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Optimized use of HV composite apparatus insulators: field experience from coastal and inland test stations

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1. INTRODUCTION

At present line composite insulators are widely accepted for use on AC overhead lines. Silicone rubber composite insulators have also become more frequently used for HV equipment like surge arresters, bushings and breakers. Composite apparatus insulators provide advantages not obtained with conventional porcelain insulators. Examples are: lower weight, higher personal safety in the event of failure, better seismic performance, better pollution performance, opportunities to integrate new technologies (i.e. optical fibres). Improved thermal characteristics as well as new application fields such as transmission line protection have also been acknowledged for surge arresters. Still, sufficient information is not yet available regarding the optimal dimensioning of insulators for the different environments. The often discussed possibility of using shorter creepage distances than for porcelain insulation has, in most cases, not been realised in spite of encouraging results. This is maybe due to some conservatism in the market but also due to the lack of long-term field test results. The cost and time involved in field testing of HV apparatus often result in that only a “standard” creepage distance is verified and then in general a creepage distance selected on the safe side. However, in this report field test results are reported on apparatus, which have different creepage distance ranging from the standard, i.e. what is selected for porcelain insulators at the site considered, to extremely short i.e. at least two pollution levels below. To gain information of optimal creepage distance of HV apparatus in different environments, a number of surge arresters, bushings and breakers with composite insulators comprising silicone rubber as external insulation have been installed at three test sites subjected to heavy or very heavy pollution levels. The test stations used are Dungeness, on the South East coast of England; Kelso, on the North East coast of South Africa and Beer Sheva in the Negev desert of Israel. In addition results are reported from an inland test station in central Sweden. This station represents typical clean environment, considered as representative of the majority of all high-voltage installations.

It is important to distinguish between pollution performance (i.e. risk for flashover) and ageing of composite insulators. Detailed inspections of the tested apparatus as well as a sophisticated data acquisition system at three of the stations have made it possible to cover both these aspects. Where possible the ageing performance of apparatus insulation is compared with the ageing performance of line insulators tested at the same site. A third parameter related to the effect of pollution environment and important for surge arresters is a possible thermal stress. In the IEC 60099-4 standard for porcelain-housed arresters, the charge of external current at a particular site has been used as a measure of site severity. The charge of external surface currents on arresters from the different tests stations, therefore, has been determined and the result is compared with data for porcelain.

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Finally, guidelines that could be used as an indication for future IEC recommendations are drawn regarding specific creepage distance for apparatus insulators as function of the site severity.

2. OVERVIEW OF DATA COLLECTION

2.1 Test sites and test objects

Details of the environmental, climatic and electrical stresses at the four test stations are given in Table 1 and details on tested insulators and their exposure time are given in Table 2.

Table 1 Details of the test stations where inspections were carried out.

Parameter	Ludvika	Dungeness	Kelso	Negev
Location	Central inland	SE coast	NE coast	Central inland
Climate	Cold	Temperate	Subtropical	Tropical
Temperature range, ^oC	-27 to +27	-1 to +32	+6 to +44	+3 to +43
Max. rain (in 10 min.), mm	12	4	43	2
Environment	Clean	Marine	Marine	Semi-desert
Max. ESDD, mg/cm^2	0,005	0,15	0,39	0,24
Pollution level (IEC 60815)	I	IV	IV	III-IV
Max. system voltage, kV	190	145	100	170
Exposure time, years	2	3-7	2-3,5	5
No. of test objects	2	9	5	6

Table 2 Details on tested apparatus insulators (mostly with alternating profile, except standard profile of arresters at Negev and spiral profile of the breaker at Dungeness) and their exposure time.

Test station	Type of apparatus	External insulation	Specific creepage, mm/kV	Average diameter[a], mm	Exposure time, years
Ludvika	Arresters	Silicone rubber	12	126	2
			16	137	2
Dungeness	Arresters		20	149	3
			25	149	3,5
			31	149	3,5
			36	168	4,5
	Bushings		25	172	7
			32	172	7
			34	206	3
	Breaker		27	265/185[b]	3
	Hollow	Porcelain	32	196	7
Kelso	Bushing	Silicone rubber	23	132	2
	Arresters		12	127	3
			16	139	3,5
			23	149	3,5
	Hollow	Porcelain	28	196	3,5
Negev	Arresters	Silicone rubber	30	168	5
			30	168	5
			38	168	5
			38	168	5
		Porcelain	32	196	5
	Bushing	Silicone rubber	27	172	5

a. According to IEC 60815.
b. Chamber/support.

2.2 Measurements and inspections

The data parameters which were either continuously monitored or periodically recorded at the test stations included: leakage current and weather parameters (continuously) and visual inspections and hydrophobicity measurements periodically, according to [1]. Inspections of the test sites were carried out on an annual base.

3. AGEING CHARACTERISTICS

At the most polluted coastal test sites, i.e. Dungeness and Kelso no deterioration except colour changes due to discharge activity (whitish and dark patterns most likely due to water dripping from the upper sheds), traces of discharge activity and slight erosion has been observed on apparatus insulators during the field tests. The details are shown in Figure 1 and Figure 2. No deterioration at all has been observed at the clean site in Sweden and at the desert site in Israel.

At the same time 15 composite line insulators were installed at the two test sites, i.e. Dungeness and Kelso. These results were partially reported in [2]. They were also complemented by one hollow insulator at each site delivered by the same manufacturer as one of the line insulators. A summary on all tested line composite (and one hollow) insulators and their exposure time is presented in Table 3 together with the description of their deterioration. Examples of deterioration/damages with some comments are shown in Figure 3 and Figure 4.

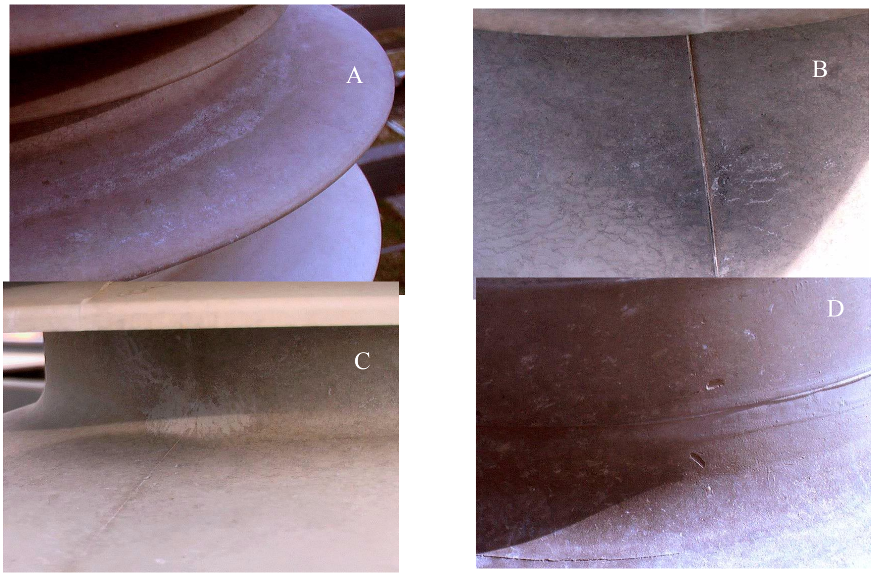

Figure 1 Dungeness, apparatus insulators. Examples of deterioration: A: breaker-27, whitish rings; B: arrester-20, dark pattern; C: arrester-25, traces of discharge activity; D: bushing-25, slight erosion.

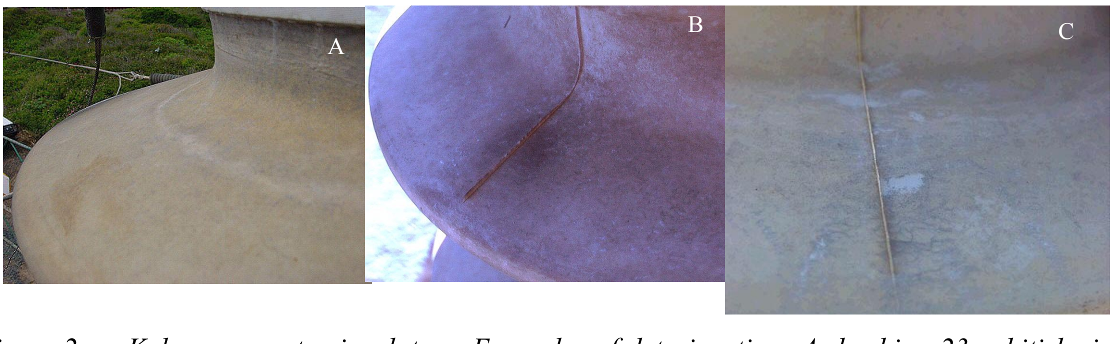

Figure 2 Kelso, apparatus insulators. Examples of deterioration: A: bushing-23, whitish rings; B: arrester-12, dark pattern; C: arrester-16, traces of discharge activity.

Table 3 Details on tested line/hollow insulators and their exposure time.

Test station	Type of insulator	Specific creepage, mm/kV	Exposure time, years	Type of deterioration
Dungeness	Line-1	18; 23; 23	5,5	Erosion
	Line-2	25	6	Erosion
	Line-3	22; 22	6	Erosion
	Hollow	21	7	Slight erosion
Kelso	Line-1	18; 23; 28; 29	4,5	Erosion
	Line-2	28	6,5	Erosion
	Line-3	22; 28; 28; 33	6,5[a]	Erosion
	Hollow	23	6,5	Start of erosion

a. The shortest insulator flashed over and was removed after 1 year in service.

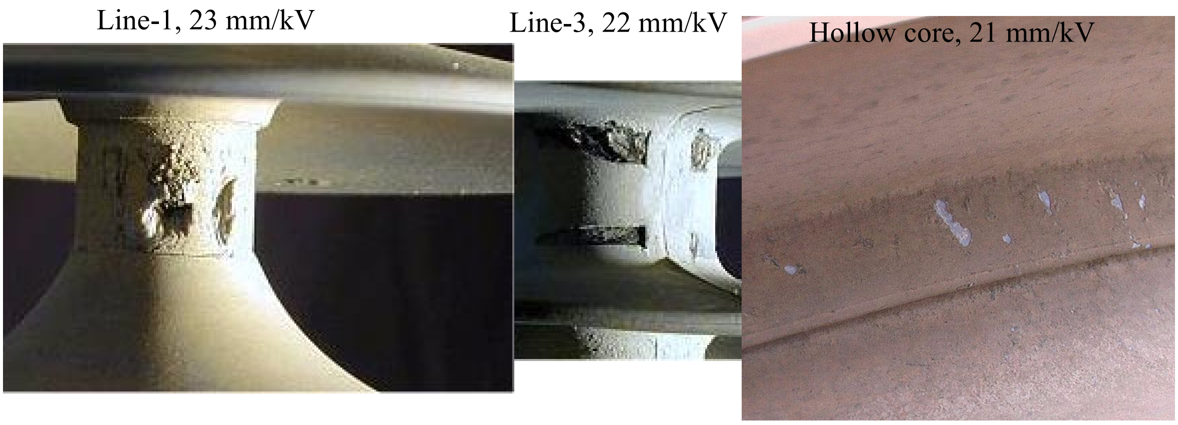

Figure 3 Dungeness. Deterioration: comparison of line and hollow insulators.

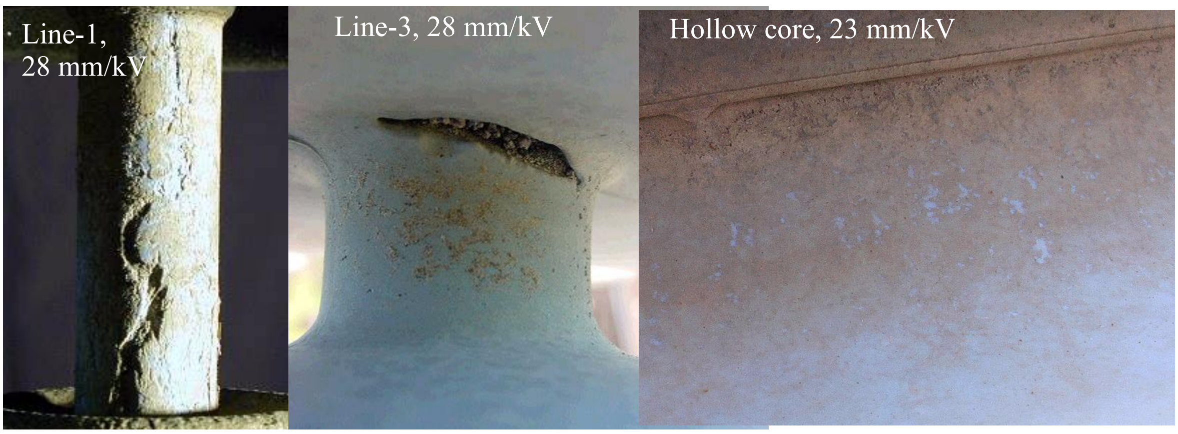

Figure 4 Kelso. Deterioration: comparison of line and hollow insulators.

4. POLLUTION PERFORMANCE

4.1 Hydrophobicity measurements

The average Hydrophobicity Class (HC) was measured according to [3] during each inspection for each of the test stations. The HC was averaged for the measurements on top, bottom and sheath. The results presented in Figure 5 show that for both of the coastal test sites the silicone rubber insulators are minimum one HC better than porcelain and the maximum of average HC is between HC 5 and HC 6. In clean conditions of Ludvika, the absolute maximum HC was limited to 4. In desert conditions of Negev, on the top of some of the sheds the HC after 5 years was limited to 5.

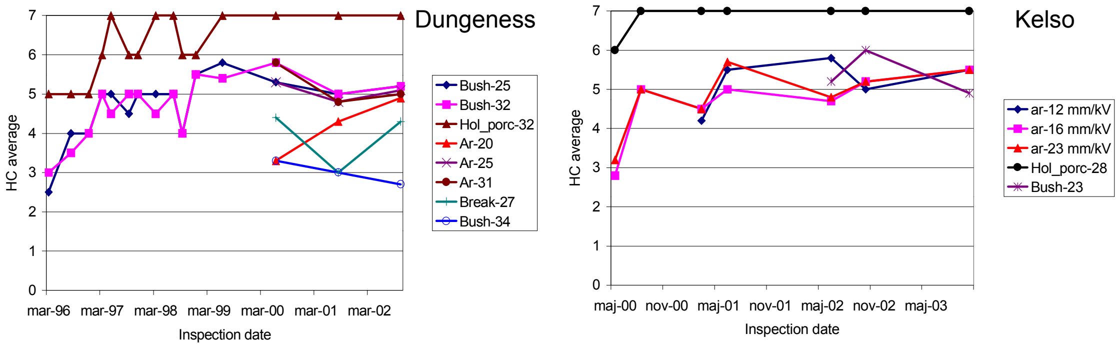

Figure 5 Average Hydrophobicity Class at Dungeness and Kelso.

4.2 Leakage current measurements

Due to the physics of the pollution event, typically, peak currents can be related to the pollution performance of an insulator. In general, a high leakage current indicates a high probability for flashover, as the partial surface discharges (arcs) over the dry bands have a greater possibility to elongate and to bridge the whole insulator. A pollution event is thus defined as the time when the leakage current pulses exceeds a certain value. Preliminary analysis showed that the Dungeness test station is the worst for the insulators from pollution point of view. Severe storms followed by long periods of high humidity and light rain are worse than more moderate breeze type winds at Kelso followed by powerful subtropical rains, see maximum rain conditions in Table 1. Therefore, typical difference in silicone rubber/porcelain performance during pollution event is presented only for the Dungeness test station. Three test objects with similar creepage distance are chosen for the analysis, i.e. arrester-31 mm/kV; bushing-32 and porcelain hollow-32. In Figure 6 the peak currents (measured at 2 kHz and stored every 10 min.) are presented vs relative humidity and rain.

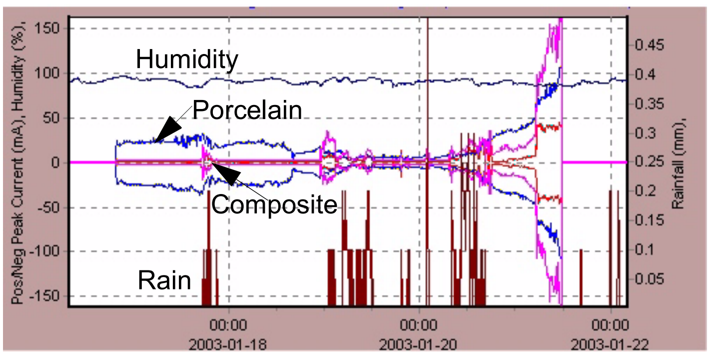

Figure 6 Example of typical pollution event at Dungeness.

High currents on porcelain insulator typically started earlier during the storm than on silicone rubber insulators. This behaviour correlates well with worse hydrophobicity (higher HC) of porcelain, see Figure 5. More moisture in the form of light rain is also needed to produce high currents on silicone rubber insulators. In a short run, at some moment during the storm, the peak currents on silicone rubber insulators can exceed those on porcelain. However, in long-term one can expect that the porcelain insulator will have a larger number of high leakage current pulses than silicone rubber insulator. This appeared to be a correct assumption and examples are shown in Figure 7 for a number of significant storms at Dungeness and Kelso (peak currents over 30 mA were calculated). Similar observations have been obtained in the laboratory tests, simulating the coastal environment. These observations are important, because high peak currents are related to the high risk for flashover and therefore, porcelain insulators would more often have a chance to flash over than silicone rubber insulators. Taking into account an average number of high peak currents during the significant storms, it can be shown that a large margin exists in the specific creepage distance of composite apparatus insulators in comparison with porcelain, see Figure 8. To obtain the same number of high current impulses on a composite insulator as on the hollow porcelain, very low specific creepage in the range of 10 mm/kV is indicated. Thus, for the same risk of flashover during pollution conditions, the creepage distance for composite insulator may be 3 times shorter. Leakage currents measured in clean conditions of Ludvika were 6 mA maximum and measured in desert conditions of Negev were 8 mA maximum, which indicate good hydrophobicity properties and possibility for further reduction of creepage distance.

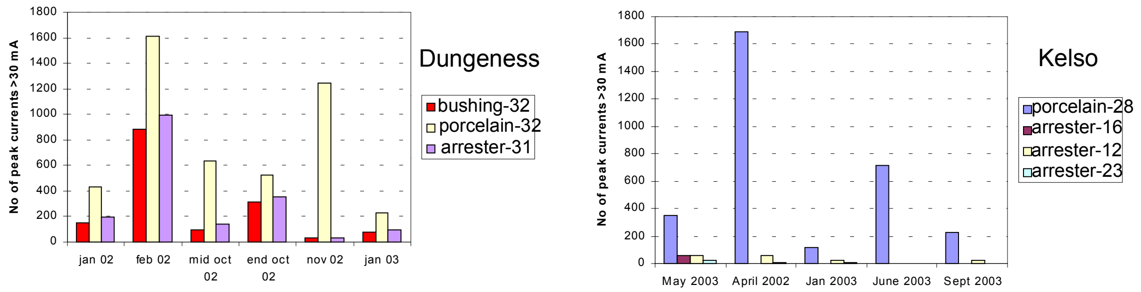

Figure 7 Dungeness and Kelso: Comparison of the number of peak currents over 30 mA for silicone rubber and porcelain apparatus insulators during the storms 2002-2003.

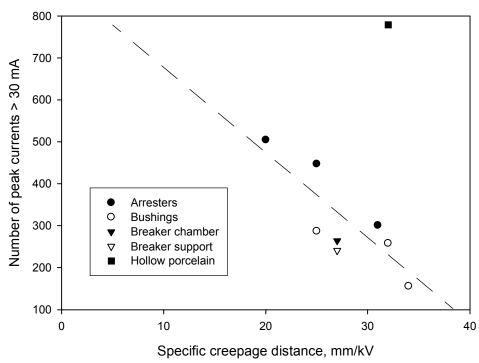

Figure 8 Dungeness: Correlation between the average number of peak currents over 30 mA during the storms 2002-2003 and specific creepage distance for silicone rubber and porcelain apparatus insulators.

4.3 Accumulated charge

As it was stated in section 4.2, peak currents are typically related to the pollution performance. The accumulated charge flowing over the insulator surface is used as an indicator of the interaction of the insulator material surface with the deposited pollution and wetting, which is, in turn, related to the ageing characteristics. The differences in accumulated electrical charge are assumed to be mainly due to the material properties and internal E-field grading. Therefore, the porcelain hollow insulators with their stable surface properties and no grading are treated as reference insulators. In this section three silicone rubber arresters installed at each of the test sites are compared with respective reference porcelain hollow insulator. A direct comparison is made during typical pollution event (see Figure 9). A direct comparison of the accumulated charge during the whole period of measurements for all tested apparatus is shown in

Figure 10 “A”. In case of arresters the measuring system calculated the charge for the current higher than 1 mA, thus avoiding integration of capacitive current, and in case of bushings the leakage current was collected from the special ring located at the silicone rubber surface close to the grounded flange. Therefore the results are directly comparable. The highest accumulated charge was obtained on the chamber of the breaker, where the continuous discharge activity produced by internal electrodes has led to the colour changes (see Figure 10 “B”) and even reduced the hydrophobicity from HC 2-3 to HC 5 exactly in the middle of the chamber. For the same type of insulators (e.g. support or hollow insulators without internal structure) a much higher accumulated charge is observed on porcelain insulator than on SIR insulator with a creepage distance that is even lower than on porcelain insulator.

A direct comparison of arresters and hollow porcelain insulator is made using parameter, specific for the arresters according to IEC 60099-4 Annex F, i.e. mean accumulated charge for worst 6-hours during the storms (pollution events), see Figure 10 “C”. According to this parameter the Dungeness station has a pollution level ranging from Heavy to Very Heavy. There is no correlation between the accumulated charge and the specific creepage distance, which previously was also found for porcelain housed arresters [4]. Comparison from year to year reveals no indication of degradation, i.e. additional increase of accumulated charge over time for silicone rubber insulators.

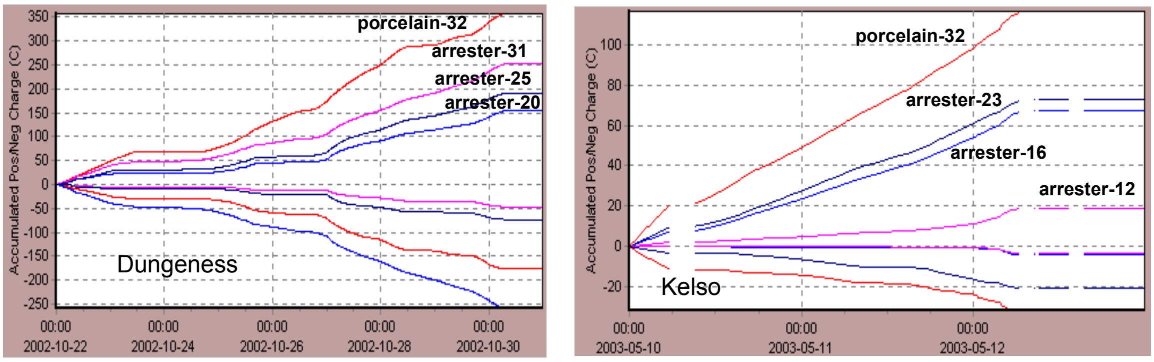

Figure 9 Dungeness and Kelso: Accumulated charge on three arresters and porcelain insulator during typical pollution event.

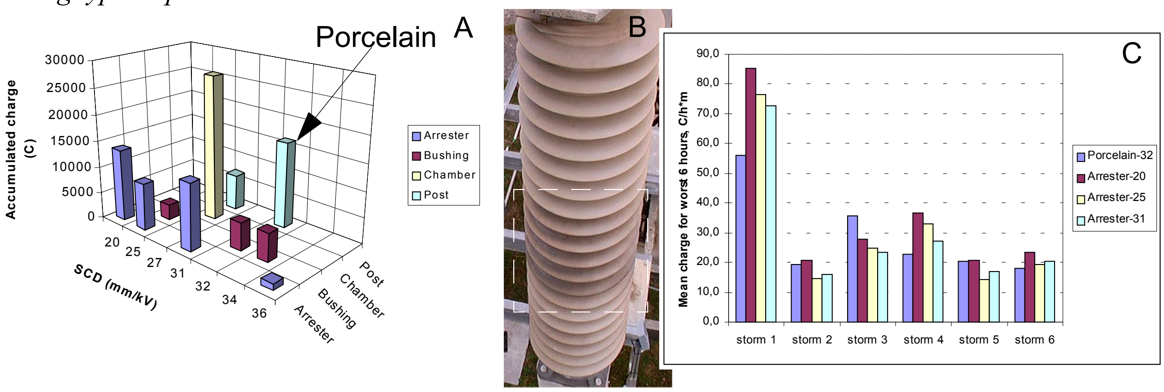

Figure 10 Dungeness: Comparison of total accumulated charge (“A”); illustration of colour changes due to influence of internal structure on breaker chamber (“B”) and mean accumulated charge for worst 6-hours during the storms for silicone rubber arresters and hollow porcelain insulator (“C”).

5. DISCUSSION

5.1 Ageing performance of apparatus/line silicone rubber insulators

Almost no deterioration has been observed on apparatus insulators at any of the four test sites. On the other hand, evaluation of deterioration at both coastal test sites, showed that on practically all composite line insulators some serious deterioration/damages were evident in the form of erosion, splitting or even punctures. However, in contradiction to that, no major problems with deterioration over time were observed for hollow insulators of the same manufacturer. It seems that the speed of deterioration on hollow insulators is roughly 5 times lower (the beginning of deterioration in the form of traces of erosion observed on line insulators after 1 year in service was almost the same as observed on hollow insulators after 5 years in service at the same test station). This is also confirmed by almost no deterioration after 2-7 years of testing of apparatus silicone rubber insulators at Dungeness and Kelso. The most important explanation is a lower E-field in the vicinity of HV flanges in comparison with line insulators and different location of corona and discharge activity. Apart from the lower E-field stress and different location of its maximum for apparatus insulators, it is also possible that apparatus insulators collect less pollution than line insulators due to larger trunk diameter (this is well known for porcelain insulators) which also influences level of currents. For *line composite insulators* the initial water drop corona will be located at the vicinity of the sheath, reducing the hydrophobicity and making easier to create the next stage of discharge activity, i.e. dry band activity. This is illustrated by the results of night UV inspection of line insulators at Kelso station, see Figure 11. The diameter of the trunk for these insulators is very small (20-30 mm) and the density of the leakage current will be rather high. This can in long-term lead to the different levels of erosion obtained at line composite insulators at the discussed test sites. For *apparatus composite and porcelain insulators* the initial water drop corona will be located at the edges of the upper sheds and will not really influence the hydrophobicity, see results in Figure 12. When an insulator becomes polluted, the density of the leakage current will be lower than for the line insulator due to large diameter of the trunk (100 mm and more). It will be more complicated to create a dry band and sustain dry band discharge activity. In all cases, the location of dry bands will be randomly distributed along the insulator, as also shown in Figure 12.

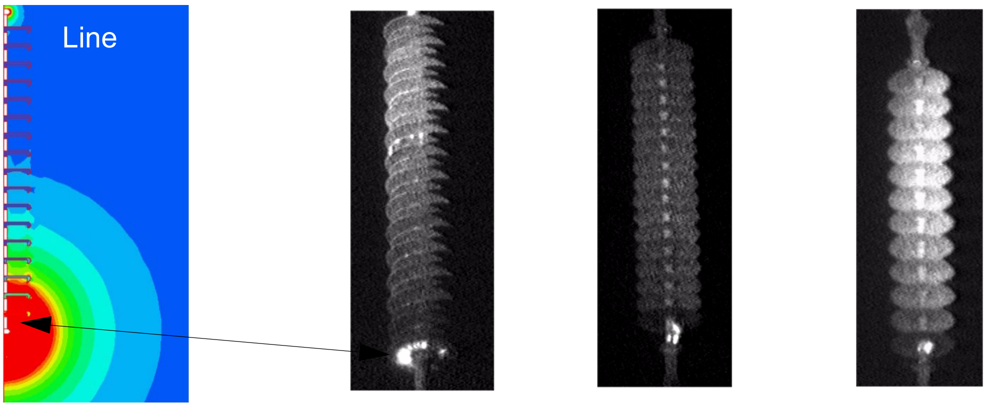

Figure 11   Line insulators: examples of typical E-field and discharge activity concentration.

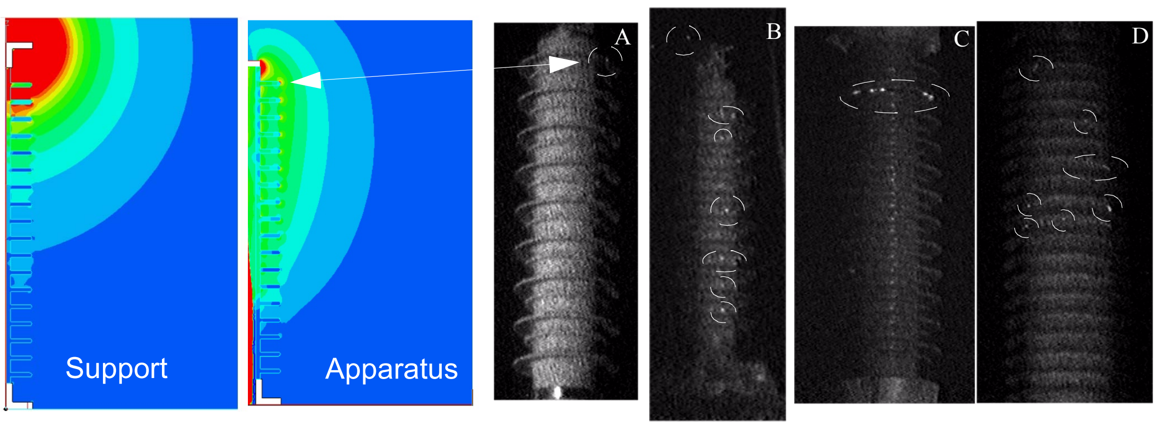

Figure 12   Apparatus insulators: examples of typical E-field and discharge activity concentration. A: arrester, silicone rubber, 12 mm/kV; B: arrester, silicone rubber, 23 mm/kV; C: hollow core, porcelain, 28 mm/kV; D: hollow core, silicone rubber, 23 mm/kV.

5.2 Pollution performance of apparatus/line silicone rubber insulators

No flashovers were registered on any of the apparatus silicone rubber or porcelain insulators at all test stations during the whole exposure time. Some flashovers were however registered during the same exposure time on some hydrophilic (i.e. porcelain-like) line insulators at Kelso test station, see Table 4 and Figure 13.

Table 4 Details on line insulators flashed over at Kelso test station.

Type of insulator	Specific creepage, mm/kV	Exposure time, years	Number of flashovers
Line EPDM	22	1	1
Longrod porcelain	28	6	7
Longrod porcelain greased[a]	28	6	7
Longrod porcelain RTV	28	6	0
Cap-and-pin glass	28	6	2

a. Grease was gone after 1 year in service.

Figure 13 Kelso. Examples of line insulators flashed over due to pollution.

It is important to note that the same porcelain longrod insulator which flashed 7 times as pure porcelain and after the silicone grease was gone (Table 4), was also tested covered by RTV and never flashed. This confirmed that silicone rubber drastically improves the pollution performance. This was one of the reasons for ESKOM distribution to make a decision of total use of RTV-coatings in all coastal substations. It is most probable that pollution performance estimated as a risk for flashover in certain environment, will be much lower for silicone rubber than for porcelain apparatus insulators. The following earlier discussed results can be taken into account:

- Comparison of service flashover performance on silicone rubber and hydrophilic line insulators
- Minimum one hydrophobicity class difference of silicone rubber apparatus insulators in comparison with porcelain apparatus insulators, see section 4.1
- Delay in time in leakage current increase during the pollution events (storms) on silicone rubber apparatus insulators in comparison with porcelain apparatus insulators, see section 4.2
- Lower number of high leakage current pulses during the pollution events of silicone rubber apparatus insulators in comparison with porcelain apparatus insulators, see section 4.2
- Lower 6-hours accumulated charge during pollution events of silicone rubber arresters in comparison with porcelain apparatus insulators, see section 4.3

5.3 Relevance of standardized tracking and erosion tests

Screening tracking and erosion tests are an important tool to be used to verify different designs for possible design/manufacturing weaknesses [2]. Is is important to note that line composite insulators are normally tested according to IEC 61109 as short pieces corresponding to voltage class of 24 kV. Even though the 5000 hours test is rather effective [2], the E-field is different in comparison to the real test objects. In case of apparatus insulators investigated in the frame of the present report, most of the prototypes were tested full-scale in 1000 hours salt fog tests with standard and reduced salinities. In particular some surge arresters were tested in accordance with IEC60099-4 where testing of the longest electrical unit with the minimum specific creepage distance and the highest rated voltage is prescribed. This gave more relevant stress on the insulators both in E-field and tracking and erosion, avoiding high current, long and unstable arcs which do not test the design and material weakneses [5]-[6]. These results were used as a basis for the new IEC standard 62217 ("Common clauses for composite insulators"), where the test salinity is dependent on the diameter of the tested insulator.

6. CONCLUSIONS

Based on the experience from the long-term testing of the apparatus silicone rubber insulators the following conclusions can be drawn regarding ageing characteristics and pollution performance.

With regard to ageing characteristics, the results of 2-7 years of field testing show that there is only slight deterioration for the apparatus insulators even with rather short creepage distance and in severe coastal environment. This is a much better performance than that of silicone rubber line insulators tested at the same site. The most important explanation of less ageing is a lower and differently located maximum E-field in the vicinity of HV flanges and lower current density due to a large diameter in comparison with line insulators.

With regard to pollution performance, the short-term and long-term hydrophobicity characteristics of silicone rubber apparatus insulators are better than of the porcelain insulators at the same site. The number of the high pulses of the leakage current provoking a flashover is much lower for silicone rubber apparatus insulators than for the porcelain insulators at the same site.

Considering both ageing as well as pollution performance, it is possible to reduce creepage distance in coastal areas with, as a minimum, one pollution level according to IEC 60815.

7. REFERENCES

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