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Improved mathematical model of polluted insulators nonlinear behaviour under ac voltage based on experimental tests

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ABSTRACT

In this paper, an improved mathematical model for flashover behavior of polluted insulators is proposed based on experimental tests. In order to determine the flashover model of polluted insulators, the relationship between conductivity and salinity of solution pollution layer of the insulator is measured. Then, the leakage of current amplitude of four common insulators versus axial, thermal conductivity and arc constants temperature was determined. The experimental tests show that top leakage distance (TLd) to bottom leakage distance (BLd) ratio of insulators has a significant effect on critical voltage and current. Therefore, critical voltage and current were modeled by TLd to BLd ratio Index (M). Also, salinity of solution pollution layer of the insulators has been applied to this model by resistance pollution parameter. On the other hand, arc constants of each insulator in new model have been identified based on experimental results. Finally, a mathematical model is intended for critical voltage against salinity of solution pollution layer of different insulators. This model depends on insulator profile. There is a good agreement between the experimental tests of pollution insulators obtained in the laboratory and values calculated from the mathematical models developed in the present study.

Keywords:*flashover; mathematical model; polluted insulators; salinity*

1. Introduction

Pollution phenomena constitute a serious problem, which must be taken into account in the design and the operation of HV insulating devices, under difficult environmental conditions, a pollution layer is entrusted on the insulator surface and when humidity is present due to frost sediment, fog or rain, a humid conducting layer is formed and a leakage current starts to stream[1-23]. The curtailment of the discharge current leads to the formation of dry tape on the surface which results in arcing. The arcs may intrusively extend among the humid surface, leading to a total flashover[1-18].

Some researchers have done very good work on the problem of polluted flashover. Several models to calculate the flashover of polluted insulators have been proposed[1,3,6-9,12,13]. The expansion of models for the flashover of contaminated insulators which could take into account the real empirical situation is not an easy labor since of the intricacy of the phenomena which can happen[6-14]. However, many efforts have been made to produce models letting one to forecast almost the critical specifications of the contaminated insulators [6]. For this order, the supposition that there is a lone major arc, a uniform contamination distribution and monotone wetting have been made. So, the arc is supposed to move alone on the surface of the insulator. But there is still no consensus as to what amounts of N and n should be used in instance of different polluted atmosphere. In fact, the optimal combination of A and n may be dependent on the chemical nature of the pollutants[16]. The experimental results allowed a great exact evaluation of the discharge constants of the insulator by means of mathematical method. It has been ascertained that the calculated values of the arc constants are autonomous of the insulator kind and the type of pollution[17]. The performance of polluted insulation has been the subject of extensive research and development, and the mechanism of flashover has been elucidated qualitatively. A detailed account of this work is given in[1-6], but the mechanism can be described briefly as follows. notwithstanding the complication of operations evolved in the flashover mechanism, several test and theoretical studies have been assigned to the comprehension of the phenomena leading to flashover of contaminated insulators in order to expansion models letting one to predict the critical voltage and critical current[1-8].

Prevalent feature between all these models is a simple display of an arc promotion arc included of a partial arc in series with the resistance of the cross section of contaminated layer. Often of these models are confined to the static state of the phenomenon and do not include to the dynamic state of some particular parameters of the flashover. In addition to, the few available dynamic models reported in literature[20]. The above discussion manifests that agreement has not been reached on the value of n, the differences of n when AC function, respectively, the relationship between n and degree of pollution, and the relationship between n and pollution level. On the other, often works offered in literature uses communication giving the critical flashover voltage deduced from the Simplified equivalent electrical circuit in[13]. In these relationships, the critical voltage dependent two experimental discharge characteristic constants n and N, the quantities of which is different from one author to another[1-12].

The present work deals with the development of a mathematical model to predict flashover voltage of polluted insulators energized with AC voltages. The objective is to involve the major parameters, namely, profile of the insulator, pollution salinity, the critical current and the environmental conditions such as humidity and temperature. An analytical model letting one to predict the critical voltage, critical current and arc length for contaminated insulators. Also constants arc are dependent insulators profile and type of pollution, given the different insulators profile and different types of pollution, each insulator has its own constant. In this paper, is determined the arc constants using programs written. For each insulator is determined an arc constant in which case the answer to experimental result have many similarities and the results are satisfactory. The experimental results allowed a highly exact estimation of the arc constants of the insulator by using a mathematical method.

Background

Model[12] among the first flash overs models is presented for contaminated insulators. The equivalent circuit model of contaminated insulators composed of two resistance together series one the contaminated layer resistance R_p and a dry bond resistance R_a and supplied by a voltage U (**Figure 1**). Thus, one can display arc voltage V_a:

$$V_a = r_a X I_a \quad (1)$$

$$U = V_a + R_p I_a$$

Where I_a is the creepage current, whereas n and N are the arc constants and R_p is the pollution layer and supplied by a voltage U . R_p indicative comprehensive segment of the contamination layer:

$$R_p = r_p (L - X)$$

Where r_p resistance per unit length and L is the total creepage length of insulator. On the other, the electrical field discharge is E_a. According to [6, 20] is such as:

$$E_a = \frac{V_a}{x} = N I_a^{-n}$$

Where N and n are the arc constants. The values of these constants depend upon the environment (i.e., the experimental conditions) in which the discharge is burning [20].

By integrating relations (1), (2) and (3):

$$U = XNI^{-n} + r_p (L - X) I_a$$

The purpose of scrutiny is development an analytical model that allowing to predict the critical voltage levels.

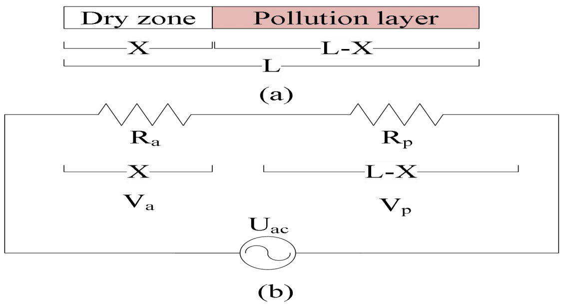


Figure 1, (a), contaminated insulation layer and dry band. (b), Model of discharge according to obenaus.

The critical length, critical current are determined using the following relations [17, 18]:

$$\frac{\partial U}{\partial X} = 0$$

$$\frac{\partial U}{\partial I} = 0$$

Using equations (5), (6) and (7), one can display the critical length of the arc: X_c , the critical current I_c and the critical voltage V_c [1, 6, 8, and 20]:

$$X_c = \frac{L}{n+1}$$

$$I_c = (\frac{N}{r_p})^{\frac{1}{n+1}}$$

$$V_c = LN^{\frac{1}{n+1}} r_p^{\frac{n}{n+1}}$$

Arc propagation can occur when $E_a \rangle E_p$ (E_p is Electrical field contaminated layer) .

The proposed model

3.1 Determine the electrical conductivity and polluted linear resistance

In order to determine the surface conductivity, according to the severity of pollution salinity, experiments have been performed in laboratory nano Chemistry Department babol University of technology. The amount of salt needed after measuring its weight by digital scales in 1000 ml of distilled water dissolved and then by conductivity meter, electrical conductivity of the solution was measured. This experiment were carried out for different amounts of salt in the range [0-100] (g) and 40(g) kaolin were in the range of all kinds of pollution intensity (light, moderate, heavy and very heavy) will be covered. In figure 2 measured values for conductivity in salinity at these experiments is given. Using data obtained and programs written in MATLAB, mathematical linear relationship for conductivity according to pollution salinity is determined:

$$\sigma_p = 1.6 \times S + 30 \tag{11}$$

Where S and σ_p are the salinity in (g/l) and surface conductivity in (μs).

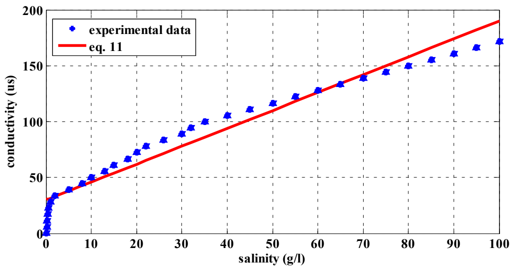


Figure 2: curve fitting experimental data of conductivity

According[8] to the total resistance of the pollution layer, it is defined by the following equation:

$$R_p = \frac{F}{\sigma_p} \tag{12}$$

where F is the form factor of the insulator:

$$F = \int_0^L \frac{dl}{(\pi \times D(l))} \tag{13}$$

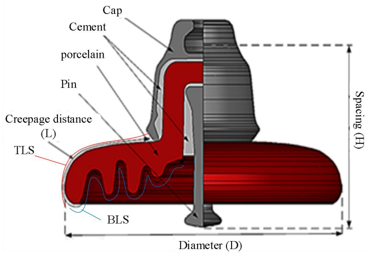
$D(l)$ is the diameter of the insulator, varying across its leakage length L .

Using equations (11) and (12) one can define the linear resistance per unit pollution layer:

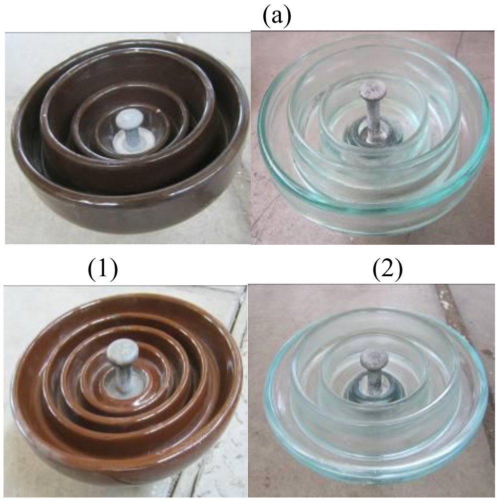
$$r_p = \frac{F}{\sigma_p L} \tag{14}$$

3.2 Investigated insulators and testing of pollution

Different type of insulator is currently used in Iran distribution network. Standard cap & pin glass and porcelain insulators are widely used in most of the old system. Some 4 different types of insulators were investigated for the purposes of this paper. The characteristics and a view of Picture these insulators are presented in Table 1 and figure 3.



(a)



(1) (2)

(3) (4)

(b)

Figure 3, a; 3D profile of insulator- b: Glass and porcelain insulators

Number of insulator	1	2	3	4
D(mm)	255	280	280	255
H(mm)	146	146	170	127
L(mm)	440	442	370	320
TLd(mm)	320	297	240	190
BLd (mm)	120	145	130	115
Material	porcelain	Glass	porcelain	Glass

Table 1. characteristics value of glass and porcelain insulators

3.3 Laboratory setup

The experimental arrangements have been prepared according to IEC60507 as shown in Fig. 4. All experiments were carried out in a fog chamber in the high voltage laboratory of Babol University of Technology with a volume of (200cm × 200cm × 200cm). The main power supply is a single phase, (220 V/100 KV), 5 kVA, and 50 Hz transformer. Supplied voltage by tables controlling and Feeders by a cable with the appropriate dielectric Durability, to testing insulators in the fog chamber is applied. (Figure.4)

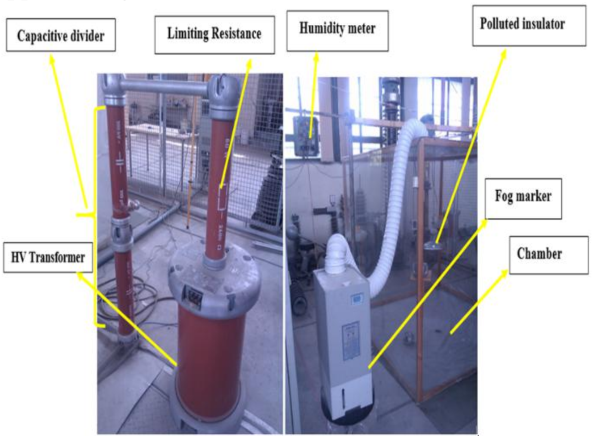


Figure 4: Laboratory investigation setup (right: HV Transformer and regulator – left: fog chamber and fog generator).

Figure 5 illustrates the schematic diagram of the experimental setup, which consists of a 500 kV ac high voltage system, a capacitance divider (C1=100 PF and C2=2500 PF) for applied voltage measurements, a shunt resistor (R =510 Ω) to measure the leakage current flowing through the test object, a data acquisition system, and a vertical circulation climate room, making possible not only very realistic simulation of different types of pollutions, but also the collection of natural frost, fog in particular.

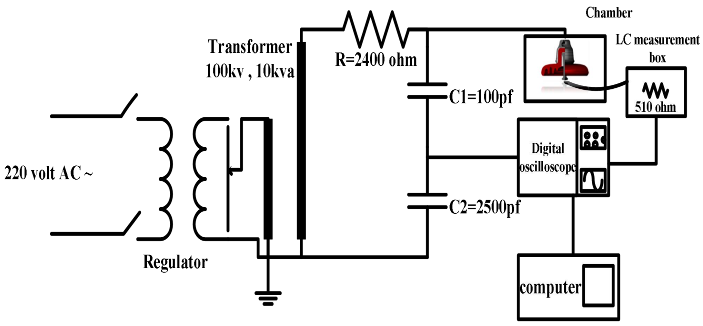


Figure 5: Circuit of the laboratory test setup

3.4 Determining the leakage current and arc resistans

For an arc burning in air and water vapour at atmospheric pressure, radiation losses are small and the majority of the electrical dissipation heats the surrounding gas. By considering that the energy P is dissipated only by thermal condition in the arc[11], one obtains.

$$P = E_a I_a = \frac{dQ}{dt}$$

Q being the quantity of heat. According to Fourier's law[11]:

$$\frac{dQ}{dt} = -\lambda A \frac{\partial T}{\partial n}$$

Where λ , A , n and T are respectively the thermal conductivity, the isothermal surface element, the normal in the direction of the temperature gradient and the temperature of the medium[11].

By using an appropriate assumption (assuming the isothermal surfaces of the arc channel to be hemispherical and the temperature propagation equation to be one-dimensional), the energy balance can be expressed as[11]:

$$E_a I_a = \pi \lambda_{av} T$$

Where T , the axial temperature is required to provide the necessary amount of thermal ionization and λ_{av} is the thermal conductivity. The thermal conductivity of such a gas mixture is not readily calculated. Some available expressions have been used to give an approximate value according to[11].

$$\lambda_{av} = \sum_{i=a}^{v} \frac{\lambda_i}{1 + \frac{A_i (1 - v_i)}{v_i}}$$

Where λ_i , v_i and A_i are the thermal conductivity, volume fraction and a kinetic gas coefficient respectively for each constituent; indices a and v are related to air and water vapour respectively [11].

On the other hand, according to Ohm's law:

$$E_a = r_a I_a = N I_a^{-n}$$

By combining (17) and (19), it yields

$$I_a = \left(\frac{\pi \lambda_{av} T}{N}\right)^{\frac{1}{(1-n)}}$$

Resistance per unit of the discharge is function of temperature based on relations (1) and (4):

$$r_a = N I_a^{-(n+1)}$$

3.5 The new model of critical current arc length and voltage

At the critical condition to wit a circle that before the complete flashover, the leakage current is called critical current. Due to the influence of the insulator geometry on the critical parameters in the most recent article of this effect is not seen in the critical current. In others, such as the [15] constant factor ($K = (\frac{\sqrt{2}}{1.3})^{-(n+1)}$) was considered. In this paper, according to the impact of insulator geometry and contamination on the leakage current, a mathematical relation is presented to have a good agreement with experimental results.

$$I_c = \left(\frac{MN}{r_p}\right)^{\frac{1}{n+1}}$$

Where M is:

$$M = \frac{TLd}{BLd} \qquad (23)$$

Where TLd is equivalent Top leakage path per shed and BLd is equivalent Bottom leakage path per shed. For arc length according to [1-15]:

$$X_c = \frac{L}{n+1}$$

hence, the critical voltage is obtained by substituting I_c and X_c into equation (5). Thus, the critical flashover voltage will be:

$$V_c = \frac{L}{n+1} N^{\frac{1}{n+1}} r_p^{\frac{n}{n+1}} M^{\frac{1}{n+1}} (M^{-n} + n)$$

The relationship 25 by approximation (n<1, $M^{-n} \approx 1$) is modified to relationship 26. To obtain this relationship, the approximation does not greatly influence the critical voltage, and numerical value calculated through these two equations.

$$V_c = L N^{\frac{1}{n+1}} r_p^{\frac{n}{n+1}} M^{\frac{1}{n+1}} \qquad (26)$$

The above equations ((22) to (26)) indicates that the critical current and the critical voltage depend to the Profile insulators, type of contamination and temperature of discharge band.

The relationship (26) indicates that having the exact values of the arc constants can be polluted insulator behaviour until complete flashover is studied.

3.6 Determining the arc constants

Using the analytical relations, which are based on the polluted insulator model, the most important agent, is the determination of the arc constants N and n . the pervious literature illustrates s that the real values of constants N and n , in the case of thin pollution layers, are in the range of (10-500) and (0-1), respectively [6, 14, 15]. Constants arc are dependent insulators profile and type of pollution, given the different insulators profile and different types of pollution, each insulator has its own constant. In this paper, to determine the arc constants using programs written in the software MATLAB, for each insulator is determined by an arc constant in which case the answer to experimental result the same insulator have many similarities and the results are satisfactory. The experimental data (U_c , against S) and the geometric characteristics of the tested insulators were put in equation (26), thus leading in relations with unknowns the discharge constants N and n . This equation, with unknowns the arc constants N and n were solved using different method (Genetic algorithm, newton-raphson and other statistical methods) that the minimum the difference between critical voltages tested with the mathematical model presented in equation (26). In table 4, the results obtained by these tests are given.

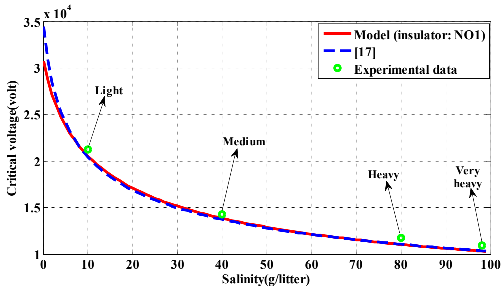
$$\sum U_c - f\,(\mathrm{N}, n) = \text{minimum} \tag{27}$$

Insulator	N	N
1	66.9218	0.5293
2	64.0350	0.5402
3	67.5785	0.5279
4	65.2565	0.5579

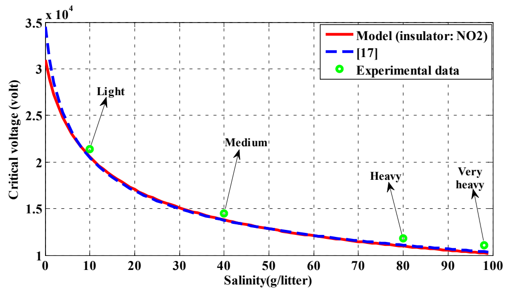
Table 4. the arc constants N and n for tested insulators

Performance model

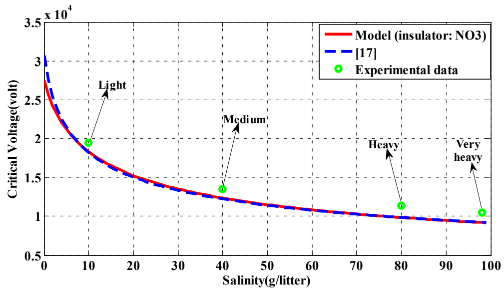
The accuracy of the model was verified by comparing the mathematical results with measurements found in the literature besides the already presented experimental results. Fig. 6 shows a collation of the presented model and experimental results. According to [17], it can be seen that there is a good relation and Accurate between the presented model and the measured data at every contamination severity. This is of great concern in act especially for the prediction of occurrence flashover. Consequently, the mathematical model developed in this work represents a good relation for predicting the critical flashover voltage and the critical current.



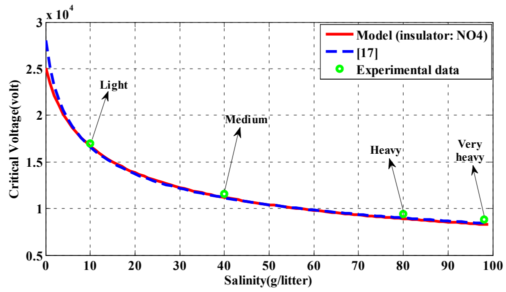
a.



b.



c.



d.

Figure 6: Critical voltage model in compared experimental test and [17]

a: NO.1, b: NO.2, c: NO.3, d: NO4

Figure 7 displays changes critical voltage in the pollution resistance using the relationships (22) and (26) .

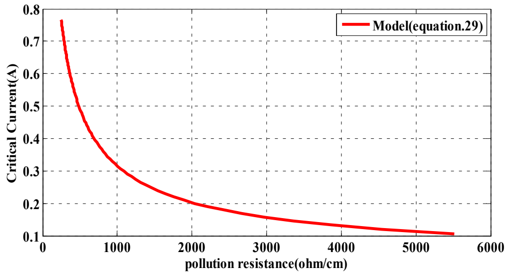


Figure 7: Critical current variation versus pollution resistance

5. Conclusion

In this paper, we presented a new mathematical model for critical parameters of polluted insulators based on experimental tests. The validity of these models was verified by comparing the computed results of critical flashover voltage based on experimental tests and theoretical data for different insulators. By using arc constants of each insulator in different polluted condition it is possible to estimate the critical voltage close to real condition. It is expected that intricate tests for the prediction of this behavior can be considerably decreased or even eliminated.

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