Experimental study of porcelain and toughened glass suspension insulators under desert contamination

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Abstract. In this paper, the performance of porcelain and toughened glass suspension insulators artificially polluted with desert contamination is investigated experimentally. The withstand flashover voltage (FOV), and equivalent salt deposit density (ESDD) of desert contaminated insulators have been studied and reported. Artificial pollution testing was carried out, and desert contaminations were prepared in advance for four solutions (NaCl, CaSO4, KCl, and CaO) of different concentration levels to investigate the influence of desert contamination on the insulators of transmission lines. The flashover analyses are completed on 11 kV insulators with artificial pollution coatings. The contaminations materials are (a) Desert Salt Pollution-Dry pollution (b) Natural Fog Condition. Results have proven that flashover voltage decreased with the increase in the dry desert pollution level at constant pressure and temperature condition. However, the study has also revealed that in the case of natural fog conditions, the flashover voltage of porcelain and toughened glass disc insulator became much lower than the dry test. From the results, it can be detected that engineers can predict and plan for the maintenance schedule of the poor performance of the insulators under different effluence environmental conditions. The study tested the effect of AC voltage flashover on the suspension insulators. However, the DC voltage is suggested to be used and results to be compared with the current study.

Keywords: Desert Contamination, Flashover, leakage current, Suspension insulator, withstand voltage.

1. Introduction

The modern development of industry produces annual intensification in the degree of atmospheric pollution by waste production. The amount almost increases in proportion to the increase in production [1]. In turn, the growth of electrical grids produces conditions where pollution of a particular part of power line close to the industrial plants or polluted natural sources of the sea and salt deserts are more escalated. Pollution reduces the electrical strength of insulation and, as a result, in some cases, causes surface overlap, thereby disrupting regular electricity supply or destroying equipment. As a result of the presence of electrical installations in the zone with a toxic atmosphere, there are several other phenomena, the ignition of supports due to the increase in leakage currents on insulators, the increase in radio rooms from discharges, accelerated corrosion of the wires, fittings and metal supports [2]. The primary air pollutant is the smoke of factories, power plants, etc. Power plants are the most apparent source of air pollution. In the UK, coal was the foremost source for generating electrical power until the late 1980s. Coal-fired power stations released a considerable amount of carbon dioxide. Greenhouse gas is responsible for global warming, in addition to sulphur dioxide, an acid gas that harms human health and plants [3].

In recent years, measures to combat air pollution have been taken everywhere, which has increased air purity in many cities (London, Moscow, Dubai, etc.). In the UK, emissions from power stations have been lowered by utilizing cleaner systems of generating units together with the use of flue gas desulphurization and low sulphur fuels. In Moscow, this was achieved through the gasification of boilers, the use of dust catchers, and many other methods. Hygiene standards may, in some cases, allow for some assessment and link to the permissible degree of air pollution in terms of the reliable operation of electrical devices.
The state of electrical energy production from the generation stage to distribution is economically accomplished by overhead lines [4]. The high-voltage of the transmission line system connects the power stations and the centres of the loads. Therefore, any disconnection within this network may hinder the process of feeding the loads. Power quality, availability, efficiency and continuity are the main characteristics of a reliable power system. The power network employs a string of insulators between the overhead line and pole or tower. Therefore, the overhead line insulators influence the reliability of the system [5].

As the electrical power demand has been increased, electrical transmission companies have improved the transmission efficiency of overhead lines. The power network efficiency is primarily established on the continuity of the supply. One of the main problems that stand against continuity is the failure of insulators as a result of the polluted environment. Environmental pollution is considered the leading reason for flashover in insulators. When the pollutants in the air sit down on the insulator, the insulator starts to fail [6].

The combination of the humidity and contaminants set up a conductive layer to allow for short circuit currents quickly passing due to the reduction of the insulator resistance. Outdoor insulators are polluted not only by natural contaminations, e.g. acid rain and gases of sulphuric and nitric oxide, but industrial pollution alike, e.g., manufacturing dust, and sea salt. Therefore, it can be concluded that with severely polluted zones and at continuous operating voltage, the conductivity of insulators initiates dry band arcing evolution and ultimately leads to flashover [7].

Insulators are suffered from flashover resulting from the combined efforts of atmospheric and moisture pollution. Insulators of the desert and coastal areas as in the Middle East regions become damp partially or entirely. The contamination layer turns into a dangerous conductive material, primarily when pollutants are gathered after a period of rain, haze, and fog. The insulator with a conductive layer can prompt an external leakage current to flow on the surface. As a result, the conducting layer becomes smashable. The non-uniformity of the body at spots of high current density causes a discontinuing of leakage flowing. Accordingly, a form of dry-band arcing accompanied by a high dielectric stress breakdown happens as the voltage across the insulator becomes highly concentrated. Therefore, when the properties of the insulation are sufficiently low, the dry-band arcs can be diffused to bridge the transmission line terminals and producing flashover [2, 6].

The choice of insulators for transmission lines is made during the development of the power line project. The correct choice of insulation elements depends on the reliability of the electricity supply, the safety of people, the life span of power lines. The choice of insulators for overhead lines is made based on calculations on the main technical characteristics: The length of the leak path or the distance between the leading elements on the surface of the insulator, destructive mechanical force and destructive electromechanical force. Essential Points should be taken into consideration when designing insulators: climatic conditions of the area (minimum and maximum temperature, humidity, wind speed and other factors), air pollution, nominal electric parameters of transmission lines, the type and material of the supporting structures (supports), and possible mechanical loads [8].

The flashover of an insulator under polluted conditions happens when the contaminant on the surface of the insulator turns wet, and the resistivity becomes low. This fact explains the reason behind the flashover voltage of contaminated insulators to be governed by the type and quantity of accumulated pollution [9]. Consequently, the amount of contamination incorporation with the chemical analysis of the natural resources is essential from the standpoint of maintenance and design of insulators. The flashover of contaminated insulators in pollution zones has attested to be one of the most important factors influencing the extra and ultra-high voltage overhead line insulation. It is not surprising, therefore, that most of the investigation in this field is mainly experimental. Tests of polluted insulators can nearly be classified as natural and artificial categories [10].

Even though the natural tests are vital as they reflect actual working conditions, the drawbacks of such tests are the high cost of performance and time consuming of accumulating adequate data. In the tests, the insulators are encountered in extreme climatic situations in areas with contamination and are
undergone with maximum operating voltage. The performance of the insulator is determined by the incidence of flashovers and by measuring leakage surges.

On the other hand, in artificial tests, a non-natural coating of pollutants, liquid or solid, is covered to the insulator surface. Artificial contamination tests differ from actual service conditions, though they consume less time than natural tests in having numerical flashover data. Many methods can be applied, for example, wetting of insulators and submission of test voltages [11].

The current study has been tackled to examine the performance of insulators under artificially contaminated conditions after that under natural fog conditions. The study also investigated the measurement of the flashover voltage of contaminated insulators under the two mentioned conditions. The quantity of contaminant (degree of pollution) represented by equivalent salt deposit density (ESDD) has been studied and reported.

When selecting insulators for power transmission lines, it is necessary to take into account the material from which the insulators are made. These devices are commonly made of porcelain, glass and polymeric materials.

- Porcelain insulators. The electrical and mechanical characteristics of this material do not change. Porcelain is resistant to chemical effects, superficial discharges. The disadvantages of this material include fragility and considerable weight. The integrity of porcelain insulation elements must be checked periodically to evade the effects of destruction.
- Glass insulators. Tempered glass is distinguished by high dielectric strength, relatively low cost, resistance to chemical aggressive substances, high humidity. The main drawback of this material is fragility. An external inspection is enough to check the integrity of the glass insulator.
- Polymeric materials. The gradual deterioration of characteristics under the influence of ultraviolet light, surface discharges and other external conditions limit polymeric material usage. The advantages of this material include low price, low weight, low dielectric losses.

2. Methods of reducing insulator contamination
The importance of the cleaning of the high voltage insulator is to save the system reliability and keep the insulators functional for a long time. Therefore, no matter which equipment will be used during the cleaning process, the power network continues of function normally [12, 13].

2.1. Automatic washing system:
This type of cleaning is used in substations where the insulators are washed with water automatically whenever the degree of pollution increases. However, these systems require regular maintenance; most of them consume a large amount of salt-free water. This method has a significant obstacle in some countries, like Oman, with few freshwater resources.

2.2. Increasing the leakage distance to prevent the flashover:
The leakage distance increases by increasing the number of units. Therefore, the flashover voltage reduces. However, this method has several drawbacks, e.g., the polluted area and the impulse flashover voltages increase. The method also leads to an increase in the overvoltages at substations.

2.3. Replacement of porcelain material insulators with non-ceramic units:
The non-ceramic material has better performance against the contamination conditions. This datum proves that non-ceramic insulator has long term pollution problems.

2.4. Covering with Grease:
Generally, the grease has water-repellent property, but shortly it becomes saturated with soil, especially in desert climate conditions. Therefore, this method needs frequent replacement, and eventually, it will cost money and time.
2.5. Periodic cleaning:
The drawback of this method is the cost. However, it is an active and very successful method as the life span increases. This, in turn, will increase the reliability and profitability of the whole system.

3. Implementation of the test
The rapid development of the economy accompanied by a great industrial revolution of the Sultanate of Oman has improved the quality of living standards which in turn has led to colossal air pollution. The pollution of transportation, plants of energy production, and industrial sectors are the source of pollution in most Omani coastal areas. The concentration of the population in these areas is the second major problem. Therefore, the combination of intense population, expanding the industrial areas and adverse natural environments aggravate air pollution complications. The northern city of Sohar can be taken as an example of sulphur dioxide air pollution [14]. As the issue of contamination is essential, the experiment was conducted in Oman.

![Image](image1)
![Image](image2)

**Figure 1:** Distribution transformer with its insulators contaminated.

**Figure 2:** Insulators in air polluted.

3.1 Desert Contaminant
In order to investigate the influence of desert contaminant (NaCl+CaSO4+KCl+CaO) and other factors on the performance of suspension insulators, artificial pollution testing is carried out, and desert contaminant is prepared for four solutions of different concentration levels. The following salt combinations have been used to contaminate the insulators artificially for experimentation [15].

Sodium chloride (NaCl) + Calcium Sulphate (CaSO4) + potassium chloride (KCl) + Calcium Oxide (CaO). This mixture was resolved in a litre of water.

Four different solutions of desert contaminants are prepared as follows:

i. Salt concentration-1 was prepared with (33.5 gm of NaCl + 50 gm of CasO4 + 33.5gm of KCl + 112gm of CaO).

ii. Salt Concentration-2 was prepared with (28 gm of NaCl+28 gm of CaSO4 + 28 gm of KCl+93 gm of CaO).

iii. Salt Concentration-3 was prepared with (21 gm of NaCl+31 gm of CaSO4 + 21 gm of KCl+70 gm of CaO).

iv. Salt Concentration-4 was prepared with (17 gm of NaCl+25.0 gm of CasO4+ 17 gm of KCL+560 gm of CaO).
4. POWER SUPPLY SYSTEM

4.1 Measuring System for Experimental Setup:
The tests were implemented using the suspension type insulators 11kV, which are widely used in the overhead transmission system in Oman and neighbouring countries. For a standard porcelain insulator, the total leakage distance is 365 mm, and the unit diameter is 420 mm. For standard glass insulator, the total leakage distance is 310 mm, and the unit diameter is 400mm [16].

![Figure 3: Porcelain suspension insulator](image)

![Figure 4: Polluted suspension insulator](image)

4.2 Power Supply and Measurement of High Voltage
Testing single-phase transformer of 150 kV, 50 Hz, 30 kVA was set up to produce a high voltage across a glass insulator under the testing condition as shown in fig 1. The voltages were recorded from the primary side of the transformer by using a voltmeter (fluke-accuracy 3%) to read the low voltage side. The value of the protective resistance is 10 KΩ.

![Figure 5. Test circuit diagram for multi-unit insulators with increased power frequency voltage.](image)

By using the sphere-sphere electrode arrangement taking a diameter of 25 cm to simulate the air breakdown high voltage, and after calibrating the curve, the corresponding high voltages were obtained [17].
4.3 Pre-treatment of specimen insulator

The surface of the insulator was cleaned carefully with a detergent to eradicate repellence. Pre-treated insulators were completely polluted by dipping the insulator in salt solution of specific contaminant for two hours in each solution for one day. The insulators were in the sunlight to dry until a layer of contaminated material was clear formed on the surface [10].

4.4 Flashover Test

The suspension insulator in this test was hung vertically and earthed. It was observed that no other earthed item was closer to the insulator string axis. The AC high voltage gained from the single-phase testing transformer was exploited across the specimen insulator and stepped up until the flashover happened to enable recorded dry power. With the assistance of the calibration curve, the voltage was taken from a low voltage side employing a fluke and transformed to its secondary side. After the test is completed, the insulator was left overnight in open-air to be dampened by fog and dew. In the morning, the measurement of the flashover voltage of natural fog conditions was carried out as described in the preceding section [11].

4.5 Measurement of pollution severity on an insulator Surface

Contamination severity was measured concerning equivalent salt deposit density (ESDD). Vacuum flasks were employed to collect the contaminated samples. The samples were taken by eradicating the sediments on the insulator surface by a brush and repetitively cleaning the brush with distilled water. The conductivity of this solution was measured with a conductivity meter [6, 13]. The expression for ESDD can be derived from:

\[
ESDD = \frac{\sigma V}{\sigma_{eq} A}
\]  

Where,
- \(\sigma\) = conductivity of wash water, \(\mu S/cm\)
- \(V\) = Volume of the distilled wash water (L)
- \(\sigma_{eq}\) = Equivalent conductance of a standard solution of one gm of NaCl in 1L of water, [1820 \(\mu S/cm\) per g/L at 20°C]
- \(A\) = Surface area wiped, \(m^2\) [13].

The concentration of the above contaminant was varied to have different salt density levels. The flashover test for each new value of ESDD was done by following the above procedure. Flashover voltages for four different values of ESDD were measured and tabulated as in Table-1 and 2 for a dry condition and Table-3 and 4 for Natural fog condition. The experimental graphical results are demonstrated in Figure 6 and 7 for dry conditions and Figures 8 and 9 for natural fog conditions.

5. Experimental results

5.1 Experimental Results in Tabular Form
Table 1. Experimental results of porcelain insulator

| ESDD (mg/cm²) | DRY CONDITION | Porcelain Insulator |
|---------------|---------------|---------------------|
|               | Flashover Voltage Peak (kV) | Flashover Time (Sec) | Temperature C |
| 1.9231        | 111.2         | 30                  | 28           |
| 1.711         | 112.5         | 30                  | 28           |
| 1.6312        | 113.88        | 33                  | 28           |
| 1.3706        | 115.2         | 32                  | 28           |

Figure 6: Porcelain Insulator ESDD vs FOV (Dry Condition Test)

Table 2. Experimental results of Glass insulator

| ESDD (mg/cm²) | DRY CONDITION | Glass Insulator |
|---------------|---------------|-----------------|
|               | Flashover Voltage Peak (kV) | Flashover Time (Sec) | Temperature C |
| 1.732         | 95.25         | 31               | 28           |
| 1.549         | 98.28         | 31               | 28           |
| 1.321         | 100.57        | 32               | 28           |
| 1.095         | 102.98        | 30               | 28           |

Figure 7: Glass Insulator ESDD vs FOV (Dry Condition Test)

Table 3. Experimental results of porcelain insulator

| ESDD (mg/cm²) | NATURAL FOG CONDITION | Porcelain Insulator |
|---------------|-----------------------|---------------------|
|               | Flashover Voltage Peak (kV) | Flashover Time (Sec) | Temperature C |
| 1.9231        | 30.5                  | 7                   | 19           |
| 1.7531        | 31.5                  | 7                   | 19           |
| 1.6312        | 32.5                  | 10                  | 19           |
| 1.3706        | 33.2                  | 13                  | 19           |

Figure 8: Porcelain Insulator ESDD vs FOV (Fog Condition Test)
Table 4. Experimental results of Glass insulator

| ESDD (mg/cm²) | NATURAL FOG CONDITION | Glass Insulator |
|---------------|-----------------------|-----------------|
|               | Flashover voltage     |                |
|               | Peak (kV)             |                 |
|               | Flashover Time (Sec)  |                 |
|               | Temperature (C)       |                 |
| 1.732         | 25.5                  | 31              | 19              |
| 1.549         | 26.3                  | 31              | 19              |
| 1.321         | 28.7                  | 32              | 19              |
| 1.095         | 30                    | 30              | 19              |

Figure 9. Glass Insulator ESDD vs FOV (Fog Condition Test)

6. CONCLUSIONS
The objective of this experiment is to measure the dielectric strength of the suspension-type insulators under dry and wet conditions. There is no direct method yet adopted for treating the contaminations of insulators. Therefore, this study has put an effort to produce a precise mechanism to determine the withstand voltage, flashover and equivalent salt deposit density of desert contaminated insulators under dry and wet conditions. The weather conditions directly impact the development of the pollution levels in the desert and coastal region. The primary air pollutant is the smoke of factories and electrical power plants. Flashover is a discharge of an arc between the conductive parts of an insulator under high voltage. It was noticed that the flashover happened when air breakdown had taken place, and also ionization happened between the connecting parts of the insulator. Therefore, flashover entirely becomes contingent on dielectric strength. At normal conditions, the dry air dielectric strength is 2.1 kV/cm. However, the dielectric strength occurred lower in wet conditions, as the ionization happened at low voltage.

The flashover analyses are completed on the 11 kV porcelain and toughened glass suspension insulators with artificial pollution coatings. The contaminations materials are (a) Desert Salt Pollution-Dry pollution (b) Natural Fog Condition. The contamination layers done are similar to pollutions that occur on the insulators of overhead lines in industrial areas. The experiment has shown that the flashover voltage is higher for polluted insulators than a natural fog insulators. This proves that the amount of leakage current of the dry polluted coating was higher than natural fog coating. As a result, the element of dry contaminating material has a higher conductivity value than the second condition, i.e., wet condition. This also evidences that salt pollution has a strong influence on leakage current than the wet coating. Consequently, environment type plays a crucial role in the design of insulators. From the experiment results and graphs, it can be detected that engineers can predict and plan for the maintenance schedule of the poor performance of the insulators under different effluence conditions.

Based on experimental results and preceding discussion, the following conclusions are made:
1. When the equivalent salt deposit density increases, the AC flashover gradient reduces.
2. From Table 1 and Table 2, it is clear that the flashover voltage decreases with the increase in equivalent salt deposit density (pollution level).
3. From Table 3 and 4, it reveals that in the case of natural fog condition, the flashover voltage of porcelain and toughened glass disc insulator becomes very low.
4. The dry flashover voltage of polluted insulators does not vary much with the degree of pollution, and it is almost equal to the flashover voltage of the clean insulators. This means
contamination alone does not pose a serious problem as long as it is dry.

5. The test has also verified even with 400 mm creepage distance, glass and ceramic type insulators do not have suitable pollution performance; therefore, they must regularly be washed to decrease corruption flashovers.

The future study can be extended to compare the direct-current arc flashover with the current study. The experiment can be applied to cold countries to study the formation of the dry band under the accretion of the snow on the insulators.

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