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Overview the Factors Affecting the Discharge of Contaminated Insulators and Intelligent Change Some of Them to Reduce the Discharge Intensity

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Abstract

In this article, the most important factors affecting the discharge characteristics of high voltage insulators will be investigated. The type and severity of pollution, geographical and climatic conditions such as fog, rain, and wind, as well as the height above sea level, and finally the appearance and constituent materials of insulators will be studied as the main influencing factors in causing flashes on their surface. In addition to its severity, the type of pollution has a great effect on the electrical properties of insulators. This issue is discussed in the first section of the article for common types of pollution with different severities. Furthermore, a mixture of pollutants in the air is also examined, and the insulation waste is also shown in the case of design only based on sea salt, which is the worst type of pollution. In the next part, a review on the influence of climatic and geographical conditions has been performed, and in it, the effect of frost, wind, humidity and altitude on the start of electric discharge is discussed as the most important of them. And finally, the effect of appearance and its associated parameters as well as the constituent materials of insulators in pollution conditions are the last factors that will be considered. In addition, in this study, it has been shown how by intelligently changing these two factors, leakage current and discharge intensity can be reduced in contaminated insulators and their premature aging and failure can be delayed.

Keywords: electrical discharge, pollution, high voltage insulators, climatic conditions, appearance of insulators, field strength
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1. Introduction

The phenomenon of discharge on insulators represents the output of an uncertain process that takes place consecutively and in a certain order. First, a layer of pollution is formed on the surface of the insulator (including coastal salt deposits, soot, fine dust, etc.). This layer becomes a conductive layer either by itself or as a result of moisture, fog, rain or dew and finally, it causes a leakage current to pass and then dry areas on the surface of the insulator. This current and voltage causes the initiation of small arcs that develop gradually and lead to the surface discharge phenomenon. This surface discharge ends with the failure of the insulator and endangering the transmission line [1-8]. Therefore, one of the important parameters in an insulator is its stability against the phenomenon of discharge in the environment in which it is installed, in other words, the insulators must be suitable for the atmospheric conditions and pollution of the area in question for their installation.

Each type of pollutant has a different and specific effect on the discharge start voltage, and this voltage changes with the change of pollutant type [9-16]. The height of each region from the sea level [17-18] and weather conditions such as rain, fog [19-21], ice and snow [22-26] and even the intensity and direction of the wind [27-31] are also factors affecting surface discharge performance on insulators. Also, the materials used [32-43] and even the appearance of the insulator [43-48] are also effective on the flash initiation voltage. Among the aforementioned factors, the type and severity of pollution and atmospheric conditions, as discussed, have the greatest and most influencing effect on the discharge performance of insulators, and therefore must be specifically and accurately analyzed for each area separately. Under the conditions of rain, fog and humidity, various pollutants are dissolved in water and form a conductive channel. The leakage current is driven by the field in this channel and the power loss on the insulator increases [49]. Therefore, the distribution of the field, potential and leakage current on the surface of the insulator is also very important, and in this article, a review of these subjects has been done in the various conditions mentioned above.

2. Effect of the type of pollutants on the surface discharge voltage and the optimal design of the chain of insulators

With economic development, industrial pollution and air pollution has become a serious problem and this issue has caused the accumulation of pollutants on the surface of transmission line insulators (more than before). In general, flashing on the surface of dry contaminated insulators is very rare, on the contrary, in conditions of fog, dew, light rain and snow, the surface of contaminated insulators becomes wet and may cause flashing on the surface of the insulator at a lower voltage [50]. Currently, ESSD (Equivalent Salt Deposit Density) is used as a characteristic of the intensity of pollution of insulators of power transmission equipment. And because real pollution is caused by mixed salt, which is a combination of NaCl and CaSo4 and on the other hand, the measurement of ESDD is based on the measurement of the conductivity of the contaminating solution, which is also obtained by deionized solution of 300 ml of water that is washed from the surface of the insulator and therefore, it does not accurately include the content of CaSo4, which is hardly soluble in water, so it cannot properly reflect the electrical properties of the contaminated insulator. Therefore, in this article, the results of the test which have been performed by the immersion method is also considered to study the electrical properties of insulators that are affected by various pollutants.

A) Testing Specimens, arrangements and test method

The specimens were selected from three types of insulators named A, B and C [51]. The various parameters of these insulators have been shown in the table below. H represents height, L leakage distance, D is the shell diameter in mm, and SIR stands for Silicon rubber.

Table.1.
Parameters of isolators

Type	***Material***	***H***	***D***	***L***
Type A: XP4-160	Ceramic	155	300	400
Type B: LXY4-160	Glass	146	280	400
Type C: FXBW-35/100	SIR	600	150/90	1370

Experiments were carried out in an artificial environment simulation chamber with dimensions of (height 11.6 and diameter 7.8 meters). A transformer YDTW2000 kvA/500 kv selected according to IEC standard (60507) was used for the energy source of the test. The test was carried out according to the IEC60507 standard method. According to this method, the polluting liquid was prepared from kaolin solution and some salt. Then the specimens are contaminated by immersion method and dried for 24 hours. Three specimens are randomly selected to measure ESDD and NSDD (Non-Soluble Deposit Density). In these tests, the (up & down) method was used to measure the 50% withstand voltage (U50) and according to IEC64507 (1991), more than ten acceptable tests were performed on the samples in a pollution intensity. With the above method, 50% of the flash voltage is obtained from the following formula.

$$U_{50} = \sum (n_i\, u_i)/N \quad (1)$$

$$\sigma = \sqrt{\left(\sum_{i=1}^{N} (U_i - U_{50})^2/N\text{-}1\right)}\;/U_{50} \times 100\% \quad (2)$$

Where U_{50} denotes the 50% flash voltage in kv, Ui is the specified applied voltage in kv, n_i is the number of tests with the same applied voltage, N is the total number of acceptable tests and σ represents the relative standard deviation of the tests.

B) Results and analysis of tests

Flashover voltage gradient is a parameter expressing the maximum voltage tolerated by the unit leakage distance and it can be shown as below.

$$E_L = U_{50}/L^* \quad (3)$$

Where L^* is the total leakage distance of the insulator chain in meters and EL is the gradient factor in kv/m. For sample pollution (NaCl, CaSo4), the results of AC flash voltage test have been shown in figures (1) and (2). The test results show a standard deviation of less than 6% and the NSDD was controlled close to 0.1 mg/cm2 during the test. The empirical formula for predicting the flash over voltage obtained from the results of previous experiments with artificial pollution is as follows.

$$U_{50} = A \times ESDD^{-b} \quad (4)$$

Table.2.
Coefficients of relation (4) for different insulators

Constituents	***Insulator types***	***a***	***b***
NaCl	Type A	15.1	0.33
	Type B	15.5	0.34
	Type C	23.3	0.24
$CaSo_4$	Type A	37.1	0.14
	Type B	37.7	0.20
	Type C	63.7	0.17

The constant A represents the type and structure of the insulator and b depends on the type of pollution. By merging the above two relationships, the following relationship is obtained.

$$E_L = U_{50}/L^* = a \times ESDD^{-b} \quad (5)$$

The results of the experiments also confirm the above relationships and also the obtained curves give the following results.

- Insulators with different materials show different flashover voltage gradients. This gradient is maximum for type C and is lower for type A than type B.
- The voltage gradient shows a decrease with increasing ESDD for both types of pollution. The exponential number b for CaSo4 shows about (0.14-0.2) and for NaCl about (0.24-0.34).
- In the equal amount of ESDD, the CaSo4 contaminant provides a much higher voltage gradient than the NaCl contaminant, and this problem is more obvious for the C-type insulator.

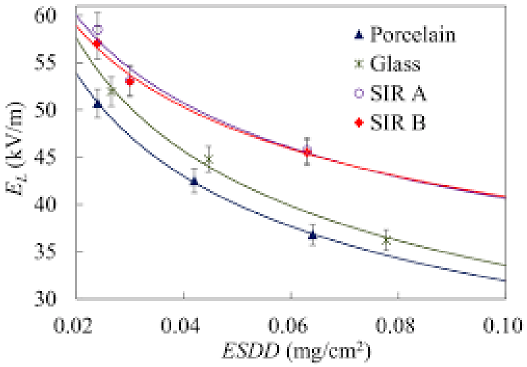

Fig. 1. Relationship between E_L and ESDD with NaCl pollution

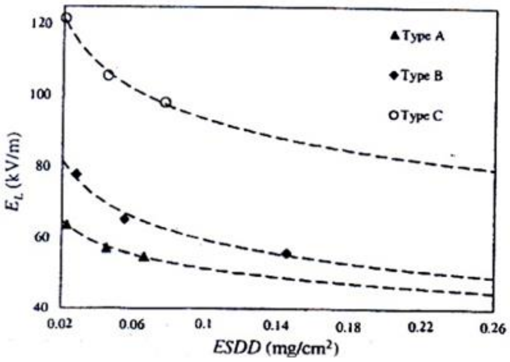

Fig. 2. Relationship between EL and ESDD with CaSo4 contamination

C) Results and analysis for multi-pollutant mixed pollution

External environmental pollution on transmission lines and their insulators is actually composed of several pollutants. The results of tests on CaSo4 and NaCl pollution can only be used as a reference for the design of insulators that can be installed in open space. However, currently, only the results obtained from the tests of insulators contaminated with NaCl are selected as a reference for design, and in this way, a large number of insulators are wasted. The pollution related to the points near the highways outside the cities and farms is composed of pollutions with the following percentages according to the conducted research. CaSo4=57.7%, NaCl=13.1%, KNO3=9%, NaNo3=8.7%, NH4No3=6.4% and MgSo4=3.7%. The mentioned values are the weight percentage of each pollutant. The results of the flash over voltage (AC) tests on the insulators with the above mixed pollution can be seen in Figure No. (3). Figure number (4) shows the comparison between the flash over voltage of type C insulator under simple and mixed pollution.

The following conclusions are obtained from the results of figures (4) and (3).

- Under mixed pollution, the difference between flash over voltage gradients for three types of insulators is almost the same as their values under simple contamination of NaCl and CaSo4.
- The flash over voltage gradient for compound contamination for all types of insulators is placed between the gradients obtained for NaCl and CaSo4 contaminations. For example, figure number (4) clearly states this issue for the C-type insulator.

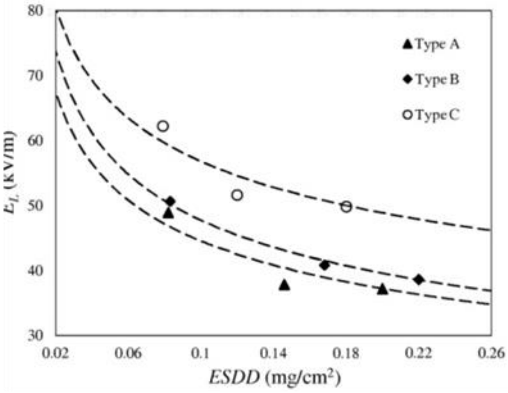

Fig. 3. Relationship between EL and ESDD with mixed pollution

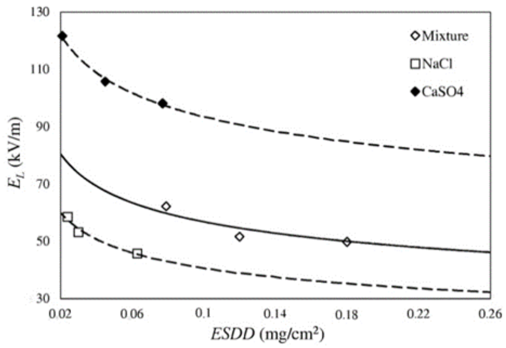

Fig. 4. Relationship between EL and ESDD under different pollution conditions for type C insulator

D) Pollution withstand voltage

According to this method, the pollution withstand voltage must be greater than the operating voltage for each phase under any condition. The pollution withstands voltage and the number of insulators in the chain follow the following relationships.

$$U_W = \frac{K_2 N U_{50}(1-3\sigma)K_3}{K_1} \text{ and } \frac{U_m}{\sqrt{3}} = U_W \quad (6)$$

$$N = \frac{K_1 U_m}{K_2.\sqrt{3}U_{50}(1-3\sigma).K_3} \quad (7)$$

Where, Um is the nominal operating voltage of the power system in kv, σ is the relative standard deviation of the test, k1 is the safety margin coefficient, k2 is the pollution correction coefficient for its non-uniformity, and k3 is the difference in flash over probabilities in single-chain and multi-chain insulators. The total insulation distance required is obtained from the following equation.

$$L = \frac{K_1 U_m}{K_2.\sqrt{3}E_L(1-3\sigma).K_3} \quad (8)$$

E) Insulation waste

Most of the time, NaCl is used as the main pollution of insulators in pollution tests. While this issue causes us to reach a lower flash over voltage under the above pollution conditions. Therefore, the experimental results may cause insulation waste compared to the actual conditions of mixed pollution, and in these conditions, the insulation waste coefficient is obtained from the following formula.

$$W = (1 - L_N/L_D) \times 100 \quad (9)$$

Where L_N is the actual distance required for flashing based on tests related to a mixture of pollutants and L_D is the same distance for flashing based on NaCl contamination.

Also, the insulation waste coefficient in the above two cases can be calculated from the following formula.

$$W = (1 - E_{LD}/E_{LN}) \quad (10)$$

E_{LN}: flash over voltage gradient under natural mixed pollution and E_{LD} is the same gradient considering NaCl pollution. But the design of insulators based on $CaSo_4$ pollution, on the contrary of NaCl, leads us to an insufficient amount of insulation. As can be seen in figure (5), if the design is based on real natural (mixed) pollution at the same time that the waste of resources and cost is avoided, we also achieve a sufficient insulation.

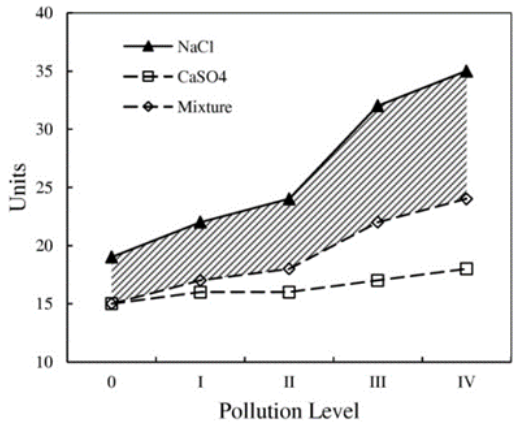

Fig. 5. Number of XP4-160 insulator units on a 500 kv line

F) Summary

- For the same value of ESDD. The flash over voltage gradient for CaSo4 is much higher than this gradient for NaCl. (Especially for composite insulators). Also, the characteristics factor b for Caso4 pollutant is lower than NaCl.
- The characteristic factor b for ceramic, glass, and composite insulators under mixed pollution conditions is 0.26, 0.27, and 0.22, respectively, all of which are lower than when only NaCl pollution is considered. The traditional design method exaggerates the role of ESDD in flash performance (surface discharge).
- Insulation waste occurs considering only NaCl and this waste increases as the severity of pollution increases (Figure 5). Therefore,

according to the obtained results, the electrical properties of the insulator under the conditions of mixed pollution, should be considered for design.

- The coefficient of insulation waste for composite insulators in light pollution is more than the two types of porcelain and glass, and it is less than the two others under heavy pollution.
- When the "withstand voltage under contaminated conditions" method is used to design outdoor insulators. Discharge performance should be considered under actual pollution conditions and insulation leakage distance (number of insulating units in a chain) should be considered based on mixed pollution.

3. The effect of climatic and geographical conditions on the discharge voltage (in pollution conditions) [52]

A) Air pressure and its relationship with flash over voltage on the surface of contaminated insulators [53 and 54]

Many researchers believe that the flash over voltage (surface discharge) for contaminated insulators decreases with decreasing air pressure (increasing height) and the relationship between flash over voltage and air pressure is a non-linear relationship that is expressed as follows.

$$U = U_0 (P/P_0)^n \tag{11}$$

Where U0 is the flash over voltage, of insulators with pollution, in normal atmospheric pressure conditions (P0) and n is an exponential number that expresses the effect of air pressure on flash over voltage under pollution conditions. Different researchers have found different values for n based on the results of their experiments.

The results of the tests show that the value of n depends on the materials used in the insulator composition, its appearance, the type of voltage, the intensity of pollution, etc. So far, the experiments have been conducted to study the flash over voltage under the conditions of pollution with artificial pollution (in the laboratory) and under standard atmospheric pressure. To what extent the above results are consistent with the field results (under natural pollution conditions) for different atmospheric pressure conditions have not been studied much. Maybe this study can be considered an effort in this regard. Various tests have been performed on insulators of different types and with pollution of different intensities, the results of which can be seen in Figure (6).

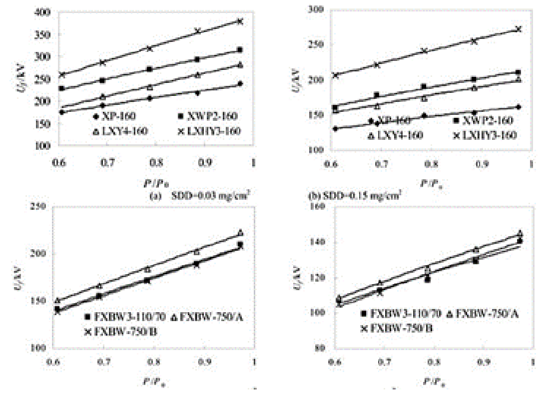

Fig. 6. Relationship between Uf and (P/P0) for contaminated insulators

B) Analysis of the results

- With decreasing atmospheric pressure and increasing SDD (Salt Deposit Density), flash over voltage decreases (under pollution conditions).
- With the increase of SDD, the influence of atmospheric pressure on the a.c. voltage becomes weaker.
- The following results were obtained for insulators of different types with different SDDs and putting the test results in formula (11).
- The value of n depends on the materials and construction of the insulators and the intensity of pollution, and varies between 0.45-0.85 for a.c voltage.
- The effect of atmospheric pressure on flashover voltage under pollution conditions is lower for porcelain insulators compared to other types (the test was performed on XP-160 porcelain insulator)
- If we call the ratio of the flashover voltage under pollution conditions (U_f) to the creepage distance of the insulator (L) as creepage flashover gradient (under pollution), the value of (U_f/L) for different insulators changes as follows.
- Under equal conditions in terms of pollution intensity and air pressure, the above ratios for composite insulators are more than porcelain and glass ones.
- The effect of air pressure on the "Creepage flash over gradient" in the case of composite insulators is greater than that of porcelain and glass insulators.

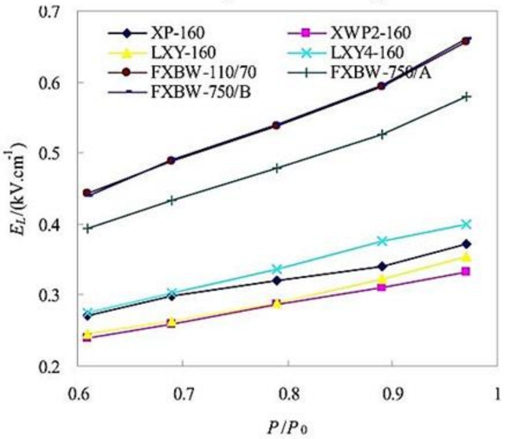

Fig. 7. Creepage flash voltage over gradient for different types of insulators (SDD=0.3 mg/cm2)

C) The effect of wind and its direction on discharge of insulators under pollution conditions

When regular wind blows from one side, leeward side of insulators may be more affected by pollution than their windward side. This creates a layer of pollution similar to an electric fan on the surface of the insulator. To investigate the above phenomenon and show the effect of wind in a study, seven Xp-70 type insulators with irregular pollution in the form of a fan have been tested. The results of the tests show that the ratio (W/L) which is the ratio of salt deposit density (pollution) on the container facing the wind to the leeward side has an effect on the discharge voltage of the insulator or chain of insulators. So that the change of the above ratio from $\frac{1}{1}$ to $\frac{1}{15}$ reduces discharge intensity by about 28%. If we call the occupation area ratio T and this ratio increases from 10% to 30%, the discharge start voltage will also decrease in the same ratio.

D) Effect of freezing on discharge voltage in the contaminated insulators

Freezing of insulators in pollution conditions is one of the constant debates in power systems. Several experiments have been conducted to determine the effect of permanent room temperature vulcanized (PRTV) waterproof cover on the electrical properties and flashover voltage of insulators in the freezing state. But contrary to expectations, the results show that the above coatings have no effect on preventing the insulators from freezing, and on the contrary, they help to accumulate ice on it. Also, based on these tests, the (PRTV) waterproof cover even lowers the discharge start voltage by ten percent. Since freezing is one of the most common phenomena in transmission lines and especially on insulators, and this category needs a separate and detailed investigation, in this review, the search for its details is omitted. However, the relevant references are mentioned at the end of the article.

E) Study of the effect of humidity on electrical discharge and leakage current of contaminated insulators

Surface discharge caused by air pollution is a serious threat to the safe and reliable operation of power systems. The discharge voltage due to pollution directly depends on the moisture level of the contaminated layer. In a study, the moisture process of the contaminated layer on all kinds of insulators has been investigated. The results of the tests show that the wetting process of the contaminated layer on the insulators can be clearly seen by changing the leakage current, and when the contaminated layer's moisture is saturated, the leakage current reaches its maximum value.

F) The effect of the appearance of the insulators on their electrical discharge under pollution conditions

In the condition of the same pollution (in terms of type and intensity), the leakage current and the intensity of the field and consequently the discharge voltage are different in insulators with different appearances [55], the reason can be briefly described as if the surface resistance of the polluting surface is assumed as Rt [56] then:

$$R_t = \frac{1}{\pi D_{eq}\sigma} \tag{12}$$

Where, Deq is the equivalent diameter of the contaminated insulator and σ represents the conductivity coefficient of the polluting substance. The equivalent diameter in centimetres is also obtained from the following equation:

$$D_{eq} = \frac{L}{\pi f} \tag{13}$$

f, which is called the form factor, is equal to: [20]

$$f = \int_0^L \frac{dl}{\pi D(l)} \tag{14}$$

where $D(l)$ represents the diameter of the insulator as a function of the location chosen on the insulator. Different insulator samples have different values of D(l), f and L. (leakage distance). Using the above theory and its expansion, Young et al. [41] in an article have studied the effect of the appearance of insulators and their electrical characteristics in detail and have calculated the leakage current and field for a type of polymeric insulator. The effect of the appearance of the insulators on their electrical characteristics can be seen in the figures below, which were obtained from the application of the

Comsol software and its outputs for two types of design of the appearance of a polymeric insulator.

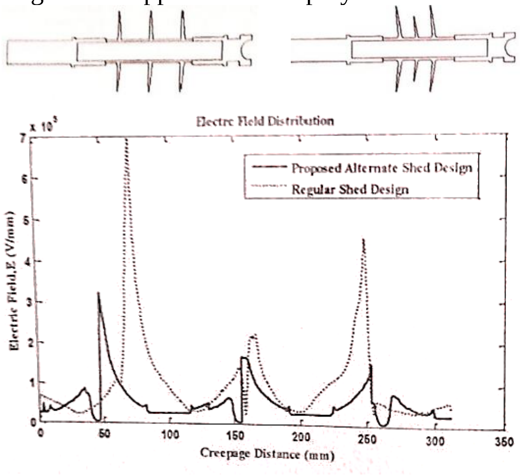

Fig. 8. The effect of the appearance of insulators on their electrical characteristics

The optimization method is based on combining Finite Elements Method (FEM) and Swarm Particle Optimization (PSO) algorithms as shown in Fig.9 [46]

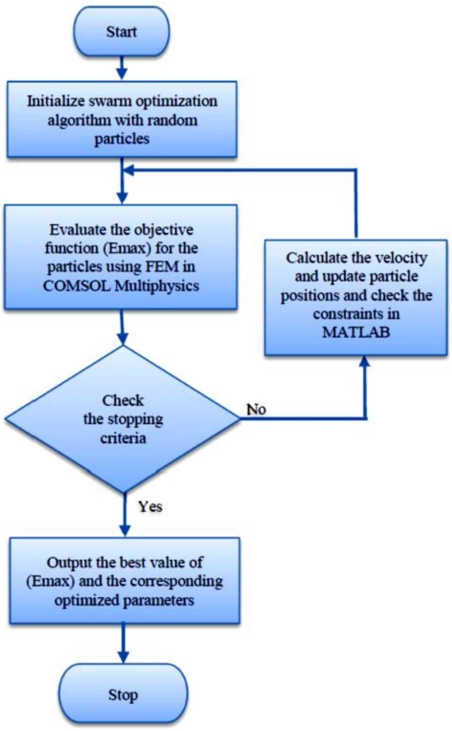

Fig. 9. Flowchart of proposed technique for composite insulator profile design

5. Effect of materials used in the construction of contaminated insulators to electrical properties

As the main materials of insulators are glass, porcelain and polymer, a review of the materials and their constituent elements is necessary. The variation of field and potential on their surface in pollution conditions, which plays a fundamental role in their discharge function, should also be investigated. In order to obtain the variation trends of the above two quantities along the creepage distance of the insulator, the finite element method and the software based on it (COMSOL) are usually used In next section, the common materials which are used in insulators and the characteristics of discharge at their surface are discussed

Glass compounds are obtained by melting the following materials at 1400 0C: Silica (Sio2) at seventy percent, Caustic Soda (Na2o) at eight to seventeen percent, lime and magnesium (Cao + Mgo) at seven to twenty two percent.

The transparency of the glass has the advantage that if there is a defect in the insulator, it can be easily detected with normal or polarized light. However, if there is a hole or a crack in the porcelain insulators, it cannot be easily detected. Another advantage of glass insulator is that they are cheap.

Another advantage of glass insulator compared to porcelain insulators is their higher tensile strength (35000 kg/cm2) and because of the natural transparency, they do not heat up in front of the sunlight, and the lack of purity and air bubbles are visible in the glass. Another advantage of glass compared to porcelain is its durability, and in other words, it ages late, and finally, the dielectric strength of glass is much higher than that of porcelain.

One of the disadvantages of glass insulators is the easy condensation of moisture on the surface of the glass and then the absorption of dust and suspended particles, which leads to the creation of a path for the leakage current. Another defect of them is the lack of irregular plasticity.

Porcelain is one of the most common materials used to isolate power transmission lines. The main component of it is aluminium silicate, which is mixed with clay, feldspar, alumina, and quartz, and it is finally cooled and its surface becomes shiny to the extent that water does not collect on its surface. As much as possible, this material should be free of air bubbles (porosity) because the presence of pores and air gaps leads to the degradation of the material's dielectric level. Also, its impurity should be negligible.

To increase the mechanical resistance of porcelain, the percentage of quartz used in it should be increased, and the percentage of clay should be increased in order to be less sensitive to temperature changes. The tensile mechanical strength of this material is about 500 kg/cm2 and its dielectric strength is about 60 kV/cm. Among the disadvantages of this type of insulator, we can point out their vulnerability to shock voltage waves, which are punctured even before a flash occurs on their outer surface, especially if the defect is invisible and permanent. The ratio of the voltage required for piercing to the voltage required to create a flash on the outer surface of the insulator is called the safety factor of this type of insulator.

Polymeric insulators usually consist of two parts. A rod-shaped body part made of fiberglass reinforced with epoxy resin, and the other part of the umbrella-like shells, which are usually made of soft silicon material or ethylene propylene diene monomer (EPDM) and protects the insulator body from the surrounding environment. Because the combination of these two parts are the main materials that make up the insulator, such insulators are also called composite. The rod-shaped body is reinforced on both sides by means of two terminals made of galvanized steel. The advantages and disadvantages of these insulators are as follows:

- Compared to glass and porcelain insulators, they are very light.
- Due to their flexibility, the probability of breaking is very low.
- Their installation cost is much less due to their lightness and portability.
- Higher tensile strength in comparison with porcelain insulators.
- Better performance in areas with contaminated air.
- Due to the lower weight, less load is applied to the supporting structures.
- Due to the waterproof nature of the insulator, there is less need to clean its surface.
- The disadvantages of such insulators can be summarized as follows:
- If there is any unusual distance between the rod-shaped body and the umberellas, moisture will enter the insulator body and may cause electrical failure of the insulator.
- Shrinkage at both ends of the terminals may cause cracking of the body and lead to mechanical failure.

Polymer insulating materials with very good electrical properties are widely used in power equipment. But when these materials are subjected to a partial discharge, they degrade in terms of electrical properties. This degradation of the insulation level varies in different polymer materials, whose resistance to partial discharge is different. In a study, the degradation of insulating properties caused by partial discharge has been compared for four types of polymer materials. These four materials are: P.P (Poly Propylene), PET (Poly Ethylene Terephthalate), PES (Poly Ether Sulphone) and LDPE (Low Density Poly Ethylene). Degradation of insulating properties of the above materials due to partial discharge was measured and their grading was done based on resistance to partial discharge.

Therefore, the research of four types of polymers based on their resistance or weakness against partial discharge are respectively [(LDPE), (PP), (PET), (PES)], where PES is the weakest and LDPE is the most resistant. The results obtained from the application of the software (COMSOL) for two types of insulators with different composition materials show that the distribution of the field and potential changes significantly with the change of these materials.

6. Conclusion

Since discharge and the factors affecting it have always been one of the concerns when choosing the right insulator for power transmission lines, this article has reviewed these factors. Based on this investigation, the type and severity of pollution and atmospheric conditions have a primary role in creating flashes on the surface of insulators, therefore more focus has been made on them and they have been evaluated in more detail. By searching the literature in this field, it was found that the most attention is placed on salt pollution in coastal areas, so that, in this review, we tried to review other types of pollution that are more likely to exist in other areas, such as industrial and mountainous areas, especially deserts. Also, a mixture of different types of pollution has been considered. Climatic conditions such as rain and fog have been considered in most of the articles and researches as an influencing factor that causes the dissolution of pollution and then the occurrence of leakage current. On the other hand, air pressure has been evaluated more precisely in this article.

The factor of wind intensity and direction, as well as icing, which are important and effective factors for causing discharge in pollution conditions, have been briefly investigated. However, more studies have been done on them in other reviews and they can independently be the subject of a separate and more detailed research. Finally, the shape and design of the insulator appearance and its constituent materials, which are very important and effective in the occurrence of discharge, have also been discussed, and its effect on the form of the field and potential distribution has also been shown.

In short, the insulation waste in case of improper selection or overdesign of insulators in power equipment, which is shown with a specific example in this research, reveals the need to check and be careful about the aforementioned factors. Furthermore, in present investigation, it has been shown that how the leakage current, electric field and consequently the discharge intensity could be reduced by smart selection of shed parameters and material composition of the insulators. Future works can include optimization of the polymeric materials (among the four types that were suggested in this paper) and the insulators' configuration simultaneously for further reduction of leakage current and discharge intensity.

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