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Performance of High Voltage Protective Air Gaps in Desert Environment

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Abstract. Rod-rod and multiple rod gaps are used for overvoltage protection of various power system apparatus. These are mostly located outdoors and are subjected to dust and sand particulate contamination in desert lands. This paper discusses the influence of these pollutants on the breakdown voltage and breakdown time of protective rod gaps. The tested gaps include single rod-rod gaps as well as multiple rod-rod gaps in series. The rod radius and its end profile are changed to find the rod configuration which is least affected by dust pollution. In addition several practical protective gaps that are used across transformer bushings are also tested to check their performance in clean and dust polluted conditions. It is found that such pollution drastically changes the breakdown voltage as well as the breakdown time. Specific recommendations are made concerning the choice of suitable protective rod gap configuration and gap spacings which depend upon geographical location.

Introduction

In high voltage power networks, rod-rod air gaps or "arcing horns" of various types are used for over voltage protection of different components such as transformers, bushings, inslators etc. When these are located outdoors in desert environment, as usually is the case in the arid and semi-arid lands, they are subjected to sand and dust storms. In addition, the rod tips may be covered by a film of fine sand/dust particles for extended time periods due to the rare rain falls in the desert areas.

In Saudi Arabia, the use of such protective gaps is widespread among different electric utilities as shown in Table 1. Although several studies have been reported for clean

Table 1. Number of protective rod air gaps used by different utilities in Saudi Arabia.

	Overhead line insulator strings				Transformer bushing		Cable termination	
Utility	**110 kV**	**132 kV**	**33 kV**	**380 kV**	**33 kV**	**110 kV**	**115/230 kV**	**110 kV**
Electricity Corporation		56000	10670		5064			
SCECO South		*	*					
SCECO Central		*	90000	*				
SCECO East							84	
SCECO West	58404			23228		136		132

*All insulator strings on these lines have protective gaps.

bi-rod air gaps and are summarized by IEEE Committee reports [1,2], the information regarding the influence of desert pollution on the performance of such gaps is quite scarce. Only recently some studies have been reported by Al-Arainy *et al* [3,5]. Their results show that under certain conditions, the performance of bi-rod gaps is strongly influenced by the presence of dust pollution in the air and/or on the rod surfaces. A reduction or increase in breakdown voltages and/or breakdown times is reported which depends on voltage waveform, voltage polarity and gap length [4,5]. The pollution effect was the most pronounced for small gap lengths commonly employed in the medium voltage distribution power networks. However, these studies do not address the effect of tip radius of such rod gaps [3-5]. Similarly, the effect of atmospheric dust pollution has not yet been studied for multiple rod gaps that are commonly used on the medium and high voltage power networks in many parts of the world. These are preferred, since they can be made to sparkover more consistently and in less time than one long gap, and comparatively at a lower voltage. They also interrupt power with greater reliability [6].

The aim of this study is to enhance the knowledge regarding protective rod gap's performance when it is subjected to desert pollution. In this paper investigation will be concerned mainly on the influence of end profile and rod diameter on overvoltage protection. In addition, results are also presented for practical protective rod gaps that are typically used on medium voltage transformer bushings. These rod gaps are either of single gap type (between two rod electrodes) or two series (multiple) gap type (between three rod electrodes). These are extensively being used by several local transformer manufactures and are being supplied to the electric utilities operating in the Kingdom of Saudi Arabia. Detailed results of some representative test cases are reported and analyzed and suitable rod arrangements are recommended for the overvoltage protection of distribution apparatus installed in the dry desert environment of Saudi Arabia.

Expermental Setup and Procedure

These studies were carried out in a specially designed environmental chamber which has the facility to provide sand/dust particles of known size, material and concentration into the inter-electro gap [7]. In the present study, particles used were of diameter (d_p) ≤

125 μm and the concentration inside the chamber was maintained ~ 1.0 g/m^3 which stimulated the condition of severe dust stroms that are common in the Arabian region. To isolate the effect of inter-electrode floating dust particles and those settled on the electrode tips, some studies were performed with the clean gaps but with dust film on the electrodes. Whenever the effect of dust film only on the electrodes was desired, a dust storm was produced in the chamber and left overnight for the particles to settle on electrodes. Therefore, in this case the chamber and the electrode gap remained clean, whereas a "dust film" was deposited on the electrodes in a natural way under gravity.

To study the effect of rod diameter and their end profiles, cylindrical rods were used with their end shapes being either hemispherical or square cut. The rod radii investigated were 5 mm and 15 mm for both shapes. For the practical gaps fitted across the transformer bushings, several units were selected and subjected to comprehensive tests. These units were either supplied by local transformer manufacturers or removed for testing from the power networks of local electrical utilities. Table 2 summarizes the main dimensions of the bushings and the gaps used for these investigations. Gaps were stressed with standard lightning (LI) and switching impulses (SI) using "Haefely" 10 stage, ± 1000 kV, 40 kV, Marx impulse generator. Voltage measurement accuracy was ± 0.5%. The breakdown times were measured by using Hafely, Type 60, time to breakdown meter. The measured breakdown voltages were corrected as per IEC 60-2 [8] to correspond to standard values of air pressure, temperature and humidity. Breakdown probability for a given gap and voltage was derived by applying 20 impulses at a fixed crest value at intervals of 30 s. The probability distribution curve was drawn by repeating this procedure 5-10 times at different values of applied voltage.

Results and Discussion

The effect of pollution on the performance of rod-rod gaps was studied by evaluating parameters such as breakdown probabilities, 50% breakdown voltages (V_{50}), volt-time (V-t) curves, average breakdown times corresponding to V_{50}, and scatters in breakdown voltages and breakdown times. The influence of dust pollution on these parameters depends upon the voltage polarity, voltage waveform, gap length, and presence of the dust film on electrodes or of air borne pollution. In present results the main emphasis is placed on the effects of rod end shape and rod tip radius and performance of practical protective gaps using single and multiple gaps.

Effect of rod end shape and tip radius

The breakdown voltages for positive polarity cases generally decreased due to contaminant particles. However, under negative polarity pollution increased breakdown voltages for some gaps. Assume that V_p and V_c represent the 50% breakdown voltages

Table 2. Gap configurations and dimensions of the practical rod gaps fitted across transformer bushing as used in this study

Gap arrangement code	Gap configuration	Rod dia. and end profile	Gap distance recommended by manufr.	Voltage class (kV)	BIL (kV)
A		8 mm cut rod	15 cm (7.5 + 7.5)	33	170
B		8 mm cut rod	16 cm	33	170
C		8 mm cut rod	15 cm	33	170
D		7 mm cut rod	6 cm (3+3)	24	125
E		8 mm hemispherical	5 cm (2.5 + 2.5)	13.8	75
F		8 mm hemisperical	4 cm (2 + 2)	11	60
G	Experimental	10 mm cut rod	Different gaps	Varying	Varying

under polluted and clean conditions, respectively, for a given gap configuration, voltage polarity and voltage waveform. Then the ratio V_p/V_c highlights the effect of pollution on the breakdown voltages. Figure 1 shows the V_p/V_c against the gap lengths for different rod radii under positive lightning and switching impulses. It is clear from this figure that for almost all cases of gaps larger than 50 cm, V_p/V_c ratio is ≈ 1 and pollution has very little or no influence on the breakdown voltages. However, for smaller gaps, (≤ 50 cm) the V_p/V_c ratio may be less than 1 indicating a reduction in V_{50} due to pollution particles. The magnitude of this reduction can be up to 40%. This figure further shows that, as for the same rod radius the square cut end shape has reduction region at shorter gaps while the reduction region for hemispherical end shape ends at large gaps. Thus, cut rods are less sensitive to the presence of pollution. Moreover, the smaller the rod radius, lesser the effect of pollution. Hence in a polluted environment, protective rods with small diameters and square cut may minimize pollution related influences on their sparkover characteristics. This may, in turn, ensure reliable operational characteristics of the protective gaps.

Figure 2 shows the breakdown performance of rod gaps under negative lightning and switching impulses. In these cases, there is a gap length region where the dust pollution can increase V_{50}. This increase can be as much as 20%, but it is smaller for rods of square cut end profiles and smaller diameters. Moreover, similar to the positive polarity cases, the gap length where increase in V_{50} is observed is restricted to smaller values if cut rods are used instead of the ones with hemispherical ends. Since, it is known that almost 90% of lightning strokes hitting the ground structures are negative in nature [9], dust coated protective gaps, may fail to operate for certain combinations of gap lengths, rod radii and rod end shapes due to their higher breakdown voltages, thus posing a potential threat towards insulation coordination. Therefore, the influence of dust pollution must be considered in the selection of rods for arid regions. Generally, cut rods with smaller rod radii should be preferred in polluted areas as they are relatively immune to smaller pollution related effects. It is also obvious from Fig. 2 that for suqare cut rods with 5 mm, radius the pollution effect is negligible if the gap length is ≥ 10 cm. This gap length range is of great importance for medium and high voltage distribution and transmision networks. For smaller gap lengths (≤ 10 cm) where observed pollution influence is significant, the system design is dependent on lightning impulse flashover characteristics only. Therefore, the evaluation of practical protective gaps used on medium voltage distribution networks is confined only to lightning impulse voltages. Nevertheless, the results of Fig. 2 show that the general behavior of pollution under lightning and switching impulses is similar and reductions or increases are more pronounced for rods with larger diameters and/or hemispherical end profiles. Thus, the guidelines as suggested above for the selection of rods for positive polarity impulses are equally applicable to negative impulses as well.

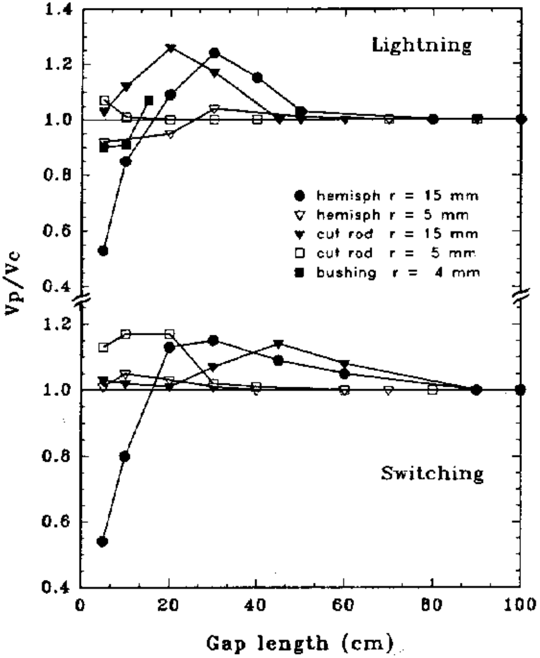

Fig. 2. The ratio of polluted to clean breakdown voltages as a function of rod-rod gap length (negative impulses).

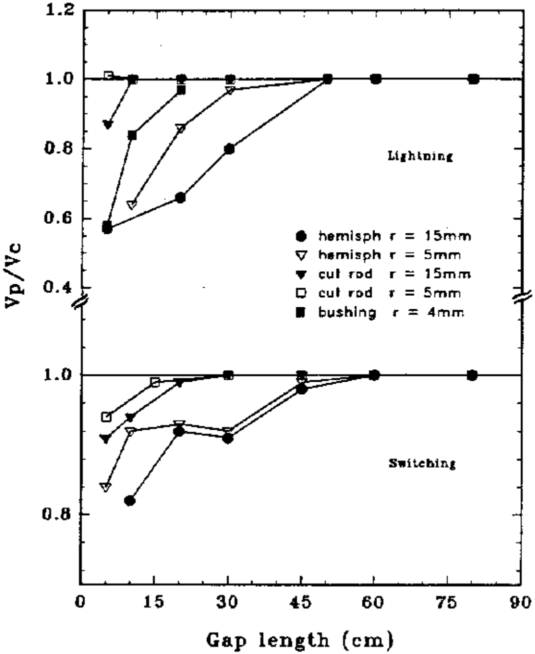

Fig. 1. The ratio of polluted to clean breakdown voltages as a function of rod-rod gap length (positive impulses).

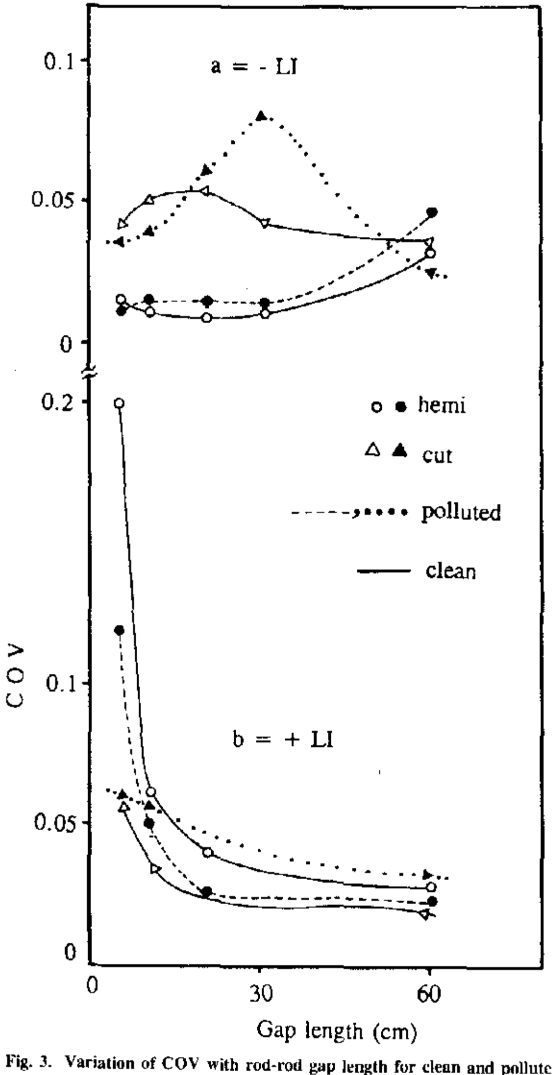

Fig. 3. Variation of COV with rod-rod gap length for clean and polluted conditions under LI (r = 5 mm).

In addition to breakdown voltages, the coefficient of variation, (COV = σ/V_{50}), where σ = standard deviation in breakdown voltages, is an important design parameter. Generally, if scatter in breakdown voltages is large than d, and hence COV will be larger, indicating that the protective gap will exhibit a larger voltage range in which it will operate. Hence, rods which exhibit lower σ values are selected, since their breakdown characteristics are then more reproducible. Figure 3 shows the variation of COV with gap length corresponding to clean and polluted conditions for both rod end shapes and under both negative and positive lightning impulse voltages when r = 5 mm. This figure shows that under positive LI voltages, COV values for both rod shapes decrease as the gap length is increased. Furthermore, COV values are similar under clean and polluted conditions and are smaller than 4% over most of the gap length range investigated. Under negative lightning impulses, COV depends upon gap length for both rod shapes. In gap length region where breakdown voltage increases due to pollution, COV in polluted gaps may be somewhat greater than the corresponding clean gap values. For other rod diameters, the behavior is roughly similar and no clear influence of rod-radius on the COV values could be identified. Thus, from the point of view of scatter in breakdown characteristics, the rod radius as well as its end shape are not the major influencing factors.

Practical rod gaps performance

In addition to the investigations of simple rod-rod gaps summarized in the last section, several outdoor transformer bushings fitted with rod gaps were investigated in detail to determine the influence of atmospheric dust pollution on their performance. Table 2 summarizes the tested bushings and their accompanying protective gap configurations. It was found that similar to the case of rod-rod gaps, the breakdown voltages of practical protective gaps were also influenced by the presence of dust pollution in the air gaps and the dust film formed on the electrode surfaces. The pollution generally decreased the breakdown voltage for the tested bushings under both polarities of the lightning impulses. The magnitude of the decrease depends upon the bushing voltage rating, its BIL and its total gap length. Figures 4 and 5 show examples of the breakdown probability distributions for negative and positive lightning impulses under clean and polluted conditions for 13.8 kV (Geometry E) and 24 kV (Geometry D) bushings along with their protective gaps. Both of these bushings have multiple rod gaps. For bushings with single protective gaps, the general influence of atmospheric pollution was similar to that of multiple gaps. Table 3 summarizes the ratio between the 50% and 95% breakdown voltages under polluted (V_{50}^F, V_{95}^F) and clean (V_{50}^C, V_{95}^C) conditions, respectively, udner both polarities of Lightning Impulse voltages for practical gaps summarized earlier in Table 2. It is interesting to note that the maximum influence of atmospheric pollution is noticed for geometries E and F which have either smaller gap lengths or electrodes which have hemispherical aend profile and coparatively larger diameter.

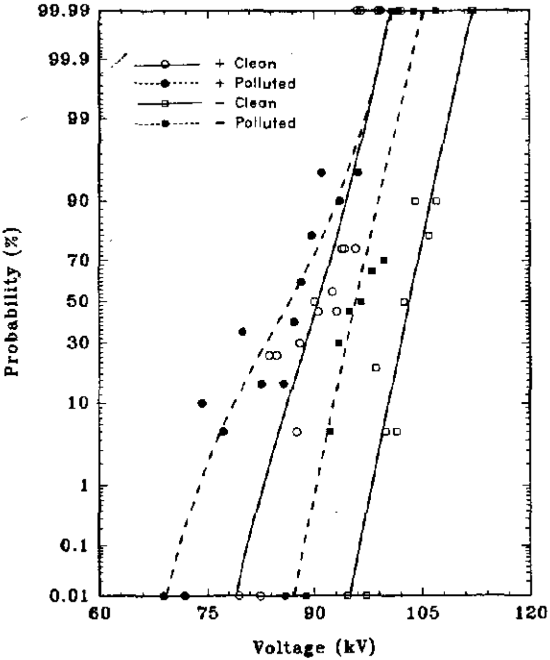

Fig. 5. The breakdown probability for 24 kV multiple rod bushing (geometry D, BIL = 125 kV) with total gap spacing of 6 cm (as suggested by manufacturer).

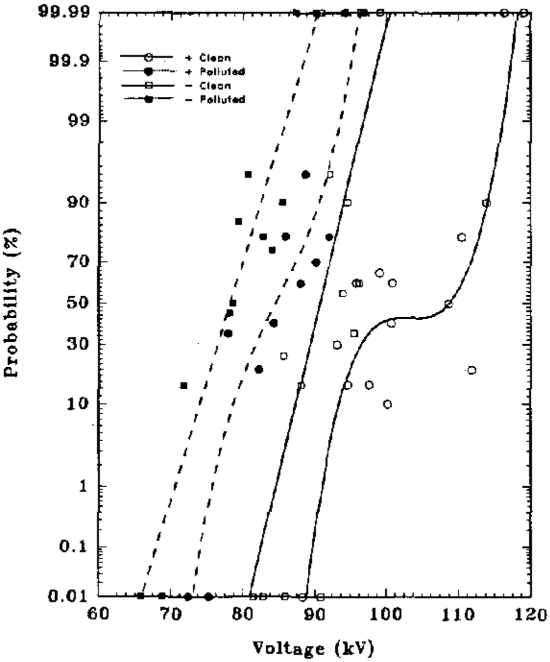

Fig. 4. The breakdown probability for 13.8 kV multiple rod bushing (geometry E, BIL = 95 kV) with total gap spacing of 5 cm (as suggested by manufacturer.

Table 3. Effect of atmospheric pollution on the 50% and 95% breakdown voltage of practical gaps

Gap geometry code from Table 1	+LI		-LI	
	(V_{50}^{p}, V_{95}^{c})	(V_{50}^{c}, V_{95}^{c})	(V_{50}^{p}, V_{95}^{c})	(V_{50}^{p}, V_{95}^{c})
A	0.91	0.96	0.99	0.98
B	0.94	0.99	0.96	1.00
C	0.92	0.95	0.95	0.96
D	0.96	0.98	0.94	0.92
E	0.78	0.81	0.87	0.87
F	0.87	0.91	0.80	0.79

These results therefore lead to the conclusion that the influence of atmospheric pollution on the performance of practical rod gaps can be minimized by using cut rods with smaller diameters. This conclusion is valid for single as well as for multiple rod gaps. From these measurements, it also becomes clear that the arrangement of the rod electrodes i.e., horizontal or vertical, does not have any major influence on the pollution related changes observed on the performance characteristics of protective gaps, since geometries A and C have approximately similar dust particulate related reduction despite their horizontal or vertical configuration.

In addition to breakdown voltages, pollution also affects volt-time characteristics of protective gaps. Figures 6 and 7 show two examples of V-t curves for gap configuration A under positive and negative lightning impulse voltages. These results show that the presence of pollution particles generally decreases the scatter in the breakdown times and the performance of the protective gap becomes more consistent. For breakdown times of the order of a few microseconds, the pollution related influences are minimal for this geometry. However, for gap configurations employing rods of larger diameters and smaller gap lengths, there were significant differences between the V-t curves under clean and polluted conditions were observed even for smaller breakdown times as shown in Fig. 8. These findings therefore lead to the conclusion that for the design of such gaps, the effect of atmospheric pollution should be fully considered.

Selection of the rod gaps geometry

In selecting gaps for overvoltage protection, the rod end profile, its radius, gap length and gap configuration i.e. single gap or multiple gaps, and horizontal or vertical gaps are the main design parameters. As seen in the last section for rod gaps which have to operate outdoor in areas frequently subjected to atmospheric dust pollution, the choice should be of geometries least influenced by dust pollution so as to have reliable performance characteristics under all atmospheric conditions. Since, the dust pollution

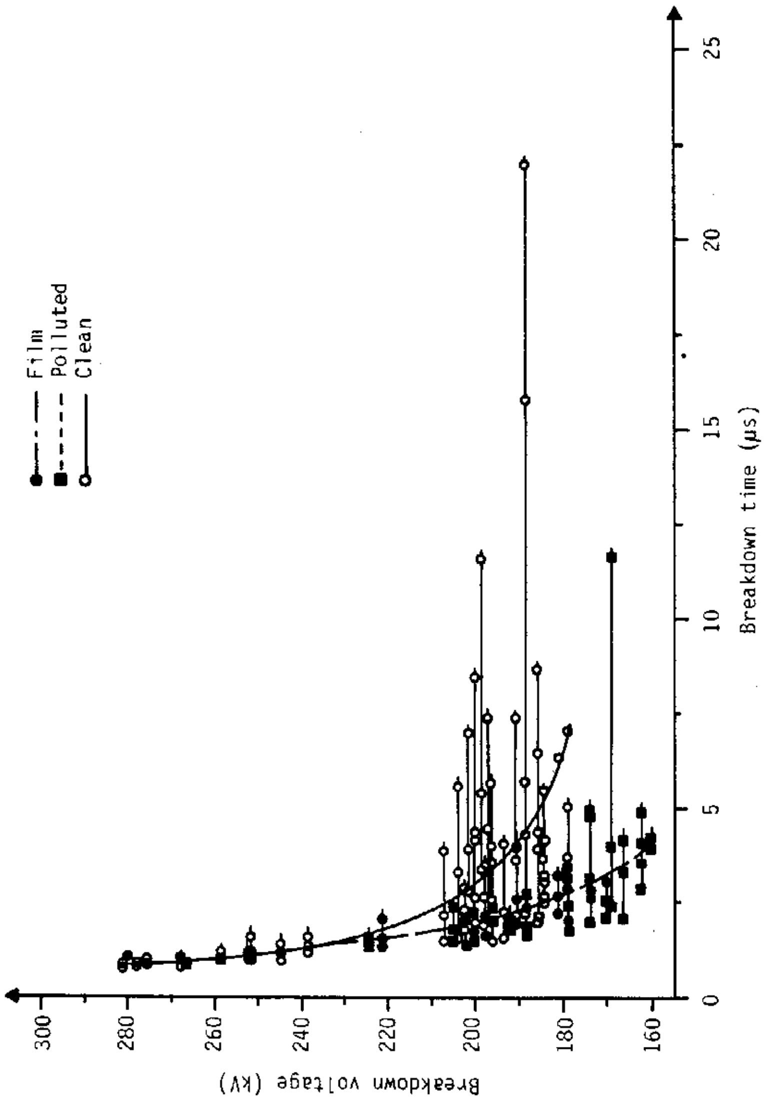

Fig. 6. Effect of dust particles on V-t characteristics for multiple rod air gap (geometry A, BIL = 170 kV) under positive LI.

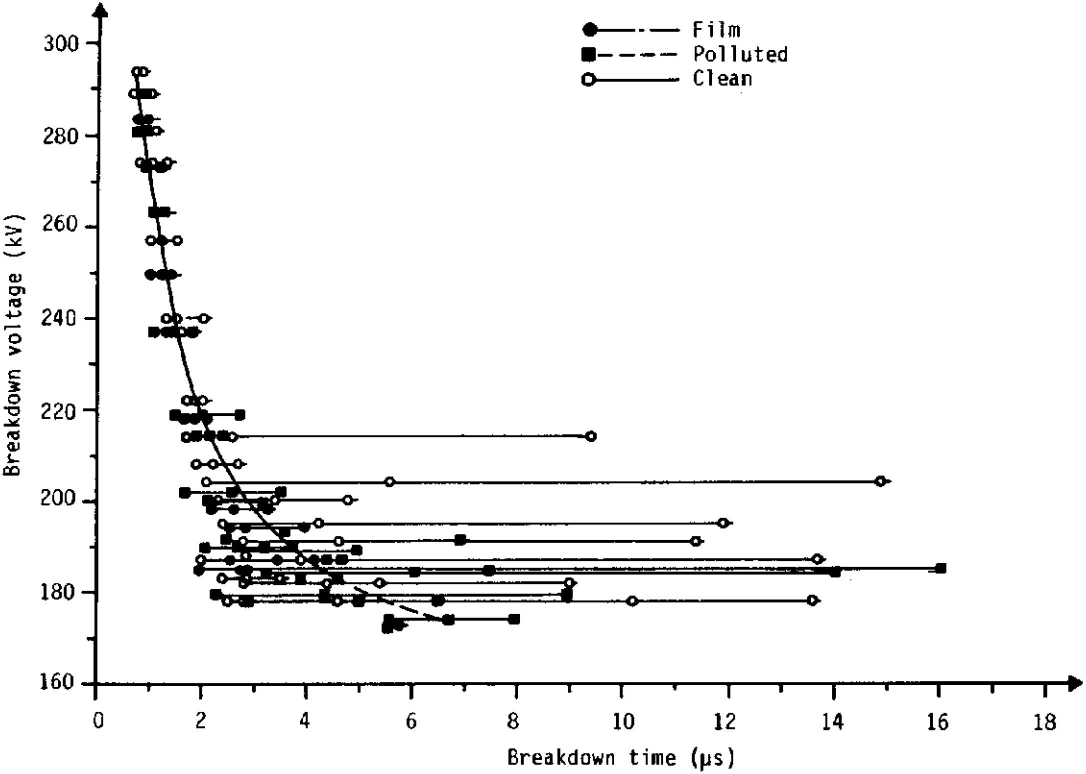

Fig. 7. Effect of dust particles on V-t characteristics for multiple rod air gaps (geometry A, BIL = 170 kV) under negative LI.

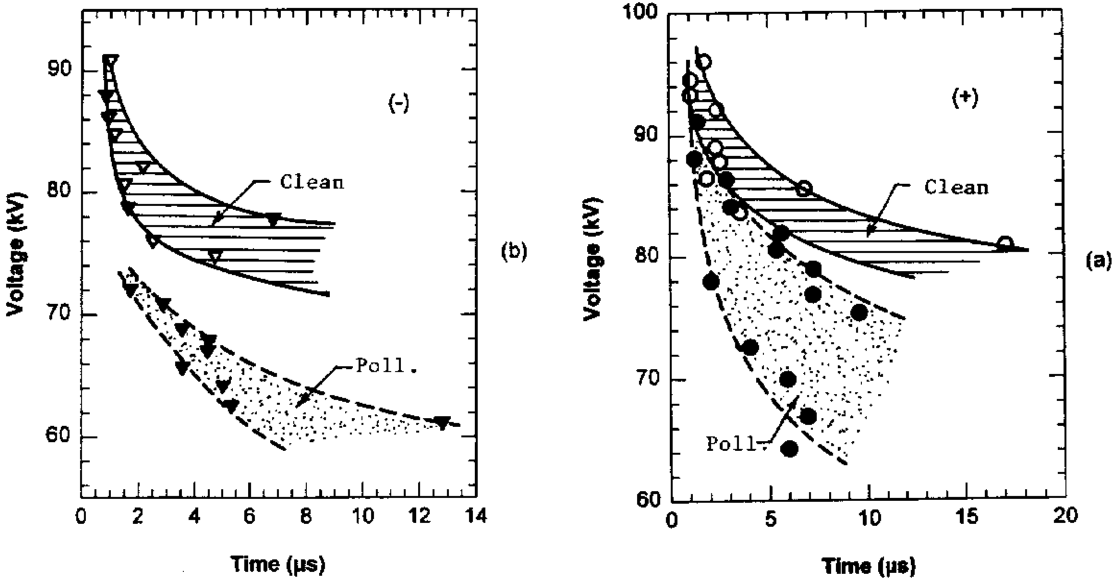

Fig. 8. Effect of dust particles on V-t characteristics for multiple rod air gap (geometry F, BIL = 60 kV) under positive and negative LI.

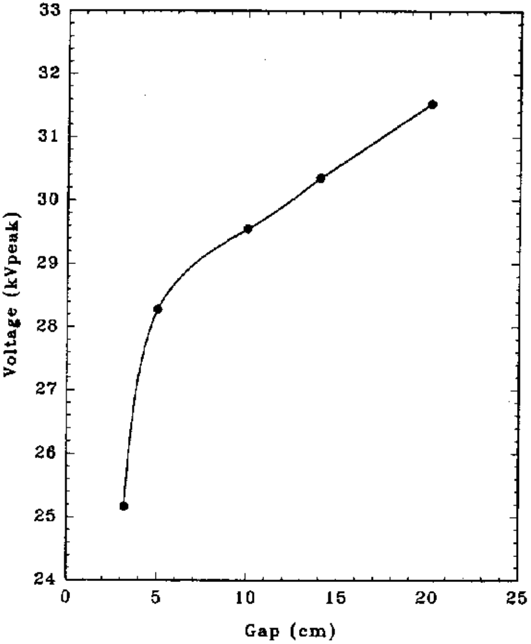

Fig. 10. Corona onset voltage of cut rod-rod protective gap (polluted) as a function of gap spacing when rod radius is 5 mm.

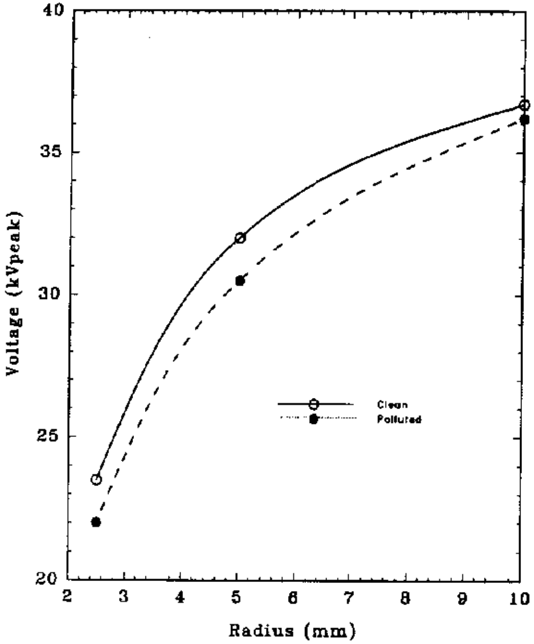

Fig. 9. Corona onset voltage of cut rod-rod protective gap as a function of rod radius with gap spacing of 14 cm.

has similar affects for single or multiple gaps as well as for horizontal and vertical gaps, the main design parameters are the rod radius, its end profile and gap length. From extensive measurements on rod-rod gaps and bushings fitted with protective gaps, it can be concluded that rods with cut ends and smaller diameters are to be preferred since these offer immunity toward dust pollution related influences. Therefore, the selected rod radius should be as small as possible to minimize the pollution effect on the gap's performance. However, it should not be so small that the gap is always coronating under normal AC voltage. Figure 9 compares the corona onset levels of clean and dust coated cut rod electrodes of different radii. For this gap of 140 mm the presence of dust film on the electrode tip reduces corona onset voltage by about 0.5 ~ 2 kV. Figure 10 illusstrates the effect of gap length on the corona onset voltage for a similar dust coated rod gap. It is clear that for 11 and 13.8 kV systems, rods as small as 4 ~ 5 mm in diameter can be used with confidence for medium voltage networks from corona point of view.

During the testing of practical gaps supplied by the local high voltage equipment manufacturers, it was observed that in some cases their recommended gap length settings have breakdown voltage higher than the system BIL. In such cases the protective gaps will not fulfill their function as these will not operate till the incoming surge has a magnitude higher than BIL for which the equipment is designed. Therefore it is important to carefully examine the gap spacing in such practical settings to satisfy the following conditions:

i. There is no continuous corona under operating AC voltages.
ii. There is no breakdown under temporary over voltages.
iii. Its breakdown voltage (~ V95) is less than the system BIL by a certain margin, called protective margin.
iv. If surge arressters are also installed in the system, the gap's breakdown voltage should be higher than the surge voltage level the arrestor will attenuate.

If these conditions are satisfied, it will ensure that the protective gap suppress the overvoltage in case the surge arrestor fails to act. This will provide a backup overvolt5age protection and will avoid unnecessary trippings that are required to clear the follow-on AC current resulting from gap's breakdown due to high voltage surges.

Surge arresters are usually selected such that the highest protected voltage level is ~ 60% of the system's BIL. Hence the arcing horn should have a 95% breakdown voltage protection level of around 70% ~ 80% of the system BIL. Since the gaps are located outdoors where pressure, temperature, humidity and atmospheric pollution parameters can vary, the gaps actual breakdown voltage will vary over a certain range. As seen from the results presented here, superimposed on this range will be the influence of dust which may be as much as 20% or even more if the rods have bigger diameters and poor sharp profiles. With these factors coupled with the seasonal changes of pressure, temperature and humidity, with the gap's breakdown voltage will vary over a certain range. Hence, in order to avoid insulation coordination problems, the extreme weather combinations of highest pressure plus lowest simultaneous temperature, and similarly lowest pressure plus highest simultaneous temperature should be considered while determining the extreme range of gaps protective performance. In a well coordinated scheme, this voltage range should lie between the system BIL and arresters operating voltages.

It is important to note that the breakdown voltage for a single gap of length d is different from multiple gaps having the same total length d. Also the statistical variation of the breakdown is different in the two cases. Table 4 shows V50 and coefficient of variation (COV) values for a single (15 cm) gap and a multiple (7.5 + 7.5) cm rod gaps under clean and polluted conditions for both polarities gap of LI. The V_{50} value for a single gap is lower than that of an equivalent multiple gap under both polarities of LI voltages. Further the COV values are generally lower for the multiple gap as compared to the single gap case. This is specially true for clean conditions. This is one of the reasons for using multiple rod gaps instead of a single gap, as they improve the reliability and consistency of operation.

Using the criterion discussed above, the recommended values for single or multiple gaps can be established for use on typical medium voltage distribution networks. As a typical study case Table 5 shows the results for single as well as multiple practical gap cases installed on 13.8 kV and 33 kV systems located in the Riyadh area. The rods are assumed to have cylindrical shape with square cut end profiles and rod diameters less than 8 mm.

The extreme range of breakdown voltage for the protective rod gaps as illustrated in Table 5 include the range of breakdown voltage probability from 5% to 100%, with temperature varying from 0° to 50°C, pressure from 925 to 940 mbar, and also the influence

Table 4. V_{50} and COV for 15 cm single and (7.5 + 7.5) cm multiple rod gap's clean and polluted conditions under LI voltage

	+ve LI				-ve LI			
	Multiple rod gaps		Single-rod gaps		Multiple rod gaps		Single-rod gaps	
	Clean	Poll	Clean	Poll	Clean	Poll	Clean	Poll
V_{50}	183	167	145	133	183	181	147	140
COV	0.034	0.07	0.04	0.043	0.034	0.037	0.05	0.02

Table 5. The recommended gap length for protective rod-rod and multiple rod gaps used across transformers bushings installed in Riyadh Region

Nominal system voltage (kV)	Bil (kV)	Recommended single gap setting (cm)	Extreme range of breakdown voltage (kV)	Recommended multiple rod gap setting (cm)	Extreme range of breakdown voltage (kV)
13.8	95	6.5	58-83	11.5 + 1.5	64-86
33	170	16	106-145	5.5 + 5.5	110-150

of dust particles (see Table 3). The above variations are expected to be different for the different regions. Thus the protective gap spacing for each region needs to be suitably adjusted, as a single spacing may not be suitable for applications in all regions.

This study has mainly concentrated on the selection and performance of protective gaps for medium voltage distribution networks. For equipment used on higher voltage transmission and subtransmission networks, additional studies are underway which will be reported in future.

Conclusions

The effect of atmospheric pollution on performance of rod-rod and multiple rod gaps is investigated. It is shown that pollution has significant influence on the performance of such gaps. This influence can be minimized by selecting rods of smaller diameter and squarecut end profile. Performance of several practical rod gaps installed across transformer bushings for use on medium voltage distribution networks was evaluated. Guidlines are proposed for selecting appropriate rod configuration and gap length for application in arid regions where dust storms are a common metreological occurence.

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أداء ثغرات الحماية الهوائية للجهد العالي في الأجواء الصحراوية

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(استُلم في ٢٤/ ٢/ ١٩٩٦م؛ قبل للنشر في ١٣/ ٤/ ١٩٩٦م)

ملخص البحث. تستخدم الثغرات الهوائية المحصورة بين قضيبين أو بين عدة قضبان لحماية بعض الأجهزة في أنظمة الجهد العالي. غالبا تستخدم هذه الأجهزة في الأجواء المكشوفة حيث تتعرض للغبار والأتربة وخاصة في المناطق الصحراوية. تبحث هذه الورقة في كيفية تأثير هذه الملوّثات على مقدار جهد ووقت انهيار تلك الثغرات. تشمل الثغرات المدروسة ثغرة منفردة (قضيب إلى قضيب) وثغرة مزدوجة (ثغرتين على التوالي). تم تغيير قطر القضيب وكذا شكل نهايته لإيجاد التصميم المناسب الذي يكون تأثره بالتلوث قليلا. وبالإضافة إلى ذلك، تمت دراسة تأثير التلوث الصحراوي على أداء عدة ثغرات حماية حقيقية موضوعة على التوازي مع عوازل المحولات. وقد وجد أن جزيئات الأتربة والغبار تُغيّر قيم جهد ووقت الانهيار. في نهاية الورقة، تم ذكر بعض التوصيات المحددة بشأن الاختيار الأنسب لثغرات الحماية الهوائية وضرورة أخذ المواقع الجغرافية في الاعتبار عند تحديد أبعاد الثغرات.