it can only be concluded that for 5 h ice accretion, the insulator of alternating profile is performing better than the insulator of "ice-breaker" profile at dripping water conductivity of 140 µS/cm (because there are no overlapping of the flashover voltages taking into account spread as plus/minus one standard deviation).

The unexpectedly poor performance of the "ice-breaker" profile in this test may be explained as follows. The vertical non-ribbed part of the insulator intended to prevent ice formation is actually effectively bridged partially by the ice accreted along the cylindrical part, partially by the icicles grown from the bottom of the ribbed part, see Figure 7.

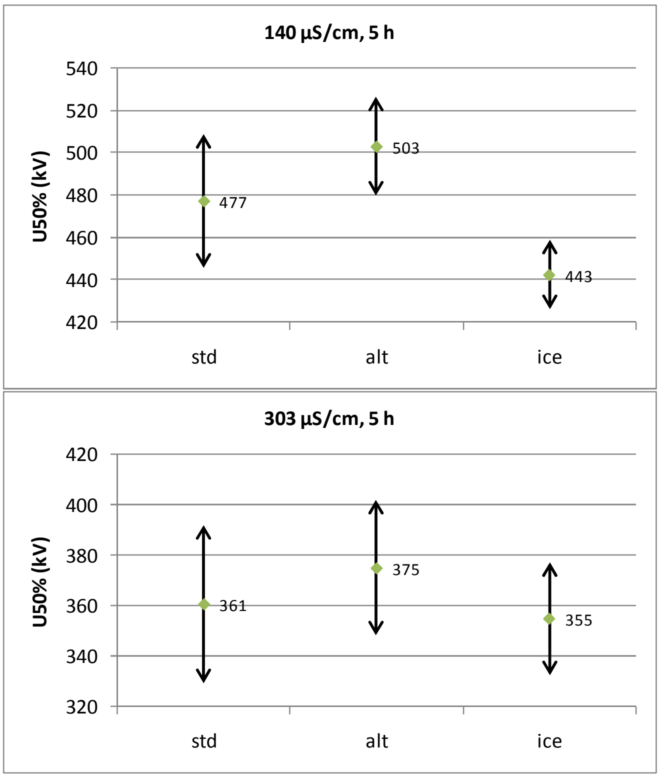


Figure 6 $U_{50\%}$-values derived from tests with 5 h ice accretion. Error bars (arrows) correspond to one standard deviation.

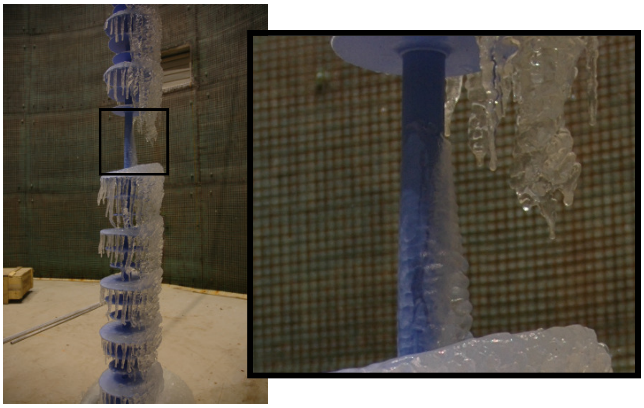


Figure 7 Ice-breaker profile with close to complete bridging of the long gap.

For the shorter period of ice accretion evaluated (3 h), direct comparison of only $U_{50\%}$ values indicates that:

- At dripping water conductivity of 133 µS/cm the insulator of alternating profile is performing as the worst, while the two others perform almost equally. The difference between the worst (alternating) and best ("ice-breaker") performing profile is 3% (less than one standard deviation).
- At dripping water conductivity of 300 µS/cm, the difference between the best and the worst performing insulators (standard and ice breaker), is about 5% which correspond to one standard deviation.

However, from comparison of both $U_{50\%}$-values and corresponding standard deviations, illustrated in Figure 8, it is evident that there is again a weak support for any ranking. Due to the overlapping of the flashover voltages taking into account spread as plus/minus one standard deviation, it can only be concluded that the standard profile shows better performance than the alternating profile. However, this is only due to the extremely small standard deviation (1%) obtained for the standard profile (data comprise two FOs only). This data is thus considered as not entirely reliable, and a more realistic value (minimum 2-3%), would give overlapping between "error bars" of all profiles.

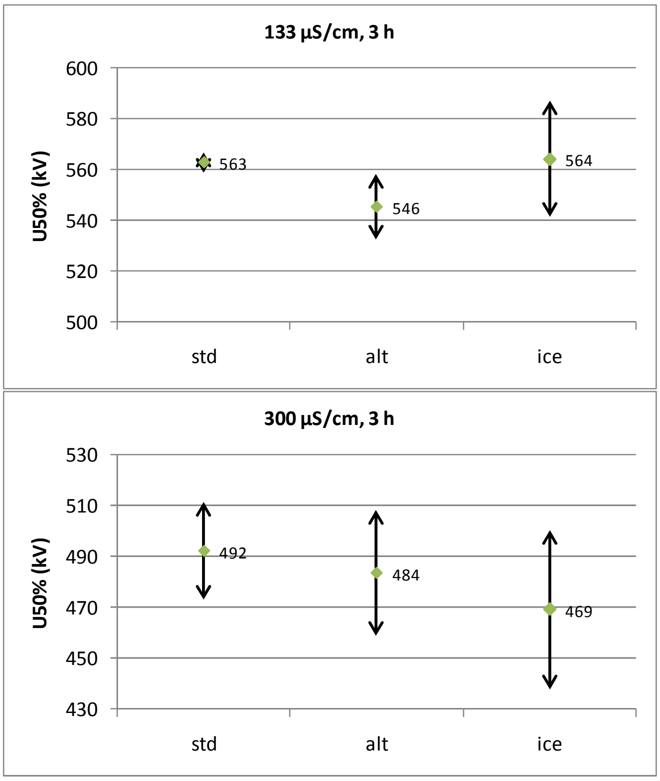


Figure 8 $U_{50\%}$-values derived from tests with 3 h ice accretion. Error bars (arrows) correspond to one standard deviation.

TABLE VI-1

AVERAGE $U_{50\%}$-VALUES AND STANDARD DEVIATIONS PER TEST CONDITION (ALL INSULATORS TOGETHER)

Ice accretion period	Dripping water conductivity (µS/cm)	$U_{50\%}$ (kV)	Standard deviation
5 h	140	472	7%
	303	364	7%
3 h	133	558	3%
	300	482	5%

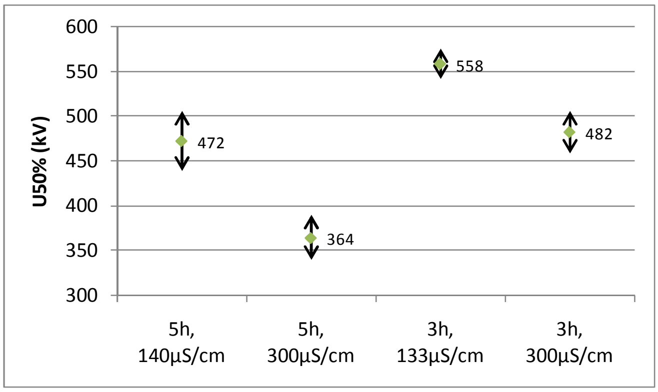


Figure 9 Average $U_{50\%}$-values per test condition. Error bars (arrows) correspond to one standard deviation.

Comparison of average flashover voltages ($U_{50\%}$) obtained at different tests conditions (ice accretion time and water conductivity), reveals that there is, as expected from physical point of view, significant impact on performance of both ice accretion time and dripping water conductivity, see TABLE VI-1 and Figure 9. For both accretion times, test with lower conductivity of water resulted in higher $U_{50\%}$. Further, for both water conductivities (130-140 and 300 µS/cm), an increase of accretion time resulted in a decrease of average $U_{50\%}$.

However, there is a difference in insulator performance during different accretion times. For the longer accretion time of 5 h, the difference between flashover voltages at low and high water conductivity is about 30%, while the same is only 16% for the accretion time of 3 h (see Figure 9). This can be explained by the fact that the level of bridging is higher in the first case and the flashover process is governed by the conductivity of a water film on the surface of the insulator. In case of the shorter accretion time, the insulators are bridged by ice to a lower extent than after 5 hours of accretion and therefore the flashover voltage is mostly governed by the air gap between the insulator electrodes, which is approximately the same for all insulators. This consideration is supported by the fact that average standard deviation for the tests with shorter accretion time is lower than for longer accretion time (TABLE VI-1). It is well known from general insulation knowledge that in case of dry air flashover the standard deviation is 3-4%, while in case of rain it is 4-6% and under pollution (ice) is 8-10%.

In summary, from the analysis of performed tests simulating freezing rain conditions it can be concluded that there is no general and clear trend indicating which insulator profile that gives the highest $U_{50\%}$ for both cases, i.e. simulating severe and light ice storms. No advantages were found for the "ice-breaker" design and there are only weak indications that "alternating" design may be better for severe ice storms.

B. *Ranking based on sun-rise simulation*

By using the same approach as applied to the results from freezing tests (direct comparison of only $U_{50\%}$ values) it can be concluded that at the applied water conductivity of 230 µS/cm the alternating profile insulator is performing as the best. The difference between the worst (standard) and best (alternating) performing profile is 10% (about one standard deviation). The difference between insulator with alternating and "ice-breaker" profile is 6%, also corresponding to one standard deviation.

However, from comparison of both $U_{50\%}$-values and corresponding standard deviations, illustrated in Figure 10, it is evident that there is once again a weak support for any ranking. Due to the overlapping of the flashover voltages taking into account spread as plus/minus one standard deviation, it can be concluded none of the three profiles should be considered as significantly better (or worse) than the others.

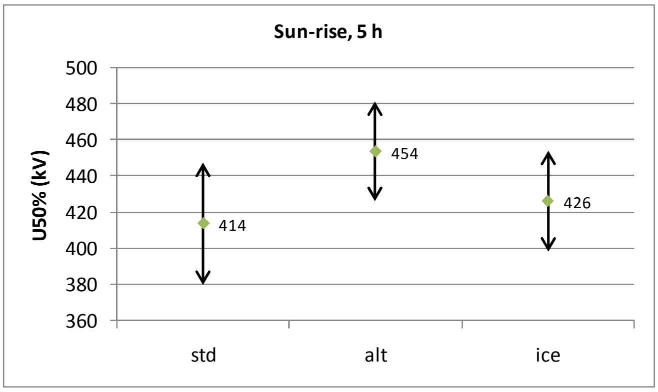


Figure 10 $U_{50\%}$-values derived from sun-rise tests with 5 h ice accretion. Error bars (arrows) correspond to one standard deviation.

C. Performance curves

Based on the average flashover voltages obtained at the freezing rain simulations (5h ice accretion only), pollution performance curves have been derived using the "standard" relation according e.g. [5] presented in Equation 1.

$$\frac{U_{50\%}}{h} = A \times SDD^{-\alpha} \qquad \text{Equation (1)}$$

In Equation 1, SDD represents the pollution level, which in our case is the dripping water conductivity, "h" represents insulator height (length), and A and α, are fitting parameters. The derived pollution performance curves are shown graphically in Figure 11.

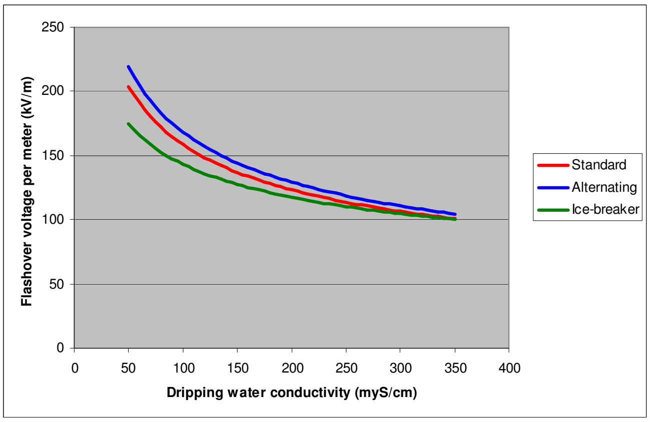


Figure 11 Pollution performance curves derived from freezing rain tests (5 hours ice accretion time).

Comparison of pollution performance curves derived from freezing rain simulations indicates that in this case observed ranking (alternating – standard – ice-breaker) is valid for dripping water conductivities up to approximately 350 µS/cm. At this rather high level, the performances of the three designs are more or less equal. This behavior, i.e. a larger difference between different designs at low pollution levels compared to higher ones, is similar to classical pollution tests where at higher pollution levels performance is determined by creepage distance rather than profile. The reason for this is that the flashover process of a polluted insulator is more dependent on the leakage current on its surface, from where the complete flashover also develops. Flashover of a fairly clean insulator is on the other hand more affected by its length and profile since the process to a large part takes place in the surrounding air, not only at the surface.

VII. Conclusions

Based on the analysis of service experience and performed tests, the following may be concluded:

- Analysis of service cases both in Scandinavia and in Japan showed that the Ice Progressive Stress (IPS) test method can be used for the simulation of both freezing rain and sun-rise service cases.
- There is no general and clear trend indicating which insulator profile that gives the highest flashover performance for both long (5 h) and short (3 h) ice accretion times, simulating severe and light ice storms respectively.
- No advantages in performance were found for the "ice-breaker" design compared to insulators with alternating and standard profile.
- There are weak indications that the alternating profile may perform better than the other profiles in severe ice storms.
- Using the IPS test method the design curves for three insulator profiles intended for the ice areas were created and are directly applicable for use in the Line Performance Estimator software program [12].

VIII. Acknowledgment

The authors wish to acknowledge the contributions and support from Statnett, Svenska Kraftnät, Nippon Katan and LAPP that made this work possible.

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