Pollution Performance of HVDC SiR Insulators at Extra Heavy Pollution Conditions

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ABSTRACT

As an integral part of transmission lines, insulators play a major role in the reliability of power systems and their failure exposes the performance of the whole system into risk. Compared to AC systems, DC static field and corresponding arc without zero crossing makes DC flashover performance more problematic. Although the utilization of composite insulators in HVDC transmission lines continues to grow, there is still a lack of investigation on DC pollution flashover performance of SiR insulators especially at extra heavy pollution conditions. This paper presents the measurement and analytical results for DC flashover of SiR insulators in terms of different polarities of voltage, hydrophobicity levels and geometrical characteristics of SiR insulator at extra heavy pollution conditions. According to the results flashover strength in positive voltage is 4% higher than that in negative voltage. In addition, different profiles of SiR insulators did not show the same pollution flashover sensitivity on hydrophobicity. The empirical modeling of pollution flashover performance of insulators in terms of specific leakage distance, average diameter, form factor and the ratio of shed spacing to shed depth, revealed that specific leakage has the highest impact on pollution-flashover voltage gradient. This is of importance especially for designing and dimensioning of SiR insulators to be used under HVDC voltage.

Index Terms — **DC flashover, pollution performance, SiR insulators, shed geometry.**

1 INTRODUCTION

DUE to its several benefits, High Voltage Direct Current (HVDC) technology is planned to be implemented in Iran power system network and many studies have been conducted on this matter. One of the major concerns ahead is the pollution flashover performance of the high voltage insulators. Because of the static electric field, DC insulators are more exposed to contamination, which is 1.2–1.5 times higher than that of AC insulators under the same atmospheric conditions [1, 2]. On the other hand, in the past few years polluting particles flying from neighboring countries have exacerbated this problem, causing disruptions to power system of the country. In some areas of the country, severe pollution of insulators with Salt Deposit Density (*SDD*) of 1.2 mg/cm^2 has been reported [3]. In these conditions, understanding of DC flashover performance of insulators in high pollution rates is necessary.

In recent years, there has been a trend towards using polymeric composite insulators in HVDC applications especially in areas with heavy pollution [4]. Among different kinds of polymeric materials, Silicone Rubber (SiR) has had a widespread use in HVDC insulators as they have better contamination based flashover performance compared to other materials. However, there are a few papers focusing on flashover performance of SiR. In [4], the influence of non-uniform pollution distribution on the flashover performance of short samples of DC composite insulators was analyzed and it was concluded that the influence of top to bottom pollution ratio on the flashover voltage of the composite insulator is weaker than those on the porcelain and glass insulators. In [5] and [6], it was shown that the pollution-flashover voltage gradients of the composite long-rod insulators are superior to those of the porcelain or glass disc insulators under DC voltage. The authors of [7] investigated the DC icing flashover performance of seven types of short samples of UHVDC composite insulator in high altitude. They demonstrated that the DC icing flashover voltage declines with the increase of ice thickness. They also showed that the DC flashover of ice covered composite insulator improve with the decrease of the ratio between insulator leakage distance and height.

In none of the aforementioned works, one can find how the geometrical characteristics of insulator (e.g. leakage distance, average diameter, shed depth, shed spacing), voltage polarity and hydrophobicity level affect the contamination based flashover of composite insulators especially in extra heavy pollution conditions. This paper focuses on the positive and

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negative pollution flashover performance of SiR insulators with different profiles and hydrophobicity levels. For this purpose, different samples of SiR insulators are exposed to extra-heavy-pollution flashover experimental tests and the results are analyzed in detail. The obtained results enrich our knowledge of designing composite insulators to be used under severe pollutions in HVDC transmission lines.

2 EXPERIMENTAL SET-UP AND PROCEDURES

2.1 TEST SET-UP

The experimental tests were performed in a cubic climate chamber with equal dimensions of 2 m. The high voltage was connected to the insulator inside the chamber through a 150 kV ceramic wall bushing. The DC power supply consisted of a step-up transformer followed by a rectifier and protecting circuit. The output voltage of the source was controlled to ensure that the voltage drop is less than 4% when the load current is 50 mA. In addition, the ripple factor was less than 3% for a load current of 100 mA. The DC voltage source meets the conditions mentioned in [8]. Figure 1 shows the schematic diagram of the test circuit and climate chamber.

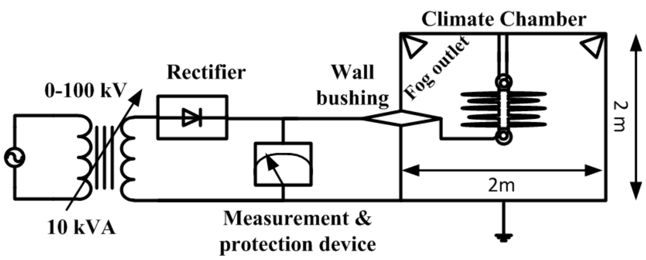

Figure 1. Test circuit and climate chamber.

2.2 TEST SAMPLES

To meet the climate chamber requirements, four different types of short samples (type A to type D) of HTV-SiR insulators have been chosen as the specimens. No further information (e.g. filler type, etc.) was available for the insulators. The geometrical characteristics of the specimens have been illustrated in Figure 2 and Table 1, in which *L* and *H* are the insulator leakage distances and height, respectively. *H* is slightly shorter than the dry arcing distance. D_{max}, D_{av} and *FF* are respectively maximum diameter, average diameter and form factor, which are considered in the next sections.

Table 1. Geometrical characteristics of the specimens in centemeters.

	L	*H*	*SL=L/H*	D_{max}	D_{av}	*FF*	*s/p*
A	54	22	2.45	13.8	6.2	4.2	0.86
B	69	20	3.45	11	5.92	4.8	0.61
C	60	25	2.4	9.6	5.04	4.69	1.19
D	63	25	2.52	10.4	4.98	5.18	1.05

2.3 TEST PROCEDURE

Tests have been performed on artificially polluted insulators, in order to determine the flashover voltage. The pollution was simulated according to the solid layer method followed by cold fog for wetting. Before suspending the insulators in the pollution chamber, they were carefully cleaned and rinsed with tap water so that all impurities and traces of grease were removed. Then the specimens were exposed to natural drying. While using solid layer method for polluting non ceramic insulators, to have a relatively uniform contamination layer, a pre-contamination process has to be done. This was carried out by application of Kieselguhr powder on insulator surface and then blowing it away [9]. As the layer of Kieselguhr was very thin, its impact on non-soluble deposit density (NSDD) can be neglected. After one hour of applying Kieselguhr, the hydrophobicity class of samples was HC4 or HC5.

The samples were polluted by dipping them in a previously prepared contaminant consisting of tap water with the volume conductivity of 0.1 mS/cm, NaCl as the conductive material, and Kieselguhr as the inert material. Compared to Tonoko or Kaolin, Kieselguhr gives slurry with higher conductivity [10]. The amount of Kieselghur and NaCl were chosen respectively 40 g/l and according to the desired salt deposit density (*SDD*). The average of top to bottom pollution ratios was found to be 0.97, indicating a relatively uniform pollution layer. After being polluted, insulators have to be in rest for proper time to let the hydrophobicity of SiR be transferred to the contaminant. In order to have specimens with different hydrophobicity levels, they were dried in ambient conditions with two different recovery periods, namely 24 hours and 1 hour. The corresponding wettability classes of the former and later recovery periods were respectively HC3 and HC4. After the specific recovery time, the samples were suspended vertically in the climate chamber.

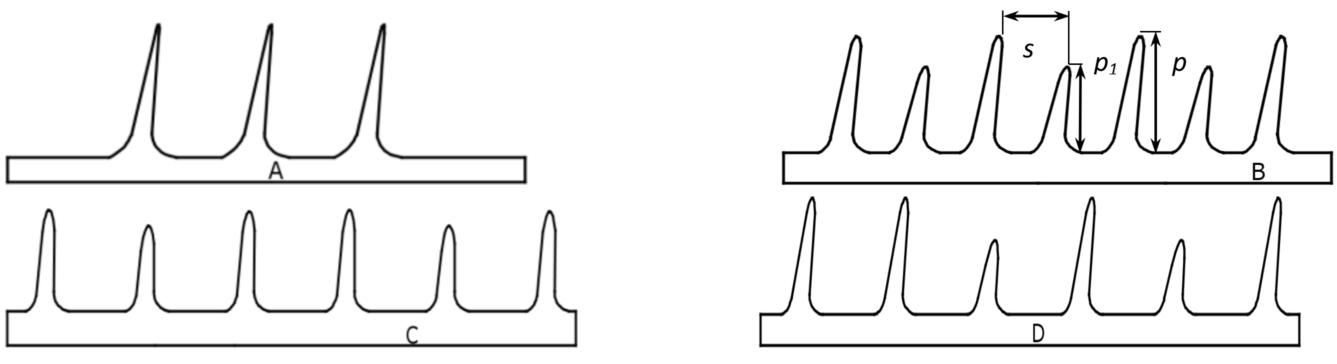

Figure 2. Configuration and geometrical characteristics of the specimens.

Table 2. Pollution flashover voltages of insulators.

Type	*SDD* (mg/cm^2)	HC=4		HC=3			
		$+U_f$ (kV)	σ (%)	$+U_f$ (kV)	σ (%)	$-U_f$ (kV)	σ (%)
A	0.292	66	5.3	78.75	1	79.25	4.2
	0.354	64	1.1	76.75	1.96	68	6.1
	0.929	50.25	4.38	53	4.92	50.25	4.3
	1.01	46.5	5.58	44.38	1.4	46	1.79
	1.96	27.75	4	38.56	2.1	39.375	3.4
B	0.414	76.75	3.2	77.25	1.6	77.5	3.2
	0.707	50	8	55	4.2	52.66	5.9
	1.375	44.5	5	45.25	7.2	45.5	6.1
	1.68	34	5	36.13	1.03	37.375	4.34
	1.933	21.25	6.1	23.38	4.8	24	7
C	0.491	79.75	0.54	78.25	1.55	79.75	2.54
	0.907	60	6.7	65.5	2.29	64.75	7
	1.79	50.5	1	52.5	3.9	52	5.2
	2.07	37.5	4.3	40.75	6.1	37.5	5.2
	2.68	21.75	3.9	23.13	5.7	22.3125	1.4
D	0.526	68	6.37	74	6.68	72	5.2
	0.802	50.75	4.03	57.5	6.1	56.25	5.9
	1.54	39.25	7.1	46	7.9	42	6.45
	1.73	35.75	8	36.25	2.75	37	4.6
	2.05	18.5	4.68	23.38	0.53	24.2	2.45

The wetting of pollution layer on the insulators was done by a fog generator with the input rate of 0.2 $kg/h/m^3$ while keeping the temperature below 25˚C. Being completely wet, the specimen was exposed to DC voltage.

In [11] and [12], it was indicated that voltage with positive polarity resulted in higher flashover voltage than with the negative polarity. To study the polarity effect of applied voltage, both positive and negative DC voltages were applied to the polluted insulators. As the voltmeter needs enough time to measure the flashover voltage, the applied voltage was increased at a constant rate of 3 kV/s, up to a flashover event. The tests were carried out while the fog generator was running.

Four different groups of SiR insulators (A to D in Figure 2) were used for flashover tests, each group having four insulators. To find a flashover voltage at a specific pollution degree, voltage polarity and hydrophobicity level, each individual insulator was tested four successive times, resulting into 16 measurements of flashover voltage per insulator type. The average flashover voltage and respected error were calculated according to the following equations:

$$U_f = \frac{\sum_{i=1}^{N} U_i}{N} \tag{1}$$

$$\sigma_{\%} = \frac{\sqrt{\frac{\left(\sum_{i=1}^{N}(U_i-U_f)\right)^2}{N-1}}}{U_f} \times 100 \tag{2}$$

Where U_f and U_i are respectively the average flashover voltage and the ith pollution flashover voltage of the insulators in kV, N is the number of valid flashover voltages, and σ is the relative standard error of the observed flashover voltages.

3 RESULTS

According to the aforementioned test procedure, the DC pollution flashover voltage of various insulators for high salt deposit densities was measured. The average flashover voltage for positive and negative voltages ($+U_f$,$-U_f$) and corresponding relative standard error (σ), for different hydrophobicity levels have been shown in Table 2. The maximum value of standard error is 8%

In order to evaluate the pollution performance of insulators by a mathematical approach, it is very common to use the following relation between *SDD* in mg/cm^2 and U_f in kV [13]:

$$U_f = a \times SDD^{-b} \tag{3}$$

Where *a* and *b* are respectively the surface pollution coefficient and characteristic exponent, which depends on the insulator types, materials, voltage types, etc.

According to equation (3) and the measurement results of Table 1, the respective values of *a* and *b* for different types of insulators, voltage polarities and hydrophobicity levels have been illustrated in Table 3.

To observe the effect of voltage polarity and hydrophobicity level on pollution flashover performance of various insulators, the curve fitting parameters of Table 3 have been used to draw Figure 3. It shows the pollution flashover voltage of each insulator (A, B, C, D) for different voltage polarities (+, -) and hydrophobicity levels (HC=3, HC=4).

4 DISCUSSION

4.1 IMPACT OF SALT DEPOSIT DENSITY

Considering the values of *a* and *b* in Table 3, for heavily polluted insulators with the same material, the following conclusions can be drawn:

1) Coefficient *a* is dependent on insulator profile and hydrophobicity level, and is rather independent of voltage polarity.

Table 3. Values of *a* and *b* corresponding to equation (3).

Type	HC=4		HC=3			
	+ polarity		+ polarity		- polarity	
	a	*b*	*a*	*b*	*a*	*b*
A	43.8	0.3604	48.99	0.4025	48.39	0.3728
B	43.76	0.622	46.08	0.588	46.13	0.5758
C	55.46	0.5435	57.6	0.4938	56.97	0.53
D	44.71	0.6604	49.97	0.6306	48.76	0.624

2) Exponent b is affected by insulator profile, hydrophobicity level and polarity of voltage.
3) The variation range of exponent b is between 0.36 and 0.66, which is higher than 0.24-0.36 in [9] and closer to 0.48-0.57 in [6] for UHVDC long rod insulators. The difference in b arises from different test methods, pollution severity and insulator profile [14]. It should be noted that refitting only the first three lower pollution levels of Table 2 to equation (3), considerably reduced exponent b. This indicates the effect of pollution severity on this exponent.

Figure 3 shows that with the increase of *SDD* the flashover voltage decreases for all kinds of insulators which is a result of higher surface conductivity and the following process leading to flashover.

4.2 IMPACT OF HYDROPHOBICITY

From Figure 3, it can be seen that with the decrease of hydrophobicity level, the flashover voltage is reduced. This effect results from the wider distribution of wet areas, with larger conductivity, in hydrophilic conditions which eventually can shorten out the insulator. Also it can be concluded that, due to the change of hydrophobicity level, insulators A and D are more prone to pollution flashover degradation than insulators B and C, though they have the same material. In addition, as the *SDD* grows, the hydrophobicity degradation does not lead to the same rate of flashover voltage reduction in different insulators. The highest reduction of flashover voltage for insulators A and D are respectively 16.2 and 12.4%.

4.3 IMPACT OF VOLTAGE POLARITY

Generally, for disc-type insulators, voltage with positive polarity results in higher flashover voltage than with the negative polarity [11, 12]. However, comparing $+U_f$ and $-U_f$ in Table 2 for HC=3, it can be observed that for half of the results $+U_f$ is less than $-U_f$. On the other hand using the curve fitted to these results (Figure 3), it is revealed that the negative pollution flashover voltage is lower than the positive one, implying the negative voltage as the worst condition. This can be justified by the different geometries of positive and negative electrodes. According to the results, the difference between positive and negative flashovers is 4 %. Considering this small difference and the statistical behavior of flashover, the effect of polarity in pollution flashover of DC composite insulators can be neglected.

4.4 IMPACT OF INSULATION GEOMETRY

Comparing the results depicted in Figures 3a, 3b and 3c, it can be seen that insulator C has the highest pollution flashover voltages for different hydrophobicity levels and polarities. This has been shown for positive polarity and hydrophobicity level HC=3 in Figure 4. However, one cannot say which insulator has the best pollution performance, because the insulators have different geometric characteristics (profile, height and leakage distance).

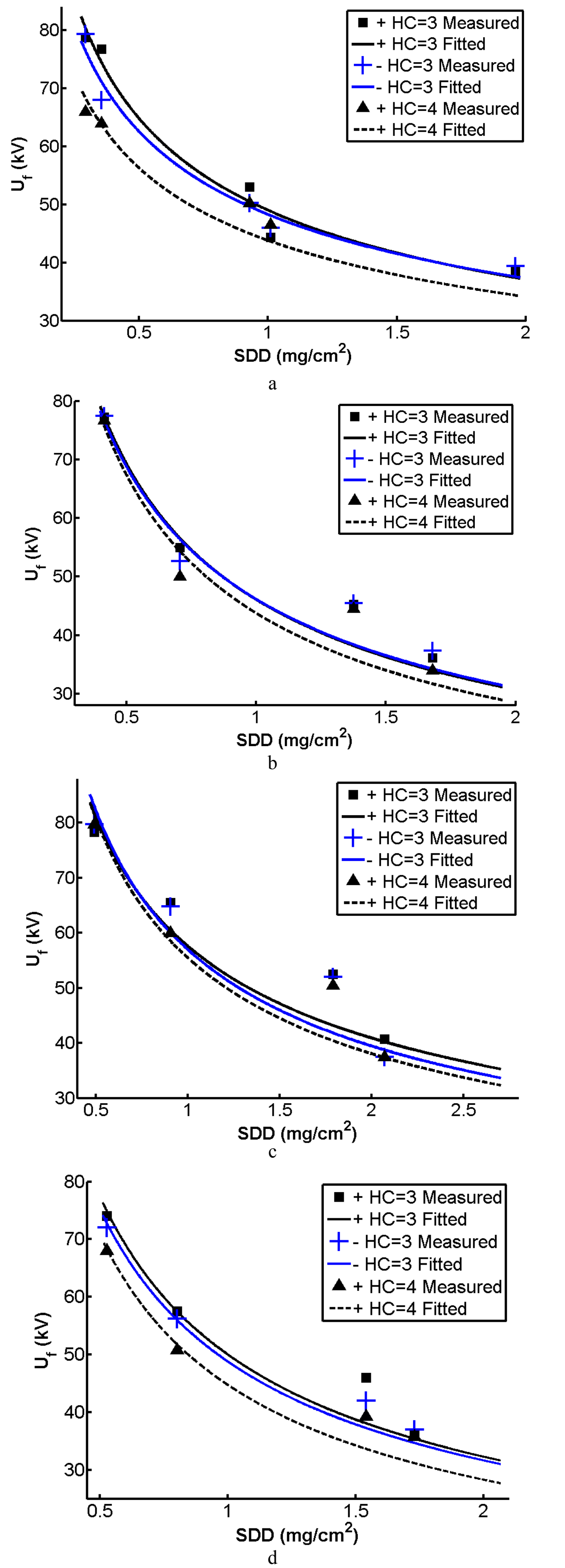

Figure 3. Pollution flashover voltage of various insulators at different hydrophobicity levels (HC=3, HC=4) and voltage polarities (+, -). a) insulator A, b) insulator B, c) insulator C, d) insulator D.

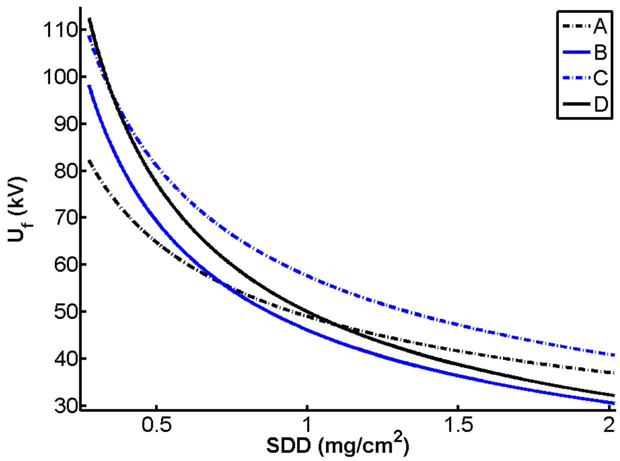

Figure 4. Pollution flashover of various insulators for positive polarity and HC=3.

One method to determine the insulator with best pollution performance is to use the following relation [6]:

$$E_L = \frac{U_f}{L}\left(\frac{kV}{cm}\right) \quad (4)$$

Where E_L is the flashover voltage gradient along the leakage distance, U_f is the flashover voltage and L is the leakage distance of the insulator. Sometimes the flashover gradient along the height of insulator is used. However the former is more common for pollution studies. Using equation (4) and the test results, the flashover voltage gradient of insulators versus *SDD* for positive voltage polarity and HC=3 has been shown in Figure 5. Hereafter, positive polarity and HC=3 results will be used for all figures.

As it can be observed from Figure 5, for the whole range of *SDD*, specimen C has the best pollution performance whereas specimen B has the worst one. In addition, although the pollution performance of specimen D is better than that of specimen A for lower pollutions, specimen A performs better in higher *SDD*s. It is also noteworthy to mention the difference between Figure 4 and 5; in Figure 5 insulator A has always a higher flashover voltage gradient E_L than insulator B, while on the contrary in Figure 4 it has a lower flashover voltage U_f than insulator B in the lower pollutions.

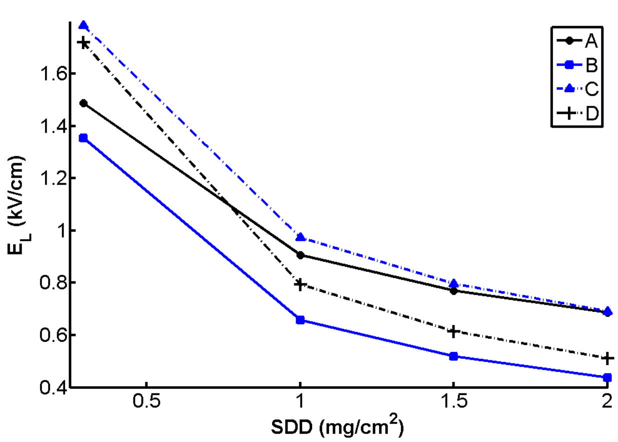

Figure 5. Pollution-flashover voltage gradient of insulators versus salt deposit density.

To analyze the effect of geometry on pollution performance in more details, different geometric parameters of insulators are taken into account in the following sections.

4.4.1 IMPACT OF SPECIFIC LEAKAGE

For different pollution levels, Figure 6 illustrates the relationship between flashover voltage gradient and specific leakage (*SL*), which is the ratio of leakage distance to insulator height.

In order to see the overall trend of gradient flashover voltage, each set of points has been fitted to a line. As it is seen all of the fitted lines have negative slope, i.e. with the increase of *SL*, the pollution performance degrades which is in agreement with the results obtained in [7]. Although it may seem that increasing the leakage distance improves the pollution flashover voltage for the same height of insulator, on the other hand it shrinks the air gaps between sheds which makes them be easily bridged by the arc.

Using the data obtained from the measurements, an empirical model has been fitted by iterative least squares method to estimate flashover gradient in terms of salt deposit density and specific leakage:

$$E_L = 1.066\, SDD^{-0.52} SL^{-0.7} \quad (5)$$

Where E_L (kV/cm) is the flashover gradient across leakage distance, *SDD* (mg/cm^2) is the salt deposit density and *SL* (cm) is the specific leakage.

4.4.2 IMPACT OF DIAMETER

In calculation of an insulator diameter, to consider the combination of shaft and shed diameters, the following relation is utilized [15]:

$$D_{av} = \frac{\int_0^L D(l)dl}{L} \quad (6)$$

Where L is the leakage distance and *D(l)* is the value of diameter at the leakage distance *l.* The average diameter of different insulators from Table 1 was used to plot E_L for various pollution levels in Figure 7. As this figure shows, a larger diameter makes insulators vulnerable to flashover.

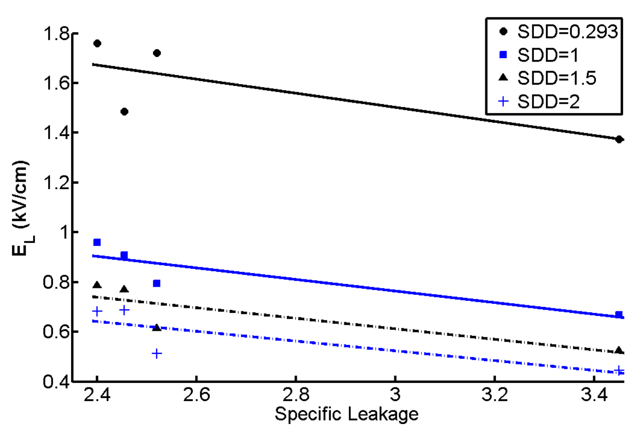

Figure 6. Pollution-flashover voltage gradient of insulators versus specific leakage

This is consistent with the results in [16] and [17]. To know the reason, one should consider the model of pollution flashover as an arc in series with the pollution layer resistance [14]. Any increase in the diameter of insulator tends to reduce pollution resistance which consequently decreases the flashover voltage.

As it can be seen from Figure 7, the exponent of diameter can vary depending on pollution level and insulator profile. Reference [17] showed that the relation between flashover gradient of large station post insulators and average diameter in AC and DC voltage can be described by the exponent of $D_{av}^{-0.3}$ and $D_{av}^{-0.43}$ respectively. Also a report [16] of the observed exponent suggests a mean value of -0.43 for DC and AC clean-fog tests. In Figure 7, the exponent for pollution levels of 0.293, 1, 1.5 and 2 (mg/cm^2) are respectively -0.96, -0.34, -0.12 and 0.02. This indicates that the higher the SDD is, the lower the effect of the diameter becomes. However, the overall tendency of the results can be found by using the least-square fitting method. The empirical fit relating E_L (kV/cm) to *SDD* (mg/cm^2) and D_{av} (cm) is:

$$E_L = 2.65\, SDD^{-0.52} D_{av}^{-0.68} \quad (7)$$

It also possible to replace D_{av} in equation with maximum diameter of insulator D_{max} (cm):

$$E_L = 1.54\, SDD^{-0.52} D_{max}^{-0.25} \quad (8)$$

4.4.3 IMPACT OF FORM FACTOR

Form factor (*FF*) is a dimensionless constant which is an indication of the depth and spacing of weather sheds. It can be calculated from the insulator geometry by the following equation [18]:

$$FF = \int_0^L \frac{dl}{\pi D(l)} \quad (9)$$

Reference [19] derived a model for AC pollution flashover by the use of form factor. The calculated value of *FF* for different insulators has been presented in Table 1. Using to the measurement results, Figure 8 shows relationship between E_L, *SDD* and *FF*.

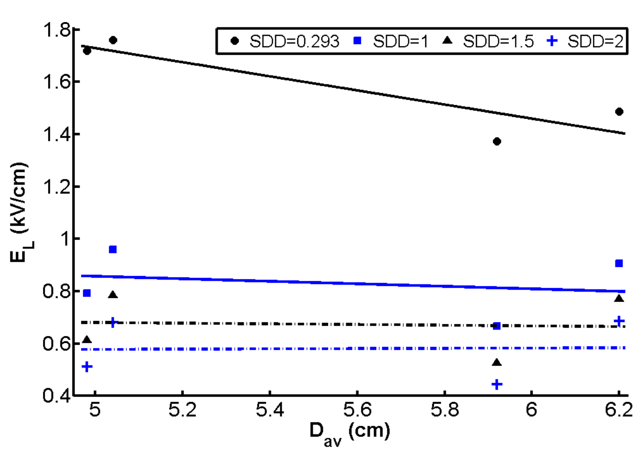

Figure 7. Pollution-flashover voltage gradient of insulators versus average diameter

This figure indicates that a higher form factor can improve pollution performance in lower level of pollutions (*SDD*=0.293) while on the contrary it reduces E_L for higher pollutions. According to equation (9), this contrasting behavior arises from the fact that a higher form factor requires a longer leakage distance, which can help the flashover strength of the insulator. On the other hand, longer leakage distance leads to a smaller space between sheds resulting into bridging them by arc and degrading pollution performance. Therefore, increase of leakage distance at lower pollution level has improved pollution performance whereas shed bypassing by arc in higher pollutions has degraded it. In general, according to the measurement data the relationship between E_L (kV/cm), *SDD* (mg/cm^2) and *FF* can be expressed as:

$$E_L = 0.97\, SDD^{-0.52} FF^{-0.1} \quad (10)$$

It is worthy to use form factor to compare the pollution performance of insulator C and D which have almost the same leakage distance (*L*), height (*H*) and diameter (D_{av}) but different profiles (see Table 1 and Figure 2). Referring to Figure 5, it is observed that insulator C is always performing better than insulator D. One element which can be accounted for that is the lower form factor of insulator C compared to that of insulator D. This can imply the effectiveness of form factor for comparing insulators with similar geometrical characteristics.

4.4.4 IMPACT OF THE RATIO BETWEEN SHED SPACING AND SHED DEPTH

The ratio of shed spacing to shed depth (*s/p*) explains the limit on providing too high leakage distance either by unreasonably increasing the number of sheds or by oversizing the shed depth [15]. *s* is the straight distance between the tips of two successive sheds and *p* is the maximum depth of sheds, as shown in Figure 2. This ratio was calculated for all insulators (see Table 1). Figure 9 depicts the effect of *s/p* on pollution flashover performance.

As it is seen from Figure 9, flashover voltage gradient will tend to increase when the ratio of shed spacing to shed depth grows. In other words, an insulator with higher *s/p*, makes better use of leakage distance.

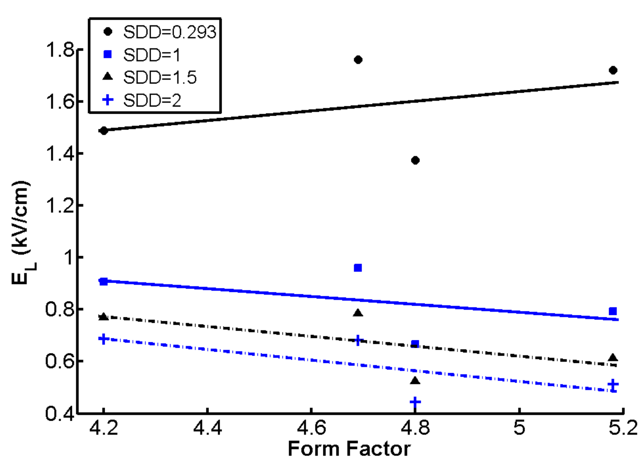

Figure 8. Pollution-flashover voltage gradient of insulators versus form factor.

The reason is that larger number of sheds leads to lower air gap between sheds and making the gap vulnerable to arcing as the voltage to bypass it becomes smaller. Furthermore, larger shed depth reduces the self-cleaning properties of insulator letting the insulator surface more conductive.

Based on the results, the empirical fit can be expressed as

$$E_L = 0.86\, SDD^{-0.52} (\frac{s}{p})^{0.42} \tag{11}$$

Although both form factor and *s/p* are an indication of shed to shed space and shed depth, comparing Figure 8 and 9 it is seen that $E_L(s/p)$ is monotonic, i.e. always increasing, whereas $E_L(FF)$ is both increasing and decreasing. As a result, the exponent of *s/p* in equation (11) is greater than that of *FF* in equation (10), implying greater influence of *s/p* in pollution flashover performance of insulator. However, similar to *FF*, *s/p* can be used to compare the pollution performance of insulators with the same length, height, diameter but different profiles. Accordingly, comparing insulators C and D in terms of their ratio of shed spacing to shed depth, it can be pointed out that the stronger insulator (C) has a higher *s/p* than the weaker one (D).

It is interesting to know that the exponent of *SDD* in all empirical equations is the same (-0.52), indicating that it is almost independent of other variables. In addition, combining E_L with two other geometrical parameters is helpful to see simultaneous effects of them. This has been shown for *SL* and *s/p* in Figure 10.

5 CONCLUSIONS

This paper presented the test results of DC pollution flashover of SiR insulators for different voltage polarities, hydrophobicities and shed profiles under extra heavy pollution conditions. Based on the results, the following conclusions can be drawn:

- The exponent *b*, describing the effect of salt deposit density on pollution-flashover voltage gradient, depends on insulator profile, hydrophobicity level and voltage polarity. It showed a variation range of 0.36-0.66 which also was affected by pollution severity.

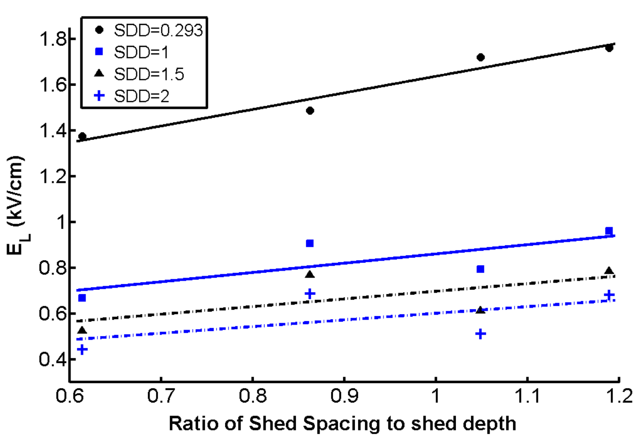

Figure 9. Pollution-flashover voltage gradient of insulators versus ratio of shed spacing to shed depth

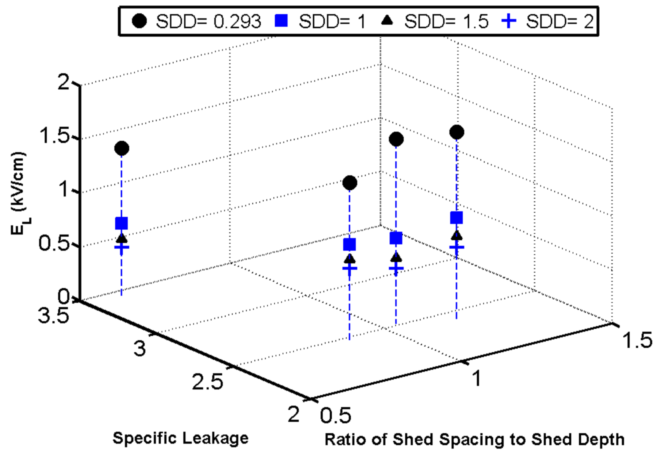

Figure 10. E_L versus *s/p* versus *SL*

- The pollution performance degradation of different SiR insulators due to the same loss of hydrophobicity was not equal. Insulators A and D, with a 16.2% and 12.4% reduction in flashover voltage, showed more sensitivity on hydrophobicity loss than insulators B and D.
- The results for positive voltage polarity were 4% higher than those for negative voltage; indicating negative polarity as the worst case similar to [11]. However, taking the statistical behavior of flashover and aforementioned small difference, the difference between negative and positive polarities can be neglected.
- Insulators C and B had the best and worst pollution performance respectively.
- Reducing specific leakage improves the pollution performance of composite insulator under DC voltage which is in agreement with the results in [7]. Higher specific leakage tends to bridge the air gap between sheds. Also the exponents relating the flashover voltage gradient to *SDD* and *SL* were found to be -0.52 and -0.7, respectively.
- Larger diameter of insulator makes it prone to flashover which can be a result of lower resistance of pollution layer. In addition, using the average diameter in the empirical fitting, the exponents of *SDD* and D_{av} were -0.52 and -0.68 respectively, whereas using the maximum diameter they were -0.52 and -0.25.
- Increasing form factor has two contrasting effects: it enlarges the leakage distance while shrinking the space between sheds. The first effect which happened at lower *SDD* (0.293 mg/cm^2) enhances E_L due to increase of the leakage distance and the second one degrades E_L at higher pollutions as the shed efficiency is reduced by the arc bypassing them. The concurrent effects of *SDD* and *FF* on flashover voltage gradient were found by least-squares method to be -0.52 and -0.1. For insulators C and D, with the same height, average diameter and leakage distance, form factor was used to compare the pollution performance. Insulator C with lower *FF* had better pollution performance.
- A higher shed spacing to shed depth ratio results into superior pollution performance, as the voltage needed for arc forming between sheds becomes greater. In addition a shallower shed improves the self-cleaning feature of the

insulators resulting into better operation of insulator under heavy and wet pollution. The exponents of *SDD* and *s/p* in this case were calculated to be -0.52 and 0.42.

- The obtained empirical exponents for different geometrical characteristics of insulators show that specific leakage and form factor have respectively the largest and smallest exponents. Also the exponent of *SDD* in all the empirical fits is the same, suggesting it's independency of other parameters. The aforementioned results are beneficial criteria to improve the design and dimensioning of SiR insulators under DC voltage and severe pollution conditions.

Further study can be done by cutting off the sheds of different places to investigate flashover performance with controlled and desirable profiles [20]. Wind effect and non-homogenous pollution layers with heavy density are also of interest for future work.

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