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THE PREDICTION OF AC BREAKDOWN VOLTAGE USING FUZZY INFERENCE SYSTEM

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Abstract: The air is the most important insulator for high voltage electrical apparatus, intended for surrounding medium; however it is unintentionally present in voids, gaps and inclusions, so it is essential to investigate the variation of the breakdown threshold of air as an insulator by means of several parameters, such as the gas pressure, the rate of voltage rise, electrode configuration and gap spacing. MATLAB/Fuzzy Logic Toolbox is used to examine the breakdown voltage variation of air via four different parameters mentioned above. An analytical expression is used to calculate the breakdown voltage for uniform field gaps as a function of gap length and gas pressure due to Townsend equation. In this study, plane-plane, sphere-sphere, and sphere-plane electrode configurations are considered. Townsend equation is arranged according to the non-uniform electrode configurations by changing the gap spacing variable as a function of utilization factor and radius of the electrodes. The utilization factors changing by different electrode configurations are analyzed with a computer program based on Finite Element Method (FEM). The analytically calculated breakdown voltages and fuzzy values compared.

1 INTRODUCTION

Owing to its complexity and physical theory, electrical discharge phenomena of gases are not easy to explain. In the paper belong to Kunhardt, the theories and formulas beginning the prebreakdown stage of gases to post streamer era is explained chronologically. Townsend formulated the self-sustaining breakdown voltage equation in the gases in uniform field [1]. Due to air that is a readily available and cheap gas, scientists generally used to examine the breakdown process in air with different electrode systems. In a study changing the pressure, electrode configuration and impulse voltage ranges, the voltage-time characteristics of air is compared with different situations [2].

Recently, the developments of artificial intelligence techniques (e.g. fuzzy logic, neural networks, adaptive neuro-fuzzy inference system) scientists use these methods to model their problems in different areas. In literature, the studies about fuzzy logic approach to the electrical discharge phenomena occupy wide area. In a study, fuzzy logic approach is used for modeling the breakdown voltage of voids artificially created in a solid dielectric [3]. Adaptive neuro-fuzzy inference system (ANFIS) is used modeling the partial discharge (PD) inception and extinction voltages [4]. PDs are categorized according to surface, internal and corona so recognition of partial discharges is important topic in literature via fuzzy logic [5]. PD pulse recognition according to pulse amplitude, pulse phases, kurtosis, skewness, pulse mean values, pulse rising times and pulse repetition values via fuzzy logic approach is also important topic [6-8]. The breakdown probability of gases via fuzzy approach is also studied [9]. In another study, discharge phenomenon of point-plane air gap is studied characterizing the breakdown threshold with fuzzy logic approach [10].

In this study, breakdown voltage of air with varying electrode gap, pressure, electrode configuration and voltage rise rate is calculated analytically. Both uniform, weakly uniform and non-uniform field parameters are applied to the Townsend's breakdown equation. The results obtained from analytical calculations are used in modeling fuzzy logic. The results of Townsend's breakdown equation and fuzzy inference systems are compared and discussed. Then the relative errors in the calculations are calculated. The electrode utilization factors are calculated using the computer software called FEMM based on finite element method.

2 ANALYTICAL STUDY

In the uniform electric field, the breakdown voltage equation of a gas is given by equation (1).

$$V_b = \frac{Bpd}{\ln\left[\dfrac{Apd}{\ln(1+1/\gamma)}\right]} = f(pd) \qquad (1)$$

In this equation, A and B are ionization constants and they vary for each gas. For air, A is equal to 14.6 $(\text{cm.mmHg})^{-1}$, B is equal to 300

V.(cm.mmHg)$^{-1}$ at 20 °C. d is the gap spacing between parallel electrodes in cm and p is the pressure of air in mmHg. γ is Townsend's second ionization coefficient, which takes value between 1/50 and 1/5000. Equation (1) is only used for uniform electric field (plane-plane electrode gap), so it is essential to transform the equation for quasi-uniform (sphere-plane) and non-uniform (sphere-sphere) electrode configurations. For this purpose, it is important to understand the analytical expressions of electrode utilization factor (η), the maximum electric field (E_{max}), mean electric field (E_{mean}), electrode gap spacing (d) and equivalent gap spacing (α) for each electrode configuration.

In parallel planar electrode system, electrode gap spacing (d) and equivalent gap spacing (α) are equal to each other. The mean electric field for plane-plane electrode is E_{mean} = V/d and maximum electric field for the other electrode configurations is E_{max} = V/α. The electrode utilization factor is the ratio of mean electric field to maximum electric field, η = E_{mean} / E_{max} = (V / a) / (V / α) = α / d. This ratio is equal to 1 for plane-plane electrode configuration. So, we can rewrite the formula replacing the electrode gap spacing (d) with η and α (d = α / η).

$$V_b = \frac{Bp(\alpha/\eta)}{\ln\left[\dfrac{Ap(\alpha/\eta)}{\ln(1+1/\gamma)}\right]} \tag{2}$$

2.1 Equivalent gap spacing (α) for different electrode geometries

The equation (3) gives the expression of α obtained from approximately analytical calculation of maximum electric field of sphere-plane electrode system.

$$\alpha = (r \times d)/(r+d) \tag{3}$$

Where r is the radius of sphere electrode and d is the gap spacing between sphere and plane electrodes.

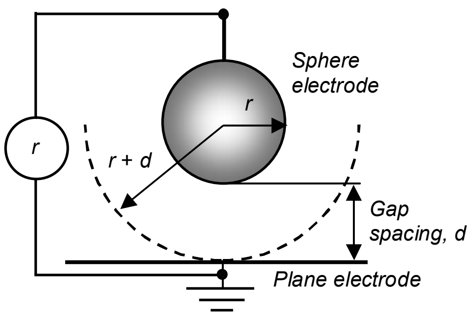

Figure 1: The sphere-plane electrode system.

The α value for sphere-sphere electrode system is given by the equation (4).

$$\alpha = (r \times d)/(r + \frac{d}{2}) \tag{4}$$

Where the diameters of the sphere electrodes are same and d is the closest distance between the spheres.

2.2 Electrode utilization factor (η) for different electrode configuration

To calculate the electrode utilization factor, all electrode configurations are simulated in the computer software and the maximum electric field (E_{max}) is computed by FEMM. The mean electric field is calculated analytically for all electrode gaps. In the study three different electrode gap spacing 2 mm, 3 mm, and 4 mm for various electrode geometries as plane-plane, sphere-plane and sphere-sphere electrodes are considered.

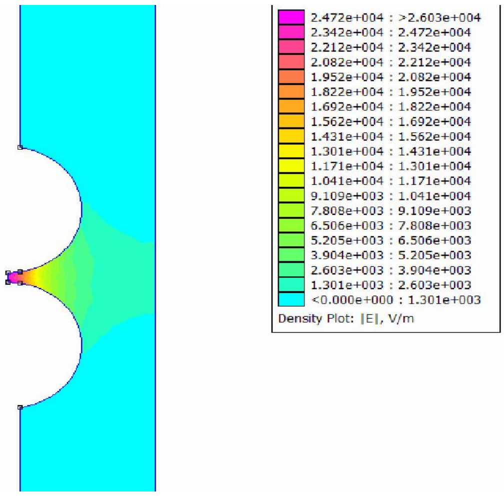

Figure 2: The electric field distribution in sphere-sphere electrode configuration.

In Figure 2, diameters of the spheres are 50 mm, the applied voltage to the upper sphere electrode is 100 V, potential of lower electrode is 0 V, and the distance between the electrodes is 4 mm. So, the mean electric field is E_{mean} = 100/4 = 25 V/mm. The maximum electric field value calculated by the computer program is 26.05 V/mm. So, η = 25/26.05 = 0.9606. η values for other electrode configurations are calculated by similar method and are given in Table 1.

Table 1: η values for some electrode configurations

Electrode configuration	Electrode distance (mm)	Electrode utilization factor (η)
Sphere-Sphere	2	0.9817782
Sphere-Sphere	4	0.96061479
Sphere-Sphere	6	0.94013767
Sphere-Plane	2	0.96467365
Sphere-Plane	4	0.91928663
Sphere-Plane	6	0.88039623
Plane-Plane	2	1
Plane-Plane	4	1
Plane-Plane	6	0.99998

The disc-shaped planar electrodes used in the calculations have a diameter of 50 mm and thickness of 7.5 mm.

2.3 Breakdown voltages of different electrode configurations

In this study, there are three different electrode configurations (plane-plane, sphere-plane, sphere-sphere) with varying air pressure (560 mmHg, 660 mmHg, and 760 mmHg), electrode gap spacing (2 mm, 4 mm, and 6 mm) and voltage rise rate (1 kV/s, 2 kV/s, and 3 kV/s). For every voltage rise rate the Townsend's second coefficient γ takes discrete values. In equation (1), γ is considered 1/50 for 1 kV/s, 1/500 for 2 kV/s, and 1/5000 for 3 kV/s respectively. As a result, eighty-one breakdown voltage values are given in Table 2, Table 3 and Table 4 are calculated analytically.

Table 2: Breakdown voltages for plane-plane electrode system

Plane-plane configuration				Breakdown voltage V_b (kV_{eff})		
d (mm)	p (mmHg)	*p.d*	η	1 kV/s (γ=1/50)	2 kV/s (γ=1/500)	3 kV/s (γ=1/5000)
2	760	152	1	7.197	7.758	8.197
2	660	132	1	6.393	6.903	7.304
2	560	112	1	5.572	6.03	6.391
4	760	304	1	12.975	13.88	14.578
4	660	264	1	11.498	12.318	12.952
4	560	224	1	9.995	10.726	11.293
6	760	456	1	18.401	19.609	20.536
6	660	396	1	16.289	17.381	18.22
6	560	336	1	14.139	15.11	15.859

Table 3: Breakdown voltages for sphere-sphere electrode system

Sphere-sphere configuration				Breakdown voltage V_b (kV_{eff})		
d (mm)	p (mmHg)	*p.d*	η	1 kV/s (γ=1/50)	2 kV/s (γ=1/500)	3 kV/s (γ=1/5000)
2	760	152	0.982	7.072	7.625	8.059
2	660	132	0.982	6.282	6.785	7.181
2	560	112	0.982	5.476	5.928	6.284
4	760	304	0.961	12.572	13.453	14.135
4	660	264	0.961	11.142	11.941	12.56
4	560	224	0.961	9.686	10.399	10.953
6	760	456	0.940	17.598	18.762	19.656
6	660	396	0.940	15.58	16.632	17.442
6	560	336	0.940	13.526	14.462	15.185

Table 4: Breakdown voltages for sphere-plane electrode system

Sphere-plane configuration				Breakdown voltage V_b (kV_{eff})		
d (mm)	p (mmHg)	*p.d*	η	1 kV/s (γ=1/50)	2 kV/s (γ=1/500)	3 kV/s (γ=1/5000)
2	760	152	0.965	6.953	7.499	7.926
2	660	132	0.965	6.177	6.673	7.064
2	560	112	0.965	5.384	5.83	6.182
4	760	304	0.919	12.28	13.145	13.813
4	660	264	0.919	10.885	11.668	12.275
4	560	224	0.919	9.463	10.162	10.706
6	760	456	0.880	17.058	18.192	19.064
6	660	396	0.880	15.103	16.129	16.918
6	560	336	0.880	13.114	14.027	14.731

3 FUZZY LOGIC

Boundaries of fuzzy sets are not clear when compared to the classical mathematic sets. The classical sets divide the universe into two different domains whereby an object either belongs to set or not. The membership function has only two values (0, 1). According to fuzzy theory the numbers between 0 and 1 can be assigned to the membership function.

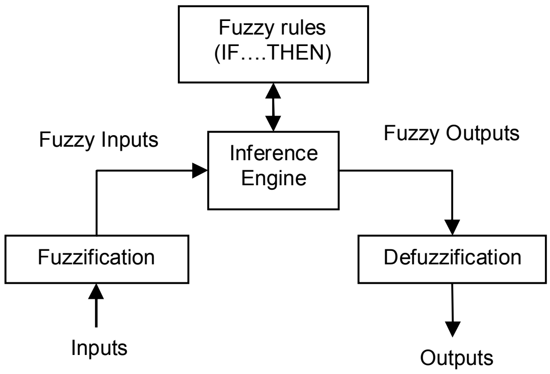

Figure 3: A fuzzy inference system (FIS).

A basic structure of FIS is given in Figure 3. First of all, the numerical input from external world transformed to the membership degrees for various linguistic variables. Inference engine checks out the rules related to the variables before creating fuzzy outputs. Defuzzification process transformed fuzzy outputs to the crisp values. In this study to built fuzzy inference systems, Matlab Fuzzy Logic Toolbox is used.

In the study, a discrete FIS for each electrode configuration is designed. The input values of fuzzy inference systems are the product of pressure with distance between electrodes, and voltage rise rate. The outputs of the systems are breakdown voltages. Before starting to set the inputs and outputs, inter values of pds in tens (120 mmHg.cm, 130 mmHg.cm, etc.) and their equivalent breakdown voltages are interpolated by 1D interpolation. These interpolated values are used for designing fuzzy sets and membership functions. 108 rules are defined for each fuzzy inference system considering interpolated values. For example, for the plane-plane configuration, the rules are set like, "IF (pd) is 150 mmHg.cm AND (kV/s) is 2 kV/s THEN V_b is 7.5 kV". The Mamdani type FIS is used. Implication method is AND (minimum), aggregation method is OR (maximum), defuzzification method is centroid.

4 OUTPUT OF FUZZY INFERENCE SYSTEM

The data obtained from the fuzzy model is given in Table 5, Table 6, and Table 7. Functional error rate (%) compared to the analytical values also are given in parenthesis.

Table 5: Breakdown voltages obtained from the FIS for the plane-plane electrode system

Plane-plane configuration				Breakdown voltage V_b (kV_{eff})		
d (mm)	p (mmHg)	*p.d*	η	1 kV/s (γ=1/50)	2 kV/s (γ=1/500)	3 kV/s (γ=1/5000)
2	760	152	0.996 (+0.45)	7.106 (+1.26)	7.706 (+0.67)	8.104 (1.13)
2	660	132	0.996 (+0.45)	6.304 (1.38)	6.705 (2.86)	7.106 (2.7)
2	560	112	0.996 (+0.45)	5.64 (-1.27)	5.911 (1.97)	6.304 (1.35)
4	760	304	0.996 (+0.45)	12.93 (0.34)	13.77 (0.78)	14.41 (1.15)
4	660	264	0.996 (+0.45)	11.37 (1.11)	12.17 (1.19)	12.77 (1.4)
4	560	224	0.996 (+0.45)	9.929 (0.65)	10.57 (1.44)	11.17 (1.08)
6	760	456	0.996 (+0.45)	18.59 (-1.02)	19.63 (-0.1)	20.29 (1.19)
6	660	396	0.996 (+0.45)	16.43 (-0.86)	17.43 (-0.28)	18.23 (-0.05)
6	560	336	0.996 (+0.45)	14.23 (-0.64)	15.23 (-0.79)	16 (-0.88)

Table 6: Breakdown voltages obtained from the FIS for the sphere-sphere electrode system

Sphere-sphere configuration				Breakdown voltage V_b (kV_{eff})		
d (mm)	p (mmHg)	*p.d*	η	1 kV/s (γ=1/50)	2 kV/s (γ=1/500)	3 kV/s (γ=1/5000)
2	760	152	0.978 (0.35)	7.007 (0.91)	7.557 (0.89)	7.954 (1.30)
2	660	132	0.978 (0.35)	6.21 (1.14)	6.705 (1.17)	7.102 (1.1)
2	560	112	0.978 (0.35)	5.586 (-2)	5.91 (0.3)	6.307 (-0.36)
4	760	304	0.961 (0)	12.47 (0.81)	13.4 (0.39)	14.04 (0.67)
4	660	264	0.961 (0)	11.07 (0.64)	11.88 (0.51)	12.49 (0.55)
4	560	224	0.961 (0)	9.602 (0.86)	10.32 (0.75)	10.86 (0.84)
6	760	456	0.944 (-0.37)	17.58 (0.1)	18.64 (0.65)	19.37 (1.45)
6	660	396	0.944 (-0.37)	15.62 (-0.25)	16.72 (-0.52)	17.54 (-0.56)
6	560	336	0.9441 (-0.37)	13.6 (-0.54)	14.53 (-0.47)	15.3 (-0.75)

Table 7: Breakdown voltages obtained from the FIS for the sphere-plane electrode system

Sphere-plane configuration				Breakdown voltage V_b (kV_{eff})		
d (mm)	p (mmHg)	*p.d*	η	1 kV/s (γ=1/50)	2 kV/s (γ=1/500)	3 kV/s (γ=1/5000)
2	760	152	0.957 (0.74)	6.906 (0.67)	7.499 (0)	7.903 (0.29)
2	660	132	0.957 (0.74)	6.109 (1.1)	6.606 (1)	6.908 (2.2)
2	560	112	0.957 (0.74)	5.458 (-1.37)	5.803 (0.46)	6.202 (-0.32)
4	760	304	0.919 (0)	12.4 (-0.97)	13.02 (0.95)	13.68 (0.96)
4	660	264	0.919 (0)	10.83 (0.5)	11.64 (0.23)	12.18 (0.77)
4	560	224	0.919 (0)	9.379 (0.88)	10.07 (0.9)	10.61 (0.89)
6	760	456	0.887 (-0.77)	17.09 (-0.18)	18.19 (0.01)	18.79 (1.43)
6	660	396	0.887 (-0.77)	15.17 (-0.44)	16.23 (-0.62)	16.95 (-0.18)
6	560	336	0.887 (-0.77)	13.19 (-0.57)	14.12 (-0.66)	14.78 (-0.33)

5 CONCLUSION

Altering electrode configuration, air pressure, voltage rise rate and electrode gap spacing values are taken into account and evaluated by Townsend equation. Analytically calculated values are used to build fuzzy models. The values from fuzzy-model and analytical values compared and relative error rates are given. Relative error rate does not exceed ± 3%. Fuzzy model can be used to predict breakdown voltages in gases for different electrode systems. In addition, ANFIS and NN can be used for modeling of the discharge phenomena.

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