# Study of Discharge in Point-Plane Air Interval Using Fuzzy Logic

**Yacine Bourek†, Leïla Mokhnache*, Nacereddine Nait Said* and Rafik Kattan****

**Abstract** – The objective of this paper is to study the discharge phenomenon for a point-plane air interval using an original fuzzy logic system. Firstly, a physical model based on streamer theory with consideration of the space charge fields due to electrons and positive ions is proposed. To test this model we have calculated the breakdown threshold voltage for a point-plane air interval. The same model is used to determine the discharge steps for different configurations as an inference data base. Secondly, using results obtained by the numerical simulation of the previous model, we have introduced the fuzzy logic technique to predict the breakdown threshold voltage of the same configurations used in the numerical model and make estimation on the insulating state of the air interval. From the comparison of obtained results, we can conclude that they are in accordance with the experimental ones obtained for breakdown discharges in different point-plane air gaps collected from the literature. The proposed study using fuzzy logic technique shows a good performance in the analysis of different discharge steps of the air interval.

**Keywords:** Air ionization, discharge, electric field due to space charge, fuzzy logic, prediction

## 1. Introduction

The air is the insulation the more used in high voltage systems (lines and stations), and the study of the electric discharge in air is an important domain from an industrial view point for resolving the problems involved in the insulation and the protection and the distribution of energy systems (high-voltage lines, transformers, generators…)[1], [2]. Air in its normal state is a very poor conductor of electricity. If the air is subjected to a sufficient electric voltage, the appearance of a current of charged particles is possible due to partial ionization of the environment, then the air is conducting and a discharge occurs [3]-[5]. Generally the gas in particular the air discharge phenomena occur within very short period. Thus the experimental approach has obvious limits in investigating the discharge characteristics. On the other hand the numerical simulation can supply the information of physical quantities that are immeasurable in the experiments during reduced time. A large amount of experimental data is available in standards of high voltage engineering and electrical breakdown of gases. Many empirical formulae are available from which breakdown or corona onset field strengths may be calculated. Such formulae are, however, valid only within certain ranges, and extrapolation can lead to large errors [6], [7]. In this order, this paper proposes a new technique for the analysis and study of gas discharge (breakdown and discharge steps in air). The proposed method is used to know the state of insulation of an air interval still a numerical measurement (limitation of the model) or experiments (limitation of the means) are unrealizable. This method consists to introduce the fuzzy logic treatment to predict the breakdown threshold voltage and to study the electric discharge (from corona to breakdown (arc)) in a point-plane air interval. The introduction of fuzzy logic theory in this study is original and of an interest considering the development of the industrial tools based on the use of fuzzy logic in their designs. Fuzzy logic is also called " logical linguistics " because its truth values are words of running language: "rather true, almost false, so cold, quite speedy …" [8]-[11]. In the proposed fuzzy inference system to study a point -plane air interval, we have introduced parameters charactering this configuration as point curvature, interval length, and applied voltage as input, and the discharge steps (Townsend avalanche growth, corona, streamer, breakdown) as output.

## 2. Breakdown in Non-Uniform Fields

In non-uniform fields, the field strength and hence the effective ionization coefficient $\bar{\alpha}$ vary across the gap. The electrons multiplication is governed by the integral of $\bar{\alpha}$ over the path $\int_0^{x_c} \bar{\alpha}\, dx$ [5].

The criterion condition for breakdown (or inception of discharge) for the general case may be represented to take into account the non-uniform distribution of $\bar{\alpha}$ by [4], [5]

$$\int_0^{x_c<d} \bar{\alpha}\, dx = k \qquad (1)$$

k: is a positive number.

$x_c$ being the critical path of the avalanche and d the gap

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length . The integration is calculated step-by-step along the highest line of the field stress (where $\bar{\alpha} > 0$ ) [4], [5].

The transformation of an avalanche to a streamer under a non-uniform field is obtained when k takes values belong to the interval $18 \le k \le 20$ [5], [12]. It should be noted that under non-uniform fields the formation of a streamer does not involve necessarily the breakdown of this interval, as in the uniform field case [5].

## 3. Electric Field Modelisation

The studied configuration is shown in Fig.1.

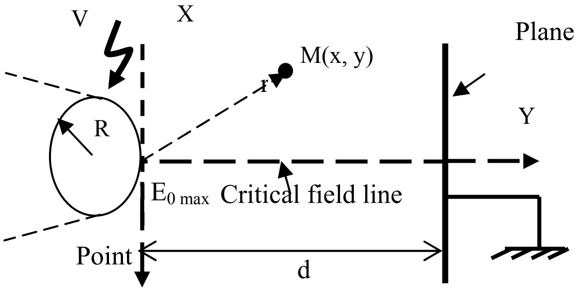


**Fig. 1.** Point -plane arrangement

M: an arbitrary point of calculation in inter-electrodes interval defined by its Cartesian coordinates (x, y)
R: the curvature radius of the high voltage (HV) point
d: the inter -electrodes distance
r: the distance between the high voltage (HV) point and a point (M) of the inter - electrode space.
V: applied voltage

To have information on dielectric strength of the point-plane air interval; we must know the value of the ambient electric field. The resulting electric field in each point of the studied interval (Fig.1) is expressed by [5]:

$$\vec{E}_r = \vec{E}_0 + \vec{E}_i + \vec{E}_e \qquad (2)$$

$\vec{E}_0$ : the applied field.

$\vec{E}_i$ : the electric field due to the created positive ions.

$\vec{E}_e$ : the electric field due to the created electrons.

According to this equation we notice that we have three types of fields to calculate.

### 3.1 Electric Field due to the applied HV to the Point

The maximum field at the point ( $E_{0\,max}$ ) is given in [5] by:

$$E_{0\,max} = 0.9\frac{V}{d}\left(\frac{R+d}{R}\right) \qquad (3)$$

For other points in the air interval around the critical field line (Fig.1), $E_0$ is calculated in an arbitrary point M in the interval using equation (3) replacing R of the denominator by r+R such as:

$$r = \sqrt{x^2 + y^2} \qquad (4)$$

### 3.2 Calculation of the Space Charge Fields due to Ions and Electrons

From the calculation of the applied field E0 in each point and having a data of the effective ionization coefficient ( $\bar{\alpha} = f(E/P)$ ) obtained from [5], [12], we can determine $\bar{\alpha}$ in each point, by considering the conditions of pressure P=760 torrs.

The generated fields due to the produced electrons and ions can be calculated by the GAUSS theorem as considered in a cylinder with a negligible thickness as the contribution of all cylinders containing the charge [14]:

$$E_e = \frac{\sum_{i=1}^{n_e} q_e(i)}{\pi \varepsilon_0 r_e^2} \qquad (5)$$

$$E_i = \frac{\sum_{i=1}^{n_i} q_i(i)}{\pi \varepsilon_0 r_i^2} \qquad (6)$$

$n_i$, $n_e$ :are number of discretization points containing respectively the electrons and positive ions.
$r_e$, $r_i$ : are respectively the Gauss radius including the positive electrons and ions(in this paper they are equal).

$\varepsilon_0 = 8.85$ x 10-14 [F/cm]

$q_i(i)$ , $q_e(i)$ Are respectively space charges due to the ions and the electrons in the air interval. They are calculated as follows [5], [14]:

$$q_i = \bar{e}\, n_0 \left[ \exp\left( \int_0^x \bar{\alpha}\, dx \right) - 1 \right] \qquad (7)$$

$$q_e = \bar{e}\, n_0 \left[ \exp\left( \int_0^x \bar{\alpha}\, dx \right) \right] \qquad (8)$$

$n_0$: The initial number of electrons.
X: Maximal distance from the point containing the charge

## 4. Simulation of Threshold Breakdown Voltage

For the simulation we followed two steps:

- The First is devoted to the determination of breakdown threshold voltage of the air interval and changing the parameters (V, d, R). The obtained results in this step are used to estimate other electric discharge steps: corona, avalanche growth, and breakdown (arc).
- The Second is to build a fuzzy inference system (SIF) to predict threshold voltage of the air interval, as well as for the other discharge steps changing the parameters (V, d, R).

### 4.1 Test of Validation of the Physical Model

Results obtained during this section concern the parameters: R = 0.1 cm, d = 100cm, V = 290 kV, the plane takes circular shape of radius 50cm. It should be noted that for the previous parameters, the calculated integral gives 19.05, which implies that the voltage V = 290 kV can be considered as the breakdown threshold voltage of the air interval.

Fig. 2, 3 represents some results obtained by simulation explain in a flow chart shown on Fig.4.

Fig. 2 represent the calculation of applied and resulting electric fields on the highest field line of the air interval.

The resulting field ($E_r$) is calculated as follows:

-The resulting field $E_r$ at the head and the tail of the avalanche is given by:

$$E_r = E_0 - E_i + E_e \tag{9}$$

-The resulting field $E_r$ within the avalanche is:

$$Er = E_0 + E_i - E_e \tag{10}$$

The integral (1) is calculated by the sum:

$$I = \sum_{i=1}^{n} \bar{\alpha}_i r_i = k \tag{11}$$

n: is the number of points where $\bar{\alpha} > 0$.

$r_i$: distance between the calculation point and the HV point.

Fig.2 shows that the applied field ($E_0$) is very high at the proximity of the point and then it decreases in the direction of the plane. In the same figure we note that the distribution of the applied field is strongly modified, because in our case (positive point), the field is subject to two modifications; the first is in the zone occupied by the free electrons and the second in the zone of positive ions. We notice that the field is enhanced by the presence of the electrons and decreased by the ions. The peak of the resulting field represents the head of the avalanche.

Fig.3 shows that the space charge due to the electrons and ions is considerable at the point and there is no ionization of the air near the plan $(\bar{\alpha} < 0)$, consequently no space charge.

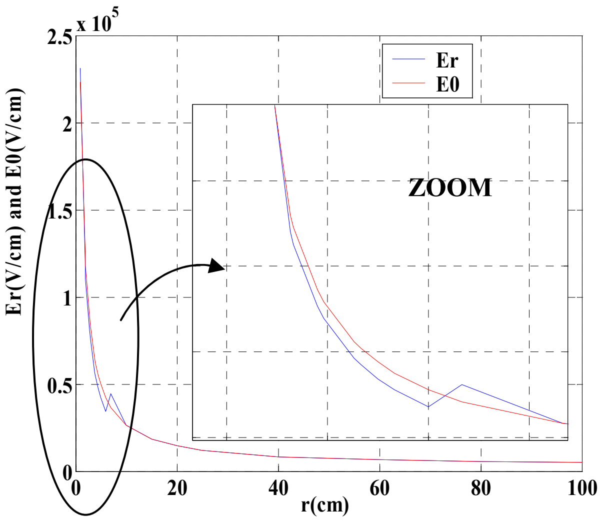


**Fig. 2.** Electric field with and without the presence of the space charge according to (d) on the highest field line

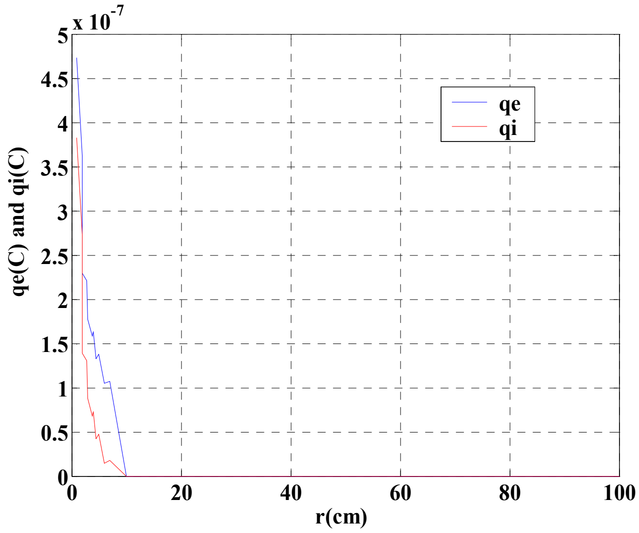


**Fig. 3.** Space charge due to the positive ions and free electrons in inter electrodes (positive) point- plan

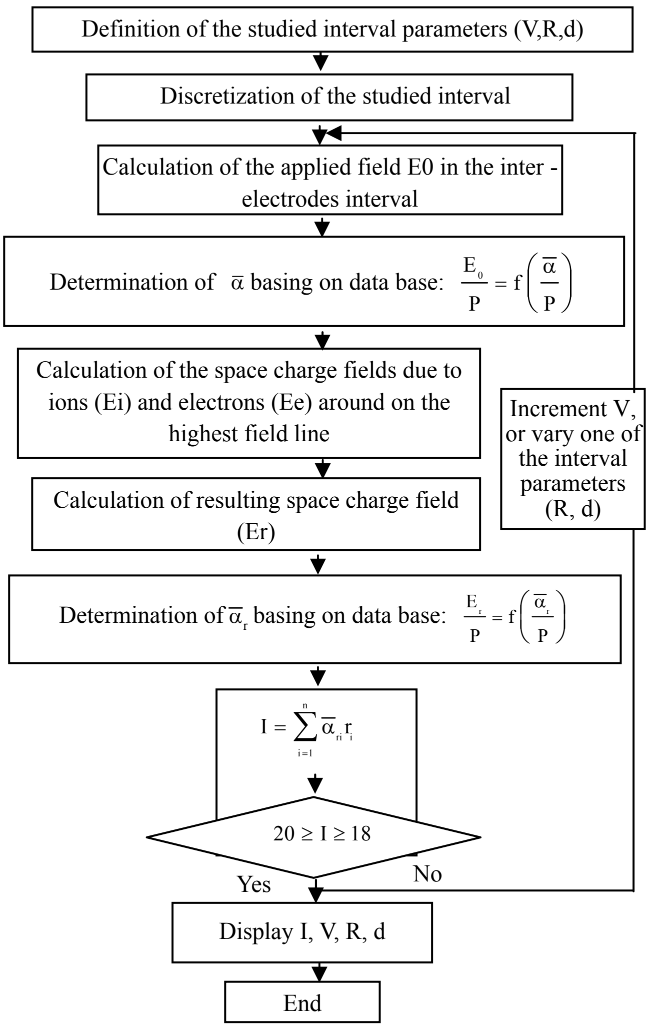


**Fig. 4.** Flow chart of calculation of the threshold breakdown voltage in the air interval, for an atmospheric pressure P=760 torrs.

## 4.2 Prediction of the Electric Discharge Steps

This section is based on the computed values of the integral I.

Table 1 gives the computed values of the integral I calculate by equation (11) changing the configuration of the interval (R, d) = (0.1, 100) and (2, 50).

The values of "k" between 18 and 20 indicate the appearance of the streamers [4], [5], [12]. If we consider that there are one step preceding the "streamer" which is "Townsend avalanche growth". The steps appearing after the "streamer" are "corona" followed by "arc" (breakdown). If we devise the values of calculated integral given in table 1 into 4 intervals (Townsend avalanche growth, streamer, corona, and arc), and if we consider the values of the integral indicating certain steps of the discharge (Townsend avalanche, streamer) given in references [13]-[17] we obtained the results shown in table 2:

**Table 1.** Values of the calculated integral for two point - plane configurations

| V (kV) | Parameters R (cm) | d (cm) | Integral (I) |
|---|---|---|---|
| 50 | 0.1 | 100 | --- |
| 150 | 0.1 | 100 | 5.47 |
| 250 | 0.1 | 100 | 10.64 |
| 290 | 0.1 | 100 | 19.05 |
| 320 | 0.1 | 100 | 27.9 |
| 400 | 0.1 | 100 | 60 |
| 200 | 2 | 50 | --- |
| 300 | 2 | 50 | 3 |
| 350 | 2 | 50 | 5.3 |
| 400 | 2 | 50 | 10.2 |
| 500 | 2 | 50 | 11 |
| 600 | 2 | 50 | 17.05 |
| 800 | 2 | 50 | 27.5 |
| 1000 | 2 | 50 | 36 |

**Table 2.** Codes of discharge steps corresponding to the integral (i) values

| Discharge step | Interval of the integral "I" |
|---|---|
| Townsend avalanche | $5 \leq I < 18$ |
| Streamer | $18 \leq I \leq 20$ |
| Corona | $20 < I \leq 24$ |
| Arc (breakdown) | $I > 24$ |

Table 2 can be used by fuzzy logic system as it is explained bellow.

## 4.3 Prediction of the Air Interval Discharge Using Fuzzy Logic

### *1) Fuzzy Inference System (FIS)*

The fuzzy inference system is made of three blocks as indicated on fig.5 [8]-[11].

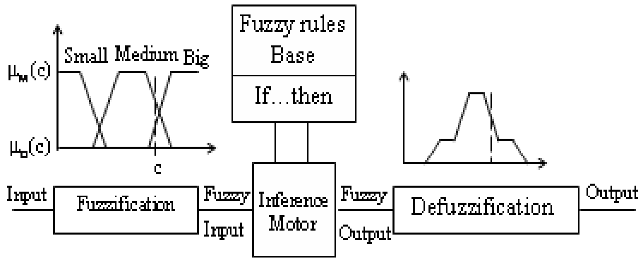


**Fig. 5.** A fuzzy inference system

The first bloc is the fuzzification one which transforms the numerical values into membership degrees for various fuzzy sets of the partition, the second block is the inference engine which consists of rules, the last one, is the block of defuzzification, to infer a net value from the results of the rules aggregation [8], [9].

### *2) Application of Fuzzy Logic to the Prediction of the Steps of Discharge*

We apply the concept of the previous fuzzy system to predict the breakdown threshold for the air interval.

**Step 1 (Definition of the inputs/outputs)**

The inputs variables are:

1- The applied positive voltage (V)

2- The inter -electrodes distance (d)

3- The curvature radius of the point(R)

The output variable is the value I of the integral (1)

**Step 2 (Fuzzification)**

The fuzzification or definition of membership functions for inputs and outputs consists to fix each variable for the linguistic values as well as the form of membership functions and the membership degree for the various states which we must define[8], [11].

The trapezoidal membership function has been chosen to represent the linguistic variables of the inputs and outputs, as it is shown on figures (6), (7), (8) and (9).

The used linguistic variables are as follows:

- **For the output:**

TOW: Townsend avalanche growth, STR: Streamer, CR: corona, ARC: breakdown (Fig.6).

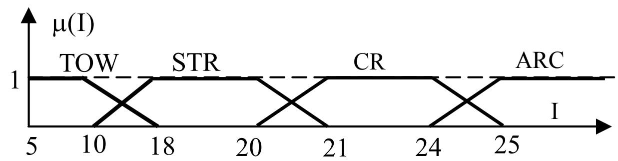


**Fig. 6** Output membership function (I)

- **For the inputs**

**- The applied voltage (V)**

MV: medium voltage, HVM: high voltage "medium", HV: high voltage, HVB: high voltage "Big", HHV: highest high voltage (Fig.7).

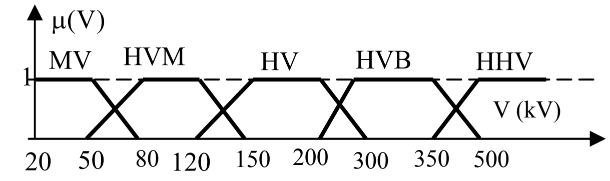


**Fig. 7.** Membership function of applied voltage (V)

**- The inter- electrodes distance (d)**

For this input, the study is made for average (medium) interval $20\,cm \le d \le 1\,m$ . For different interval of "d" we keep MD "medium" distance, MDM: medium distances "medium", MDB: medium distances "Big" (Fig.8).

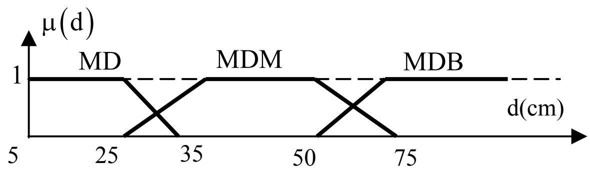


**Fig. 8** Membership function of interval length (d)

**- The curvature radius of the point (R):**

**VS**: very small, **S**: small, **M**: medium, **B**: Big (Fig.9).

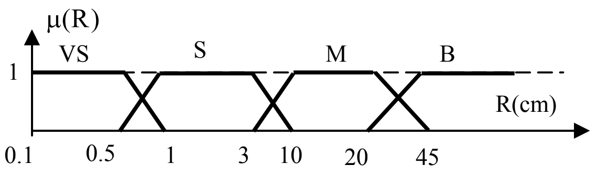


**Fig. 9** Membership function of the point curvature

**Step 3 (Inference rules)**

To simplify this step and to represent the linguistic rules connecting inputs to outputs in a best way we have used a representation, called inference matrix shown in Table.3.

**Table 3.** Inference matrix using simulation results of the integral (i)

| | V | MV | | | HVM | | | HV | | | HVB | | | HHV | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | d | MD | MDM | MDB | MD | MDM | MDB | MD | MDM | MDB | MD | MDM | MDB | MD | MDM | MDB |
| R | VS | | | | | | | STR | STR | TOW | ARC | CR | CR | ARC | ARC | ARC |
| | S | | | | | | | TOW | TOW | | CR | STR | STR | ARC | CR | CR |
| | M | | | | | | | | | | | | | TOW | TOW | STR |

***3) Tests and Results***

The fuzzy system has been developed in MATLAB Fuzzy logic Tolboox environment. The results obtained by the FIS graphic editor are shown on figure10. These results are obtained using parameters: V=290 kV, R = 0.1 cm and d = 100 cm.

We based on the "streamer" step because it is the more explicit in literature concerning the value of the Integral "I".

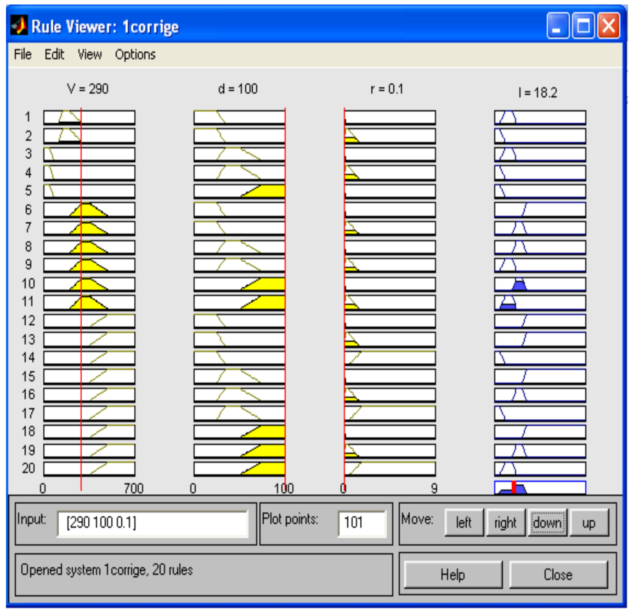


**Fig. 10.** Test of the rules using the fuzzy graphic editor

We carried other tests for different values of (V, R, d), using both of programs: calculation and fuzzy logic (Table 4).

For the calculation (for each same line of table 4), we fix R and d, and we vary the applied voltage (V) until obtaining the value of the integral "I" higher or equalizes to "18" and inferior to "20". This obtained voltage is considered as breakdown threshold voltage of the air interval.

Table 4 contains an experimental data collected from literature [13]-[17], with the simulation results obtained by the calculation program (Fig.2) and those obtained by fuzzy logic.

We have noted, that certain breakdown threshold voltage of the air interval obtained by fuzzy logic are the same ones for various distances "d", because the selected distances belong to the same membership function. To improve the obtained fuzzy logic system, we have proceeded as follows:

We have fixed the values of the variables (d, R), and an experimental breakdown threshold voltage ( $U_{50\%}$ ); then we change the form of the membership functions of each fuzzy input and output variable as it is shown on figures (11), (12), (13) and (14) (this change has been done with respect of acceptable limits of each interval), and we check output, until the integral is higher than "18" and inferior to "20"

This change of membership functions is made in a way to avoid overlapping of the fuzzy subsets. This adjustment is not made for the states: corona, Townsend avalanche because we have not numerical values characterizing these states of discharge, it is an estimation which we proposed for a positive point.

The new table of results is given on table 5.

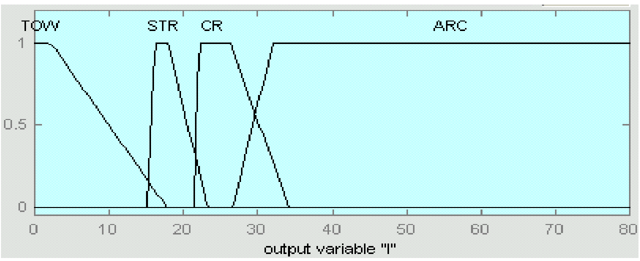


**Fig. 11.** New membership function of the output (I)

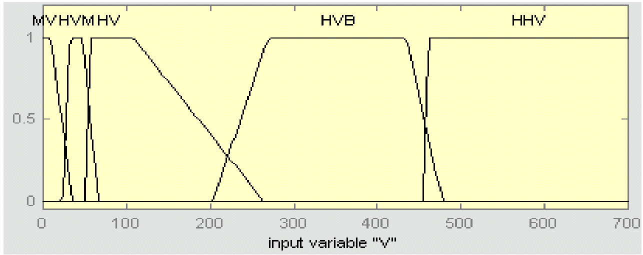


**Fig. 12.** New membership function of the applied voltage (V)

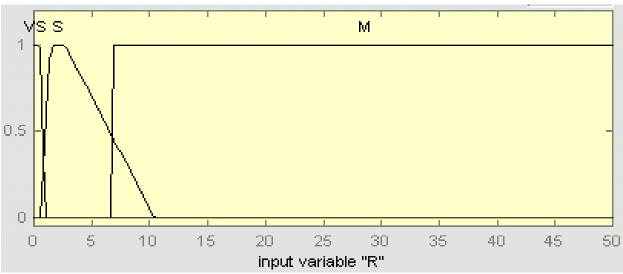


**Fig. 13.** New membership Function of the point curvature radius (R)

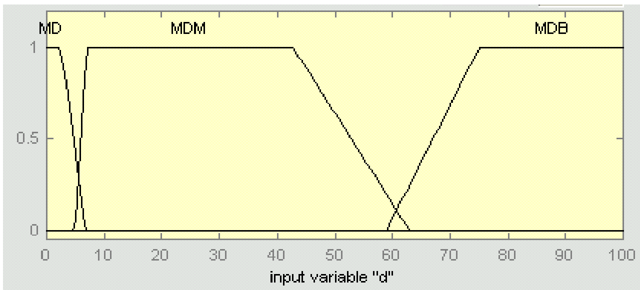


**Fig. 14.** New membership function of the interval length (d)

**Table 4.** Comparison of experimental data, simulated one and by fuzzy logic

| parameters | | Breakdown threshold voltage | | | Value of integral (I) | |
|---|---|---|---|---|---|---|
| R(cm) | d(cm) | Vexperimental ( kV) | Vprogram (kV) | Vfuzzy (kV) | Iprogram | Ifuzzy |
| 0.12 | 40 | 210 | 239 | 270 | 18.67 | 18.5 |
| 0.12 | 30 | 160 | 225 | 203 | 18.88 | 18.6 |
| 0.12 | 20 | 140 | 205 | 202 | 18.44 | 18.3 |
| 2 | 20 | 180 | 291 | 280 | 18.05 | 18.4 |
| 2 | 40 | 280 | 330 | 450 | 18.3 | 18.2 |
| 2 | 60 | 380 | 350 | 450 | 18.67 | 18 |
| 2 | 80 | 430 | 355 | 450 | 18.03 | 18.2 |

**Table 5.** Comparison of experimental and simulated breakdown threshold voltages of the air interval after the change of the membership functions

| parameters | | Breakdown threshold voltage | | | Value of integral (I) | |
|---|---|---|---|---|---|---|
| R(cm) | d(cm) | Vexperimental (kV) | Vprogram (kV) | Vfuzzy (kV) | Vprogram | Ifuzzy |
| 0.12 | 40 | 210 | 239 | 200 | 18.67 | 18.2 |
| 0.12 | 30 | 160 | 225 | 170 | 18.88 | 18.0 |
| 0.12 | 20 | 140 | 205 | 150 | 18.44 | 18.0 |
| 2 | 20 | 180 | 291 | 180 | 18.05 | 18.0 |
| 2 | 40 | 280 | 330 | 280 | 18.3 | 18.0 |
| 2 | 60 | 380 | 350 | 380 | 18.67 | 18.7 |
| 2 | 80 | 430 | 355 | 430 | 18.03 | 18.0 |

According to the obtained results we can say that:

- The trapezoidal form of the membership function that we have chosen had given good representations of the linguistic variables
- It is necessary to determine the linguistic universe of each subset which represents the input variables (V, R, d) and output variable (I). Because we have not enough experimental data, the step of validation was delicate. We based on some published experimental data and on the simulation program results to obtain the streamers appearance voltage which can be considered as the threshold breakdown.

## 5. Conclusion

In this paper, we have presented a model of study of electric discharge for a positive point- plane air gap. This study based on the streamers theory (streamer breakdown criterion). The model obtained by this theory is used in a second approach to develop a system to predict the breakdown threshold of the same interval of air using fuzzy logic. This system predicts also other steps in the discharge (corona, Townsend avalanche and arc). It should be noted that only the parameters: applied voltage, curvature radius of the point, and inter-electrodes distance, are considered in this study. In spite of the loss information of the influence of each parameter on the breakdown of air interval, fuzzy logic by its flexibility in its establishment helped us to generalize the carried study for V=290 kV, R=0.1cm, d=100cm at various distances, radius and voltage for any air point (positive)-plane interval. To improve the results obtained by fuzzy logic, it is necessary to choose goodly the membership forms for the inputs and outputs variables.

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