MODELLING OF BREAKDOWN VOLTAGE OF WHITE MINILEX PAPER IN THE PRESENCE OF VOIDS UNDER AC AND DC CONDITIONS USING FUZZY LOGIC TECHNIQUES

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

Bachelor of Technology in Electrical Engineering

By

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Department of Electrical Engineering
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UNDER THE SUPERVISION OF

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NATIONAL INSTITUTE OF TECHNOLOGY , ROURKELA

CERTIFICATE

This is to certify that the thesis entitled "**MODELLING OF BREAKDOWN VOLTAGE OF WHITE MINILEX PAPER IN THE PRESENCE OF VOIDS UNDER AC AND DC CONDITIONS USING FUZZY LOGIC TECHNIQUES**" submitted by **Sunil Behera , Sarthak Patnaik** in partial fulfillment of the requirements for the award of Bachelor Of Technology degree in Electrical Engineering at the National Institute Of Technology, Rourkela is an authentic work carried out by them under my supervision and my guidance.

To the best of my knowledge , the matter embodied in the thesis has not been submitted to any other University/Institute for the award of any degree or diploma.

Date :

Place :

Prof. SanjeebMohanty

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It is our pleasure to refer "Microsoft Word " exclusive of which the compilation of this project report would have been impossible. Also it would not have been possible to complete the project without the simulation software "**MATLAB 7.1**".

A project of this nature could never have been attempted with our reference to and inspiration from the works of others whose details are mentioned in the reference section. We acknowledge our indebtedness to all of them.

SUNIL BEHERA

SARTHAK PATNAIK

ABSTRACT

Gaseous cavities present in the insulation materials can lead to continuous deterioration and eventually breakdown of insulation materials. To determine the stability of use and to acquire the data for the modeling and designing of electrical insulation systems ,breakdown voltage (BDV) of the insulation should be determined. In this paper, Fuzzy Logic (FL) method is used to model breakdown voltages of White minilex paper samples based on experimental data generated in the laboratory. Different models are proposed with different membership functions for the FL under both dc and ac voltage conditions. The cavities are created artificially. Low values of mean absolute errors of the estimated breakdown voltage of the test data show the efficiency of the models.

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FIGURES

Chapter 1

INTRODUCTION

INTRODUCTION

In industrial insulating systems, aging can be contributed to microdefects present in bulk of insulation . The increase in microdefects in number and sizes makes the aging process critical and difficult to determine as the insulation samples were both thermally as well as electrically aged. Breakdown voltage tests were widely used to test for degradation of insulation systems. The breakdown of solid dielectrics is an event that is catastrophic. The insulation will not be able to withstand the service voltage that follows it. The breakdown can be due to various causes such as electromechanical ,intrinsic, thermal micro discharges in the cavities . Due to the application of voltage, the electrical stress experienced by the cavities entrapped into the insulation initiate discharges when the stress value exceeds a certain critical limit. At a particular voltage, these discharges produce deterioration of the insulating properties in ways depending on geometrical factors and the nature of the dielectric material. These factors eventually cause the material degradation and lead to breakdown of the insulation.

Nowadays , the modeling of breakdown voltage is done using soft computing techniques, such as, Artificial Neural Network and FL(Fuzzy Logic) .The advantage of using a soft computing model is that it is highly flexible . In this paper, FL techniques have been used to model breakdown voltage for White Minilex Paper both under DC and AC condition. As a diagnostic tool, FL techniques have been used for breakdown voltage estimation under artificially created air cavities of various sizes. In the next section,the experimental set up and the procedure for obtaining the experimental data on the breakdown voltage is described which is followed by the FL (fuzzy logic)model proposed and results obtained by assuming six different shapes of the Membership Functions (MFs).

CHAPTER 2

EXPERIMENTAL SETUP

EXPERIMENTAL SETUP:

2.1 **Sample preparation:**

The samples are prepared from commercially available insulation sheets. Three different thickness of the insulation material 0.125 mm, 0.18mm and 0.26 mm were used. Before testing the conditioning procedure was adopted to the test specimen to ensure that the surfaces of the insulating sample were cleaned and dry, since the contamination on the insulating specimen or absorption of moisture might affect the breakdown voltage.

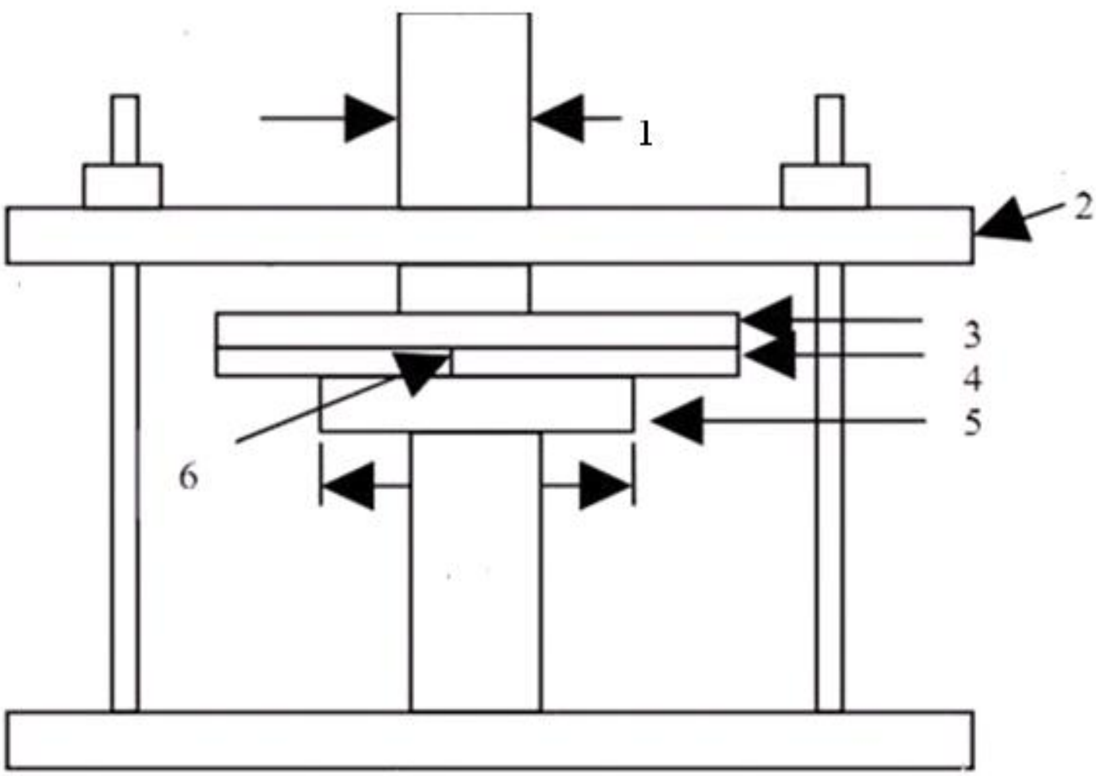
2.2 **Creation of void:**

The voids were artificially created with the help of a spacer made up of Kapton film, with a punched hole at the center whose diameter values were 1.5mm, 2 mm, 3 mm, 4mm and 5 mm. The thickness of the spacer used was of 0.125mm. Thus, the volume of air space, that is, the sizes of the voids depend on a typical diameter of the punched hole and the thickness of spacer.

2.3 **Electrode Geometry:**

The cylinder-plane electrode system as shown in the Figure 1 was used for breakdown voltage measurements. The electrodes were made of brass. They were polished and cleaned with ethanol before the start of the experiment. Further, the electrodes contact surfaces were cleaned by ethanol between two consecutive applications of voltage. Sufficient care had been taken to keep the electrode surfaces scratch-free and away from dust and other impurities. The insulation sample was then sandwiched between the electrodes as shown in Figure 1 with the help of insulating supports as shown below.

2.4. **Measurement of Breakdown Voltage(BDV):**



1. High Voltage Electrode 2. Insulating Supports with nuts and bolts 3. Insulation sample under test 4. Spacer 5.Ground electrode 6. Cavity (All dimensions are in mm)

FIGURE 1:-**Experimental setup to determine breakdown voltage of insulation**

2.5 **Measurement of DC breakdown voltage**

The dc voltage applied was obtained from a 40 KV ac/dc Series Hipot Tester . The voltage was raised insteps of 1 KV and held constant for a period of 30s in each level until the breakdown of the insulation occurs. The total time from the application of voltage to the instant of occurrence of breakdown were noted down.

Five data points were obtained for a particular sample and the mean value other voltage is taken for modeling. All the tests were carried oft in air at room temperature and atmospheric pressure. The breakdown data obtained are then corrected for atmospheric condition before being used for modeling. It is observed that the sample break in the middle in each case which was due to maximum stress in the middle and presence of cavity at the center.

2.6 **Measurement of ac Breakdown Voltage**

In this case an ac voltage of 50 Hz was applied from the Hipot Tester to the insulating sample. The voltage was raised in steps of 200V. Rest of the procedure was identical to that presented in subsection D. It was observed that the breakdown occurs at much lower ac voltage than dc condition for the identical samples and cavity.(AC rms is considered where as in DC peak).

CHAPTER 3

PROPOSED FUZZY LOGIC MODELS

3.1 : FUZZY LOGIC

The breakdown voltage of White Minilex Paper under dc and ac conditions has been modeled using Fuzzy Logic techniques. 45 sets of input-output data are used for modeling purpose for both dc and ac conditions, oft of which 38 sets are used for framing the rule base and remaining 7 sets for the testing purpose. The breakdown voltage is a function of the thickness of the paper and the diameter of the void ,that is V = f (t, d). The relationship between the linguistic values and the actual values for t, d and V are presented in Table 1 and Table 2.

Table 1:**Relation between the linguistic values and the actual values for t and d.**

Linguistic Values	t (mm)	d (mm)
Low	0-0.13	1.0-3.0
Medium Low	0.05-0.18	1.7 -3.7
Medium	0.10-0.23	2.4-4.4
Medium High	0.15-0.28	3.1-5.1
High	0.20- 0.33	3.8-5.8

TABLE2.Relation between the linguistic values and the actual values for V_{dc} and V_{ac}

Linguistic Values	V_{dc} (kV)	V_{ac} (kV)
Low	17-21	1.6-2.0
Medium Low	19-23	1.8-2.2
Medium	21-25	2.0-2.4
Medium High	23-27	2.2-2.6
High	26-30	2.4-2.8

The set of linguistic values assigned to t, d and V are givenas b_vL= {Low (L), Medium Low (ML), Medium (M), Medium High (MH), High (H)}.The Membership Functions (MFs) for t, d and V are μ_t, μ_d and μ_V respectively. Since, t and d can have five linguistic values; the rule base can be created with a maximum of 25 rules from the experimentally generated data. Also, μ_t, μ_d and μ_V would be having 5 components corresponding to each linguistic value :-

$$\mu t = \{\mu_t L, \mu_t ML, \mu_t M, \mu_t MH, \mu_t H\} \tag{2}$$

$$\mu d = \{\mu_d L, \mu_d ML, \mu_d M, \mu_d MH, \mu_d H\} \tag{3}$$

$$\mu V = \{\mu_V L, \mu_V ML, \mu_V M, \mu_V MH, \mu_V H\} \tag{4}$$

The Mamdani Rule Based Inferencing (MRBI) is computationally very efficient and saves a lot of memory and time. Hence, it is a very popular method and has been used here to evaluate the modeled values of the breakdown voltage.

3.2 BREAKDOWN VOLTAGE MODELLING

A. **Under AC condition:**

Similarly under ac conditions corresponding to the 38 training sets, 38 ‘if then’ rules are formulated. Oft of these 38 rules, 22 rules were used to form the rule base and the rest 16 rules could not be considered .The 22 rules have been presented in Table. The 7 sets of crisp input for the thickness of the paper and the diameter of the void, fired each of the 22 rules given in Table 4.

The procedure followed to calculate the aggregated Fuzzy MFs and the MAE under AC conditions is identical to the DC conditions and hence equations(5) to (7) can be used for this case also.

For computational efficiency, efficient memory utilization, and performance analysis needs, a uniform representation of the MFs is required. This uniform representation can be achieved by employing MFs with uniform shape and parametric definition. The most popular choices for the shapes of the MFs include Triangular, Trapezoidal, Generalized Bell,Gaussian, PI shaped. In our work the MFs μ_t , μ_d and μ_V have assumed these shapes.

B. **Under dc condition:-**

Corresponding to the 38 sets, the 38 if then rules are formulated under dc conditions. Of these 38 rules, 22 rules have been used to form the rule base and the rest 16 rules could not be considered. This is because these 16 rules satisfied the inconsistency property of the if-then rules . Since 7 sets of input output data have been used for testing purpose,

the number of crisp input output pairs are 7 in number. The 22 rules have been mentioned in Table 3. The 7 crisp input value sets for the thickness of the paper and the diameter of the void, fire each of the 22 rules given in Table 3.

A typical fuzzified MF obtained by firing a rule is as follows:

$$\mu_V MH1 = \text{minimum}_3 (\mu_t^* , \mu_d^* , \mu_V MH) \quad (5)$$

Where μ_t^*, μ_d^* are the MFs corresponding to the crisp inputs for the thickness of the paper and the diameter of the void respectively. Similarly the other fuzzified MFs obtained by firing the rest 21 rules are aggregated to form the aggregated fuzzified MFs.

The aggregated fuzzified Membership Functions is given by

$\mu_A 1(V)$ = maximum $_{22}$ (μ_VMH1, μ_VH1, μ_VMH2 ………………., μ_VL3, μ_VMH4) (6)

Equations (5) and(6) have been implemented in MATLAB 7.1 environment by writing suitable codes for it. The defuzz function in the toolbox was used to compute the defuzzifiedvalue of the breakdown voltage V_b2 from $\mu_A 1(V)$.Just go to the command window of MATLAB 7.1 and type fuzzy. You will get the fuzzy toolbox.

The Mean Absolute Error (MAE) gives a good performance measure for finding the accuracy of the Fuzzy Logic System .The MAE under dc conditions expressed in (%) is given by

MAE_{dc}= (1/7)* | ((∑ ($V_b1(s)$ –$V_b2(s)$)/($V_b1(s)$)|*100 (7)

Where V_b1 is the experimental or the crisp value for the breakdown voltage under dc condition and s in this case varies from 1 to 7.Now, the analysis is done for AC and DC conditions respectively for triangular and trapezoidal MFs each.

TABLE 3: RULE BASE UNDER DC CONDITION

THICKNESS ,t	DIAMETER , d	BREAKDOWN VOLTAGE,V
MH	L	ML
H	ML	M
MH	ML	MH
H	L	ML
ML	M	M
L	ML	M
ML	L	L
M	ML	L
L	M	L
M	MH	MH
ML	ML	MH
H	H	M
MH	MH	M
ML	MH	ML
M	H	MH
ML	H	ML
L	H	M
ML	L	MH
MH	H	MH
H	MH	M
M	L	M
MH	M	H

TABLE 4 : RULE BASE UNDER AC CONDITION

THICKNESS,t	DIAMETER OF VOID ,d	BREAKDOWN VOLTAGE, V
MH	L	M
H	ML	MH
MH	ML	ML
H	L	MH
ML	M	M
L	ML	ML
ML	L	M
M	ML	ML
L	M	M
M	MH	MH
ML	ML	M
H	H	ML
MH	MH	MH
ML	MH	M
M	H	ML
ML	H	M
L	H	M
ML	L	M
MH	H	MH
H	MH	M
M	L	M
MH	M	MH

CHAPTER 4

RESULTS

Triangular Membership Function

The triangular curve is a function of a vector variable, x, and depends on three scalar parameters

given by:-

$$f(x;a,b,c)=\begin{Bmatrix} 0, & x\le a \\ \frac{x-a}{b-a}, & a\le x\le b \\ \frac{c-x}{c-b}, & b\le x\le c \\ 0, & c\le x \end{Bmatrix}$$

Or

$$f(x;a,b,c)=\max\left(\min\left(\frac{x-a}{b-a},\frac{c-x}{c-b}\right),o\right)$$

MATLAB command :**-trimf**

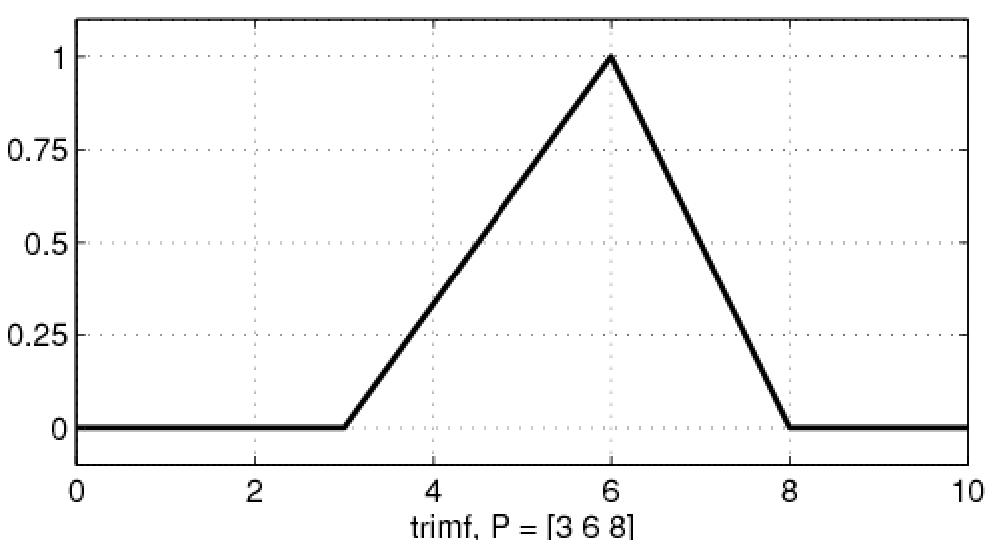


FIGURE 2:**TRIANGULAR MEMBERSHIP FUNCTION**

TRAPEZOIDAL MEMBERSHIP FUNCTION:-

The trapezoidal curve is a function of a vector, x, and depends on four scalar parameters. The relation is given by :-

$$f(x;a,b,c,d)=\begin{Bmatrix} 0, & x\le a \\ \dfrac{x-a}{b-a}, & a\le x\le b \\ 1, & b\le x\le c \\ \dfrac{d-x}{d-c}, & c\le x\le d \\ 0, & d\le x \end{Bmatrix}$$

Or,

$$f(x;a,b,c,d)=\max\left(\min\left(\frac{x-a}{b-a},1,\frac{d-x}{d-c}\right),o\right)$$

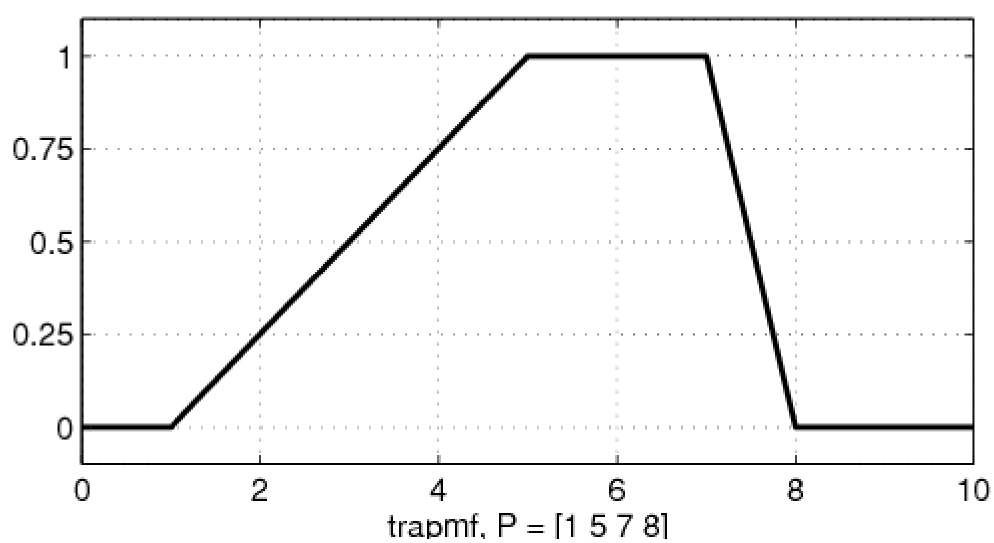


Figure 3: Trapezoidal Membership Function(trapmf)

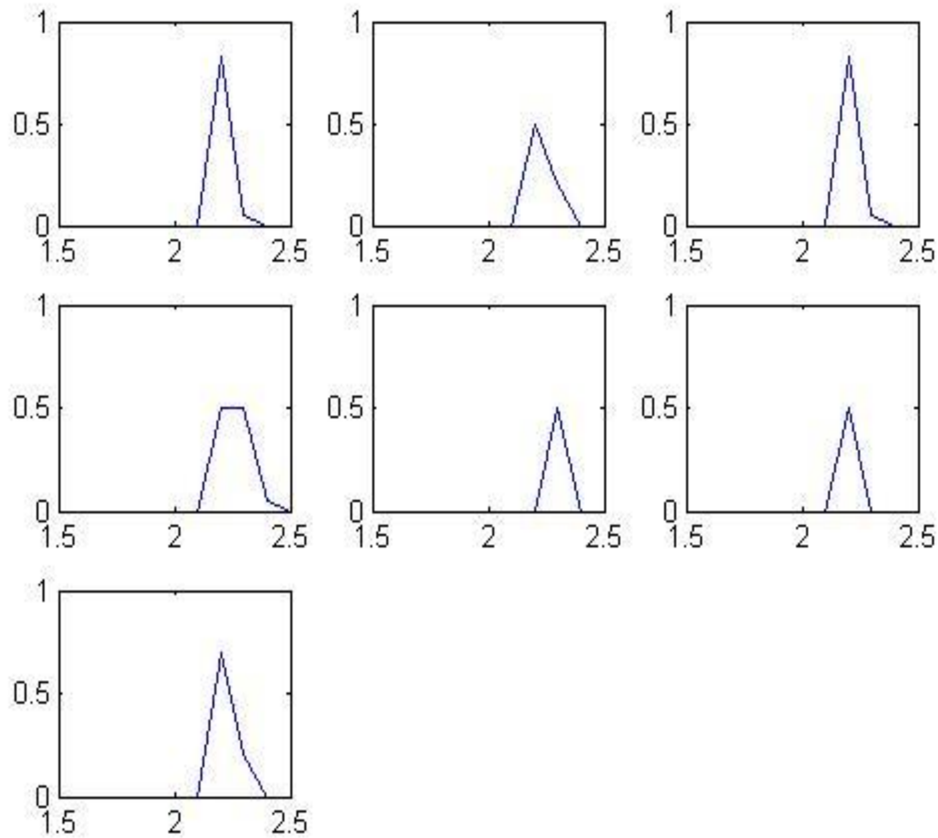
TABLE 5: Table for AC breakdown voltage for White Minilex paper.

Sl.no.	Thickness of the material (mm)	Void Depth (mm)	Void Diameter (mm)	Mean value of Breakdown Voltage (Experimental) (kV)
1.	0.26	0.025	1.5	2
2.	0.26	0.125	3.0	2.1
3.	0.26	0.025	1.5	2
4.	0.26	0.125	2.0	2.1
5.	0.18	0.025	3.0	2.2
6.	0.125	0.125	3.0	2.4
7.	0.125	0.025	1.5	2
8.	0.125	0.125	1.5	2.1
9.	0.125	0.025	3.0	2.3
10.	0.18	0.125	5.0	2.2
11.	0.18	0.025	3.0	2.4
12.	0.18	0.125	2.0	2.3
13.	0.26	0.025	3.0	2.1
14.	0.26	0.125	5.0	2.4
15.	0.26	0.025	5.0	2
16.	0.26	0.125	2.0	2.3
17.	0.125	0.025	5.0	2.3
18.	0.18	0.125	2.0	2.1
19.	0.18	0.025	4.0	2.1
20.	0.18	0.125	5.0	2
21.	0.125	0.025	5.0	2.3
22.	0.125	0.125	2.0	2.2
23.	0.18	0.025	3.0	2.2
24.	0.18	0.125	5.0	2.0
25.	0.125	0.025	4.0	2.0
26.	0.26	0.125	1.5	2.3
27.	0.18	0.025	1.5	2.4
28.	0.26	0.125	2.0	2.2
29.	0.26	0.025	4.0	2.1
30.	0.18	0.125	4.0	2.2

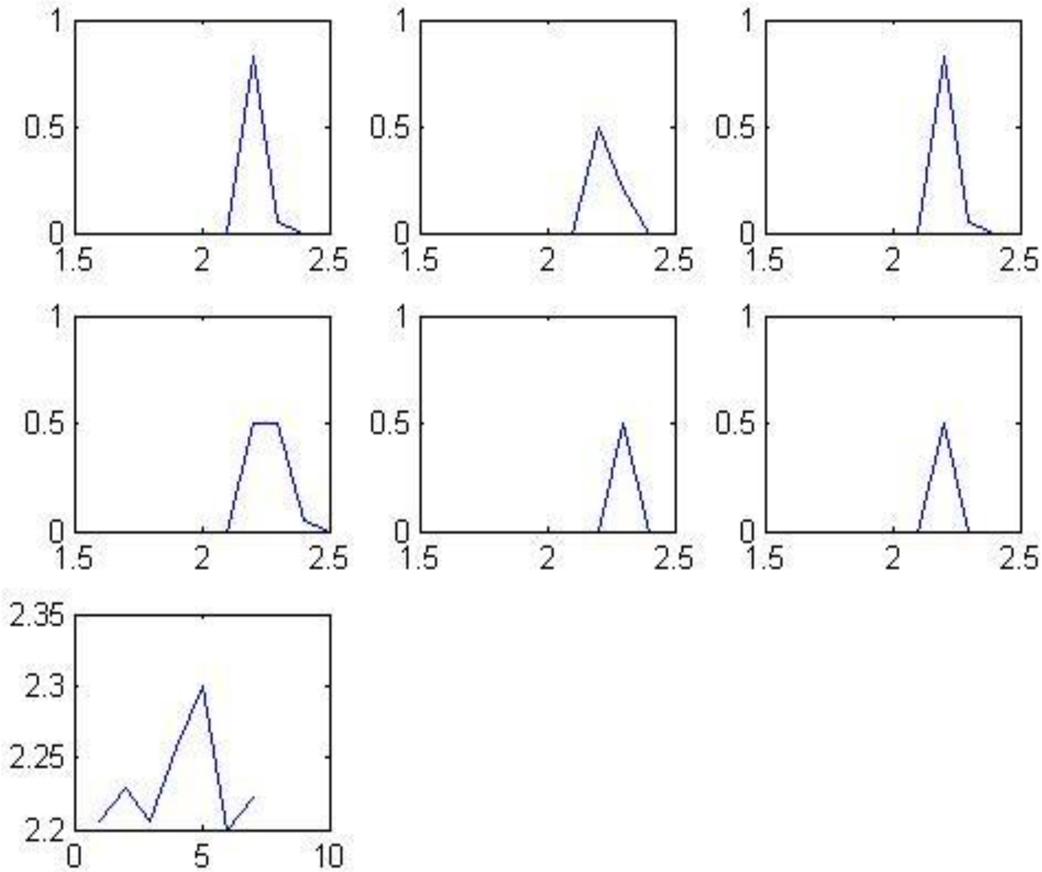
These are the crisp data on which we worked oftforcalculation the breakdown voltage models under AC conditions

t(mm)	t1(mm)	d (mm)	Breakdown Voltage (V_b1) (kV)	Breakdown Voltage V_b2 (kV)	MAE (%)
0.125	0.025	1.5	2.0	2.2057	6.7501
0.26	0.125	3.0	2.1	2.2286	
0.125	0.025	1.5	2.0	2.2057	
0.125	0.025	3.0	2.3	2.2571	
0.18	0.025	3.0	2.2	2.3000	
0.26	0.125	5.0	2.4	2.2000	
0.26	0.025	3.0	2.1	2.2222	

Table 6: Comparison of the Crisp (V_b1) and defuzzified values (V_b2) of the Breakdown Voltage with Triangular MF for White Minilex under AC condition



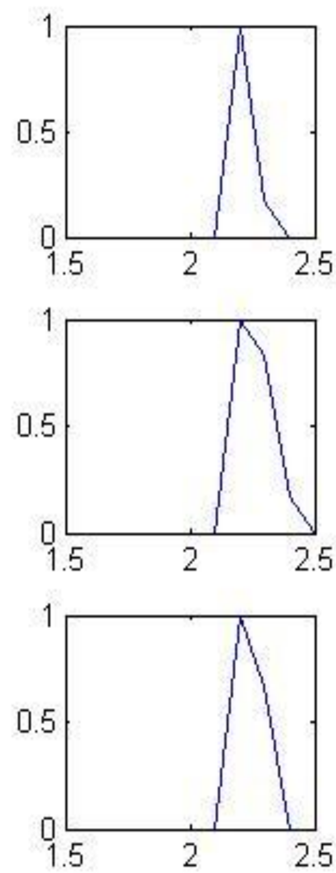
<u>FIGURE 4</u>:FUZZIFIED TRIANGULAR MODELS OF BDV(AC)



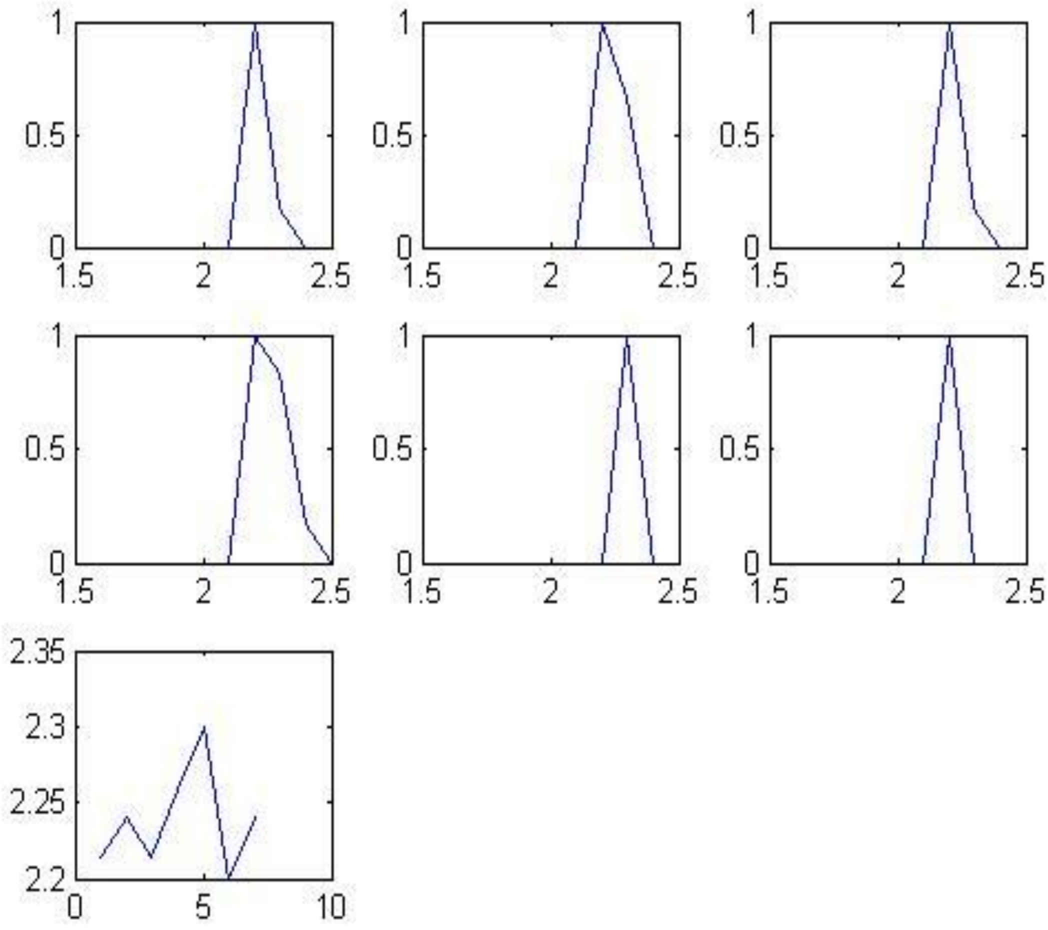
<u>FIGURE 5</u>:DEFUZZIFIED TRIANGULAR MODELS OF BDV(AC)

t(mm)	t1(mm)	d (mm)	Breakdown Voltage (V_b1) (kV)	Breakdown Voltage V_b2 (kV)	MAE (%)
0.125	0.025	1.5	2.0	2.2143	7.0646
0.26	0.125	3.0	2.1	2.2400	
0.125	0.025	1.5	2.0	2.2143	
0.125	0.025	3.0	2.3	2.2583	
0.18	0.025	3.0	2.2	2.3000	
0.26	0.125	5.0	2.4	2.2000	
0.26	0.025	3.0	2.1	2.2400	

Table 7: Comparison of the Crisp (V_b1) and defuzzified values (V_b2) of the Breakdown Voltage with Trapezoidal MF for White Minilex under AC condition



<u>FIGURE 6</u>: FUZZIFIED TRAPEZOIDAL MODELS OF BDV(AC)



<u>FIGURE 7</u>: DEFUZZIFIED TRAPEZOIDAL MODELS OF BDV(AC)

DC Breakdown Volatage modelling

In this part, we are doing the breakdown voltage modeling of high volatage insulation under DC

TABLE 8: Table for DC breakdown voltage for White Minilex paper.

Sl.no.	Thickness of the material (mm)	Void Depth (mm)	Void Diameter (mm)	Mean value of Breakdown Voltage (Experimental) (kV)
1.	0.125	0.025	1.5	23.44
2.	0.125	0.025	2.0	22.88
3.	0.125	0.025	3.0	23.22
4.	0.125	0.025	4.0	24.44
5.	0.125	0.025	5.0	22.55
6.	0.18	0.025	1.5	23.55
7.	0.18	0.025	2.0	23.22
8.	0.18	0.025	3.0	24.44
9.	0.18	0.025	4.0	23.77
10.	0.18	0.025	5.0	22.88
11.	0.26	0.025	1.5	23.33
12.	0.26	0.025	2.0	23.00
13.	0.26	0.025	3.0	24.44
14.	0.26	0.025	4.0	23.77
15.	0.26	0.025	5.0	23.22
16.	0.125	0.125	1.5	24.44
17.	0.125	0.125	2.0	23.55
18.	0.125	0.125	3.0	22.55
19.	0.125	0.125	4.0	23.22
20.	0.125	0.125	5.0	23.77
21.	0.18	0.125	1.5	23.00
22.	0.18	0.125	2.0	24.33
23.	0.18	0.125	3.0	23.77
24.	0.18	0.125	4.0	22.88
25.	0.18	0.125	5.0	24.33
26.	0.26	0.125	1.5	23.22
27.	0.26	0.125	2.0	23.55
28.	0.26	0.125	3.0	23.44
29.	0.26	0.125	4.0	23.77
30.	0.26	0.125	5.0	22.88

t(mm)	t1(mm)	d (mm)	Breakdown Voltage (Vb1) (kV)	Breakdown Voltage Vb2 (kV)	MAE (%)
0.125	0.025	1.5	23.44	21.4759	8.0773
0.125	0.025	2.0	22.88	23.4093	
0.125	0.025	3.0	23.22	26.2015	
0.125	0.025	4.0	24.44	21.7904	
0.18	0.025	3.0	24.44	23.9194	
0.26	0.125	1.5	23.00	25.2807	
0.26	0.025	4.0	23.77	21.3643	

Table 9: Comparison of the Crisp (V_b1) and defuzzified values (V_b2) of the Breakdown Voltage with Triangular MF for White Minilex under dc condition

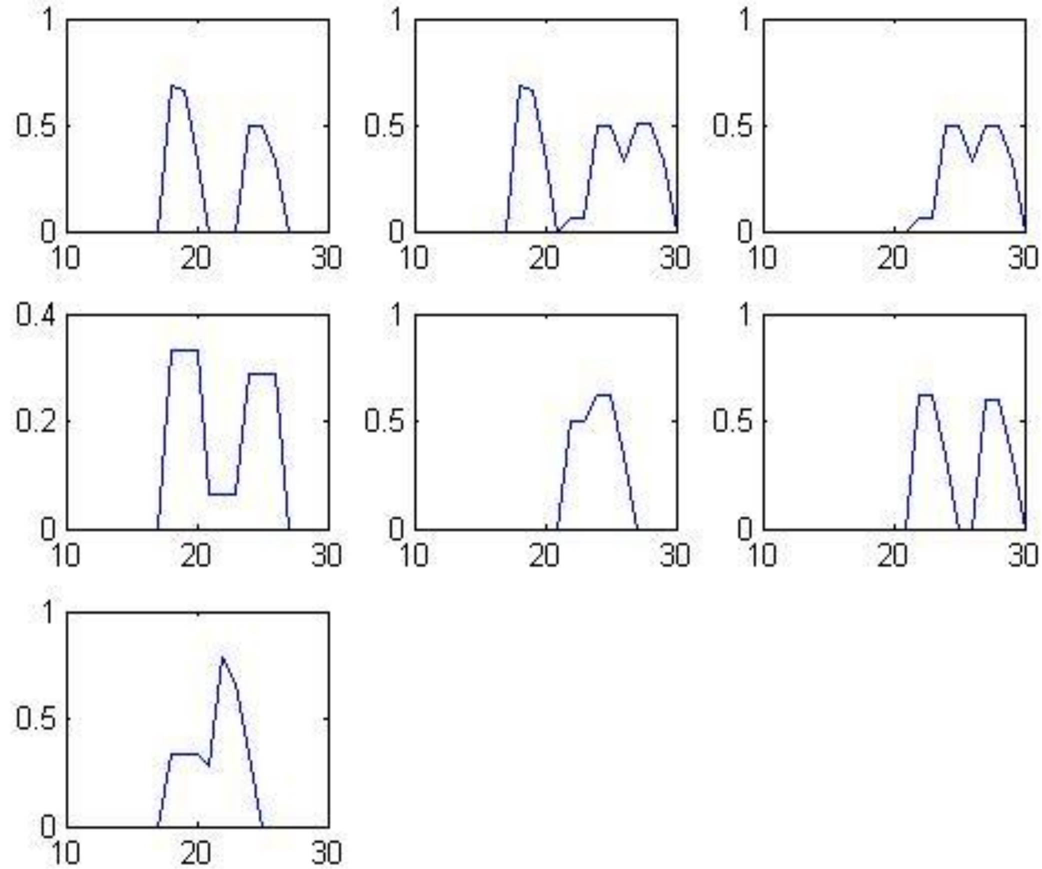
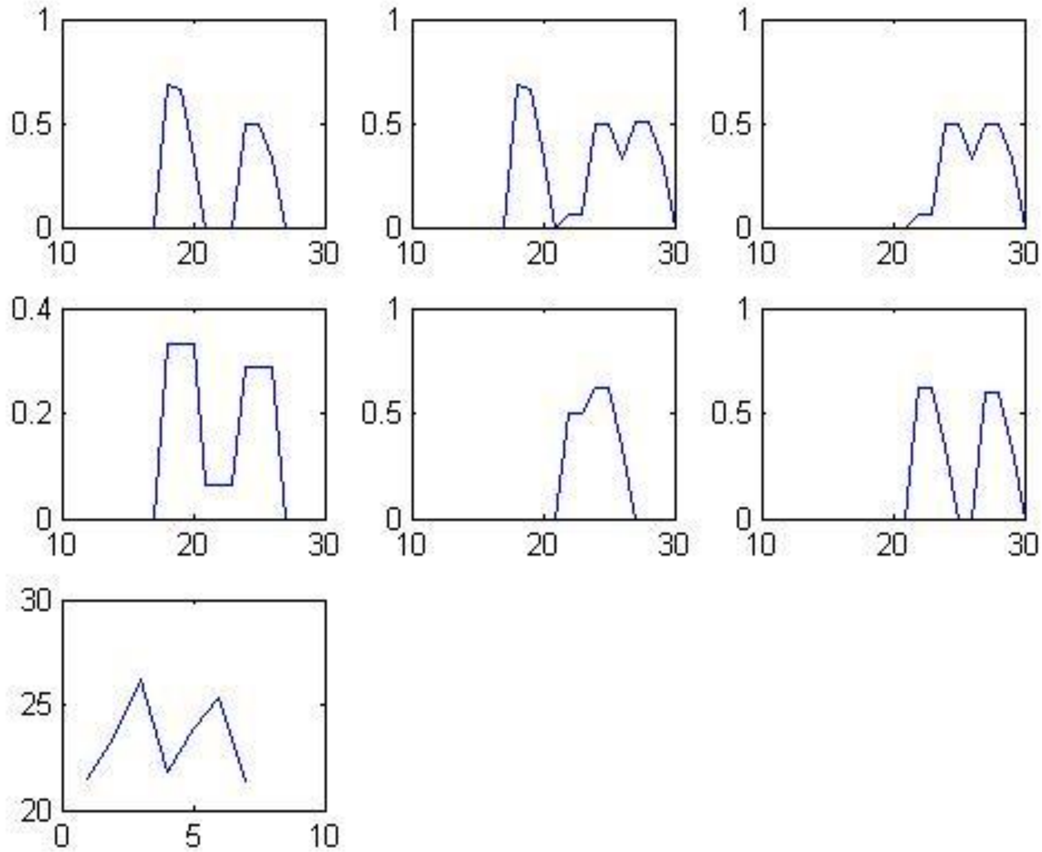


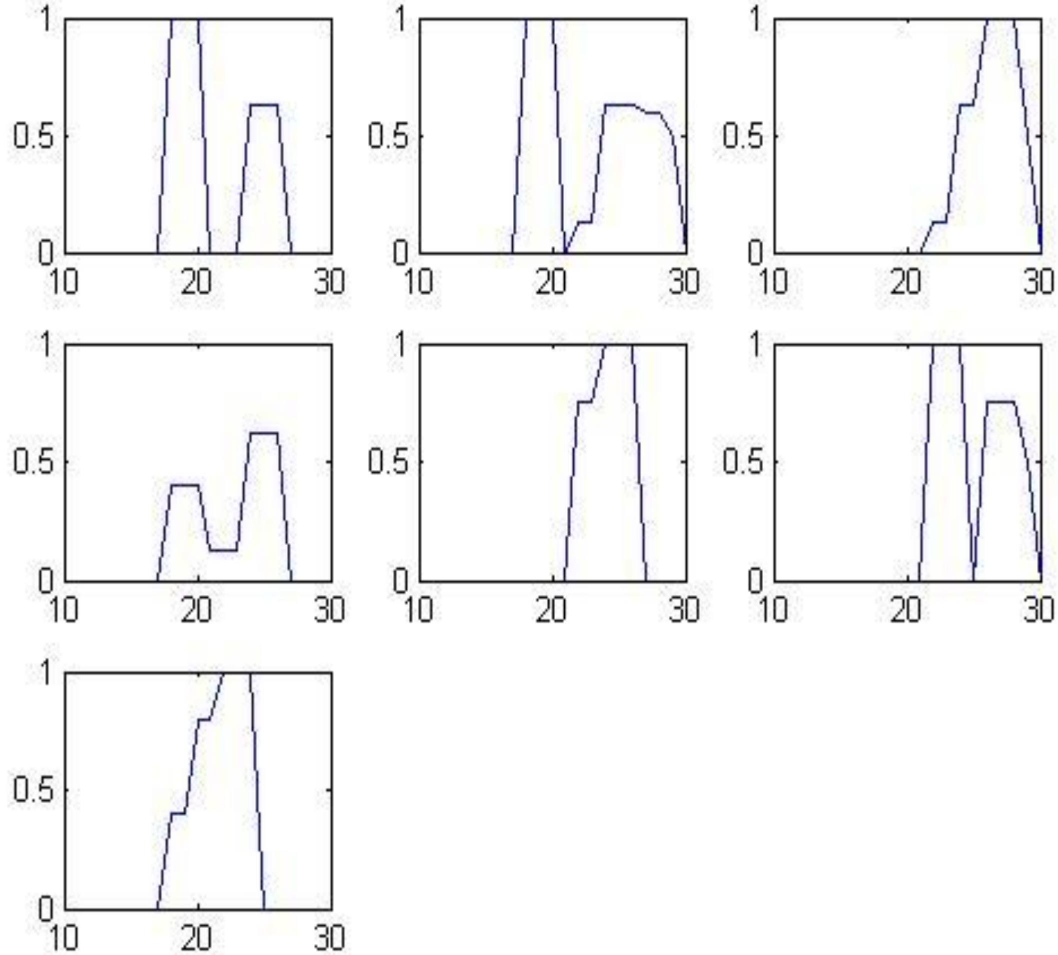
FIGURE 8: FUZZIFIED TRIANGULAR MODELS OF BDV(DC)



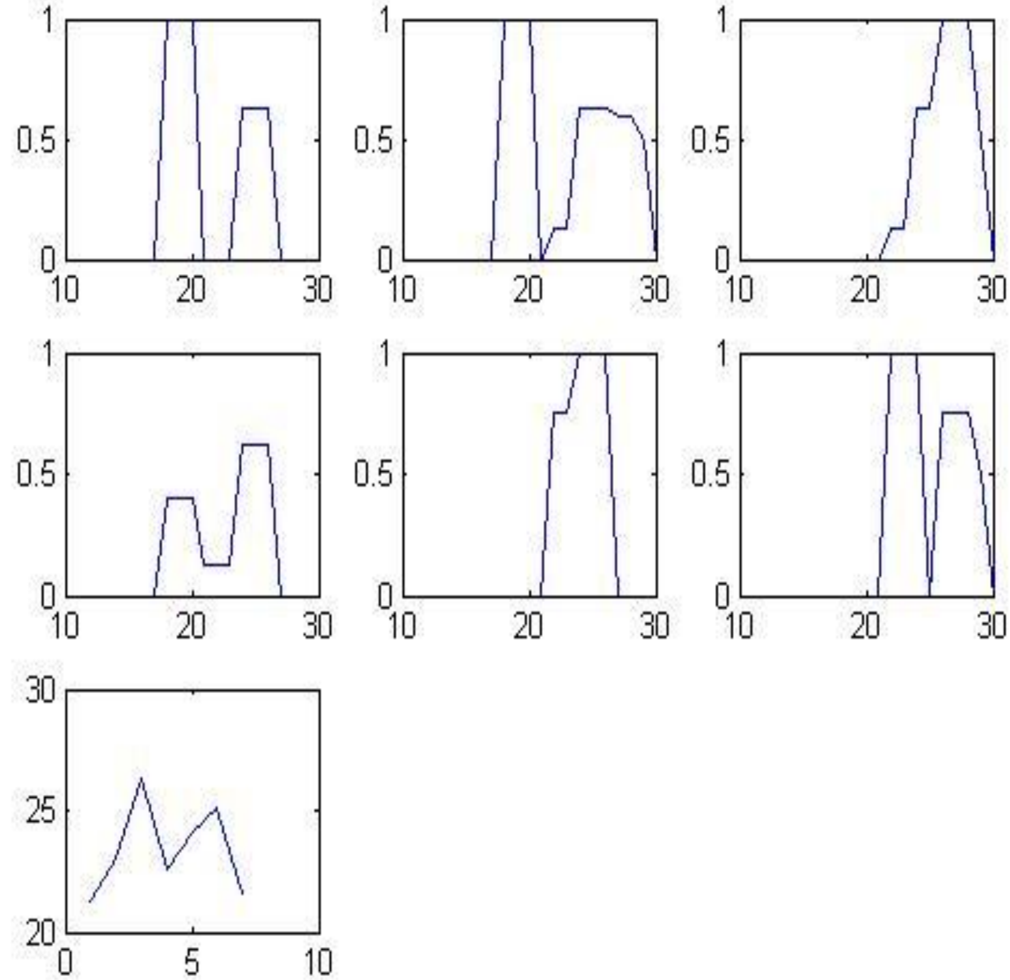
<u>FIGURE 9</u>: DEFUZZIFIED TRIANGULAR MODELS OF BDV(DC)

t(mm)	t1(mm)	d (mm)	Breakdown Voltage (Vb1) (kV)	Breakdown Voltage Vb2 (kV)	MAE (%)
0.125	0.025	1.5	23.44	21.3077	7.1502
0.125	0.025	2.0	22.88	23.0037	
0.125	0.025	3.0	23.22	26.3500	
0.125	0.025	4.0	24.44	22.5870	
0.18	0.025	3.0	24.44	24.1667	
0.26	0.125	1.5	23.00	25.0870	
0.26	0.025	4.0	23.77	21.5926	

Table 10: Comparison of the Crisp (V_b1) and defuzzified values (V_b2) of the Breakdown Voltage with Trapezoidal MF for White Minilex under dc condition



<u>FIGURE 10</u>: FUZZIFIED TRAPEZOIDAL MODELS OF BDV(DC)



<u>FIGURE 11</u>: DEFUZZIFIED TRAPEZOIDAL MODELS OF BDV(DC)

CHAPTER 5

CONCLUSIONS

CONCLUSION:

The breakdown voltage of various samples of White Minilex paper of various thickness with artificially created voids were modeled using two different shapes of the Membership functions under ac and dc conditions. The results suggest the benefits of FL in modeling the BDV of insulating samples. An advantage of this technique is that the dielectric behaviour can be analyzed at a virtually negligible computing cost. In this work the triangular and trapezoidal MFs was used to predict the breakdown voltage of White Minilex under AC as well as DC conditions. Similiarly, the work can be easily extended to by assuming Gaussian,Trapezoidal, Generalized Bell , Pi shaped MF for all the input and Output MFs.

REFERENCE

REFERENCE

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APPENDIX

APPENDIX-1

Matlab Code for BDV modeling under AC conditions using fuzzy logic and triangular MF

```
clear all;
% Three Inputs (thickness of material, thickness of void and diameter of
% void)
% To model the BDV under AC conditions using fuzzy logic
% and triangular MF(Mamdani Rule Based Inference
%  andCentroidal Defuzzification)
% MF  of the thickness of the dielectric
t= (0:0.005:0.33)';
at=0.03;
ftL=trimf(t,[0 at 0.13]);
ftML=trimf(t,[0.05 at+0.05 0.18]);
ftM=trimf(t,[0.10 at+0.10 0.23]);
ftMH=trimf(t,[0.15 at+0.15 0.28]);
ftH=trimf(t,[0.20 at+0.20 0.33]);
ft=[ftL,ftML,ftM,ftMH,ftH];
% MF of the thickness of the void
t1= (0:0.005:0.15)';
at1=0.02;
ft1L=trimf(t1,[0 at1 0.07]);
ft1H=trimf(t1,[0.08 at1+0.08 0.15]);
ft1=[ft1L,ft1H];
% MF of the diameter of the void
d= (1.0:0.1:5.8)';
ad=1.6;
fdL=trimf(d,[1.0 ad 3.0]);
fdML=trimf(d,[1.7 ad+0.7 3.7]);
fdM=trimf(d,[2.4 ad+1.4 4.4]);
fdMH=trimf(d,[3.1 ad+2.1 5.1]);
fdH=trimf(d,[3.8 ad+2.8 5.8]);
fd=[fdL,fdML,fdM,fdMH,fdH];
% MF of the breakdown voltage (BDV)
B= (1.9:0.1:2.5)';
a1=2.0;
```

```
fBL=trimf(B,[1.9 a1 2.1]);
fBML=trimf(B,[2.0 a1+0.1 2.2]);
fBM=trimf(B,[2.1 a1+0.2 2.3]);
fBMH=trimf(B,[2.2 a1+0.3 2.4]);
fBH=trimf(B,[2.3 a1+0.4 2.5]);
fB=[fBL,fBML,fBM,fBMH,fBH];
% Program for using the Fuzzy Logic System to evaluate the MAE
% (Thickness of material)
t3=[0.125;0.26;0.125;0.125;0.18;0.26;0.26];
% (Thickness of void)
 t4=[0.025;0.125;0.025;0.025;0.025;0.125;0.025];
%(Diameter of the void)
d3=[1.5;3.0;1.5;3.0;3.0;5.0;3.0];
% (Breakdown voltage)
bve1=[2.0;2.1;2.0;2.3;2.2;2.4;2.1];
%Fuzzification (thickness of material)
for z=1:7
ftL1(z)=trimf(t3(z),[0 at 0.13]);
ftML1(z)=trimf(t3(z),[0.05 at+0.05 0.18]);
ftM1(z)=trimf(t3(z),[0.10 at+0.10 0.23]);
ftMH1(z)=trimf(t3(z),[0.15 at+0.15 0.28]);
ftH1(z)=trimf(t3(z),[0.20 at+0.20 0.33]);
%Fuzzification (thickness of void)
ft1L1(z)=trimf(t4(z),[0 at1 0.07]);
ft1H1(z)=trimf(t4(z),[0.08 at1+0.08 0.15]);
%Fuzzification (diameter of void)
fdL1(z)=trimf(d3(z),[1.0 ad 3.0]);
fdML1(z)=trimf(d3(z),[1.7 ad+0.7 3.7]);
fdM1(z)=trimf(d3(z),[2.4 ad+1.4 4.4]);
fdMH1(z)=trimf(d3(z),[3.1 ad+2.1 5.1]);
fdH1(z)=trimf(d3(z),[3.8 ad+2.8 5.8]);
% Mamdani Rule Based Inference(MRBI)
for k=1:size(B)
% 1st rule fired
fBM11(z,k,:)=[ftH1(z),ft1L1(z),fdL1(z),fBM(k)];
fBM1(z,k)=min(fBM11(z,k,:));
% 2nd rule fired
fBM21(z,k,:)=[ftH1(z),ft1H1(z),fdML1(z),fBM(k)];
fBM2(z,k)=min(fBM21(z,k,:));
% 3rd rule fired
fBM31(z,k,:)=[ftMH1(z),ft1L1(z),fdL1(z),fBM(k)];
fBM3(z,k)=min(fBM31(z,k,:));
% 4th rule fired
fBMH11(z,k,:)=[ftH1(z),ft1H1(z),fdL1(z),fBMH(k)];
fBMH1(z,k)=min(fBMH11(z,k,:));
% 5th rule fired
```

```
fBH11(z,k,:)=[ftM1(z),ft1L1(z),fdM1(z),fBH(k)];
fBH1(z,k)=min(fBH11(z,k,:));
```
% 6th rule fired
```
fBH21(z,k,:)=[ftML1(z),ft1H1(z),fdML1(z),fBH(k)];
fBH2(z,k)=min(fBH21(z,k,:));
```
% 7th rule fired
```
fBMH21(z,k,:)=[ftL1(z),ft1L1(z),fdL1(z),fBMH(k)];
fBMH2(z,k)=min(fBMH21(z,k,:));
```
% 8th rule fired
```
fBM41(z,k,:)=[ftML1(z),ft1H1(z),fdL1(z),fBM(k)];
fBM4(z,k)=min(fBM41(z,k,:));
```
% 9th rule fired
```
fBMH31(z,k,:)=[ftM1(z),ft1L1(z),fdML1(z),fBMH(k)];
fBMH3(z,k)=min(fBMH31(z,k,:));
```
%10th rule fired
```
fBM51(z,k,:)=[ftMH1(z),ft1H1(z),fdH1(z),fBM(k)];
fBM5(z,k)=min(fBM51(z,k,:));
```
% 11th rule fired
```
fBM61(z,k,:)=[ftML1(z),ft1L1(z),fdML1(z),fBM(k)];
fBM6(z,k)=min(fBM61(z,k,:));
```
% 12th rule fired
```
fBM71(z,k,:)=[ftM1(z),ft1H1(z),fdML1(z),fBM(k)];
fBM7(z,k)=min(fBM71(z,k,:));
```
% 13th rule fired
```
fBM81(z,k,:)=[ftH1(z),ft1L1(z),fdM1(z),fBM(k)];
fBM8(z,k)=min(fBM81(z,k,:));
```
% 14th rule fired
```
fBM91(z,k,:)=[ftH1(z),ft1H1(z),fdMH1(z),fBM(k)];
fBM9(z,k)=min(fBM91(z,k,:));
```
% 15th rule fired
```
fBM101(z,k,:)=[ftH1(z),ft1L1(z),fdH1(z),fBM(k)];
fBM10(z,k)=min(fBM101(z,k,:));
```
% 16th rule fired
```
fBMH41(z,k,:)=[ftMH1(z),ft1H1(z),fdML1(z),fBMH(k)];
fBMH4(z,k)=min(fBMH41(z,k,:));
```
% 17th rule fired
```
fBM111(z,k,:)=[ftL1(z),ft1L1(z),fdMH1(z),fBM(k)];
fBM11(z,k)=min(fBM111(z,k,:));
```
% 18th rule fired
```
fBM121(z,k,:)=[ftM1(z),ft1H1(z),fdH1(z),fBM(k)];
fBM12(z,k)=min(fBM121(z,k,:));
```
% 19th rule fired
```
fBM131(z,k,:)=[ftML1(z),ft1L1(z),fdL1(z),fBM(k)];
fBM13(z,k)=min(fBM131(z,k,:));
```
% 20th rule fired
```
fBMH51(z,k,:)=[ftM1(z),ft1H1(z),fdMH1(z),fBMH(k)];
```

```
fBMH5(z,k)=min(fBMH51(z,k,:));
% 21st rule fired
fBM141(z,k,:)=[ftL1(z),ft1L1(z),fdH1(z),fBM(k)];
fBM14(z,k)=min(fBM141(z,k,:));
% 22nd rule fired
fBMH61(z,k,:)=[ftL1(z),ft1H1(z),fdMH1(z),fBMH(k)];
fBMH6(z,k)=min(fBMH61(z,k,:));
% 23rd rule fired
fBH31(z,k,:)=[ftL1(z),ft1L1(z),fdML1(z),fBH(k)];
fBH3(z,k)=min(fBH31(z,k,:));
% 24th rule  fired
fBM151(z,k,:)=[ftM1(z),ft1H1(z),fdL1(z),fBM(k)];
fBM15(z,k)=min(fBM151(z,k,:));
% 25th rule fired
fBM161(z,k,:)=[ftML1(z),ft1L1(z),fdH1(z),fBM(k)];
fBM16(z,k)=min(fBM161(z,k,:));
% 26th rule fired
fBM171(z,k,:)=[ftML1(z),ft1H1(z),fdMH1(z),fBM(k)];
fBM17(z,k)=min(fBM171(z,k,:));
% Fired27th rule
fBM181(z,k,:)=[ftM1(z),ft1L1(z),fdL1(z),fBM(k)];
fBM18(z,k)=min(fBM181(z,k,:));
% Fired28th rule
fBM191(z,k,:)=[ftMH1(z),ft1H1(z),fdL1(z),fBM(k)];
fBM19(z,k)=min(fBM191(z,k,:));
% Fired29th rule
fBMH71(z,k,:)=[ftMH1(z),ft1L1(z),fdML1(z),fBMH(k)];
fBMH7(z,k)=min(fBMH71(z,k,:));
% Fired30th rule
fBM201(z,k,:)=[ftH1(z),ft1H1(z),fdH1(z),fBM(k)];
fBM20(z,k)=min(fBM201(z,k,:));
% Fired31st rule
fBMH81(z,k,:)=[ftH1(z),ft1L1(z),fdMH1(z),fBMH(k)];
fBMH8(z,k)=min(fBMH81(z,k,:));
% Fired32nd rule
fBM211(z,k,:)=[ftMH1(z),ft1L1(z),fdMH1(z),fBM(k)];
fBM21(z,k)=min(fBM21(z,k,:));
% Fired33rd rule
fBMH91(z,k,:)=[ftML1(z),ft1H1(z),fdH1(z),fBMH(k)];
fBMH9(z,k)=min(fBMH91(z,k,:));
% Fired34th rule
fBM221(z,k,:)=[ftL1(z),ft1H1(z),fdM1(z),fBM(k)];
fBM22(z,k)=min(fBM221(z,k,:));
% Aggregated Membership function(taking the maximum of all 34
% outputs  for each value of input& each value of
fB2(z,k,:)=[fBM1(z,k);fBM2(z,k);fBM3(z,k);fBMH1(z,k);fBMH1(z,k);fBH2(z,k);
```

```
fBMH2(z,k);fBM4(z,k);fBMH3(z,k);fBM5(z,k);fBM6(z,k);fBM7(z,k);fBM8(z,k);fBM9(z,k);
fBM10(z,k);fBMH4(z,k);fBM11(z,k);fBM12(z,k);fBM13(z,k);fBMH5(z,k);fBM14(z,k);
fBMH6(z,k);fBH3(z,k);fBM15(z,k);fBM16(z,k);fBM17(z,k);fBM18(z,k);fBM19(z,k);
fBMH7(z,k);fBM20(z,k);fBMH8(z,k);fBM21(z,k);fBMH9(z,k);fBM22(z,k)];
fB3(z,k)= max(fB2(z,k,:));
end;
end;
% Defuzzification(Centroidal Method)
for z=1:7
bve2(z,:)= defuzz(B,fB3(z,:),'centroid');
end;
% MAE
MAE=0;
for z=1:7
MAE = MAE+abs((bve2(z,:)-bve1(z))/(bve1(z)))*(100/7);
end;
subplot(3,3,1); plot(B, [fB3(1,:) ]);
subplot(3,3,2); plot(B, [fB3(2,:) ]);
subplot(3,3,3); plot(B, [fB3(3,:) ]);
subplot(3,3,4); plot(B, [fB3(4,:) ]);
subplot(3,3,5); plot(B, [fB3(5,:) ]);
subplot(3,3,6); plot(B, [fB3(6,:) ]);
subplot(3,3,7); plot(B, [fB3(7,:) ]);
```

Appendix 2

Matlab Code for BDV modeling under AC conditions using fuzzy logic and trapezoidal MFs

```
clear all;
% Three Inputs (thickness ofthe  material, thickness of void and diameter of
% void)
% To model the BDV under AC conditions using fuzzy logic
% and trapezoidal MF(Mamdani Rule Based Inference
% & Centroid Defuzzification)
% MF of the thickness of the dielectric
t= (0:0.005:0.33)';
at=0.03;
ftL=trapmf(t,[0 at at+0.07 0.13]);
ftML=trapmf(t,[0.05 at+0.05 at+0.12 0.18]);
ftM=trapmf(t,[0.10 at+0.10 at+0.17 0.23]);
ftMH=trapmf(t,[0.15 at+0.15 at+0.22 0.28]);
ftH=trapmf(t,[0.20 at+0.20 at+0.27 0.33]);
ft=[ftL,ftML,ftM,ftMH,ftH];
% MF of the thickness of the void
t1= (0:0.005:0.15)';
at1=0.02;
ft1L=trapmf(t1,[0 at1 at1+0.03 0.07]);
ft1H=trapmf(t1,[0.08 at1+0.08 at1+0.11 0.15]);
ft1=[ft1L,ft1H];
% MF of the diameter of the void
d= (1.0:0.1:5.8)';
ad=1.5;
fdL=trapmf(d,[1.0 ad ad+1 3.0]);
fdML=trapmf(d,[1.7 ad+0.7 ad+1.7 3.7]);
fdM=trapmf(d,[2.4 ad+1.4 ad+2.4 4.4]);
fdMH=trapmf(d,[3.1 ad+2.1 ad+3.1 5.1]);
fdH=trapmf(d,[3.8 ad+2.8 ad+3.8 5.8]);
fd=[fdL,fdML,fdM,fdMH,fdH];
% MF of the breakdown voltage
B= (1.9:0.1:2.5)';
a1=1.95;
```

```
fBL=trapmf(B,[1.9 a1 a1+0.1 2.1]);
fBML=trapmf(B,[2.0 a1+0.1 a1+0.2 2.2]);
fBM=trapmf(B,[2.1 a1+0.2 a1+0.3 2.3]);
fBMH=trapmf(B,[2.2 a1+0.3 a1+0.4 2.4]);
fBH=trapmf(B,[2.3 a1+0.4 a1+0.5 2.5]);
fB=[fBL,fBML,fBM,fBMH,fBH];

% Program for using the Fuzzy Logic System to evaluate the MAE
% (Thickness of material)
t3=[0.125;0.26;0.125;0.125;0.18;0.26;0.26];
% (Thickness of void)
 t4=[0.025;0.125;0.025;0.025;0.025;0.125;0.025];
 %(Diameter of the void)
d3=[1.5;3.0;1.5;3.0;3.0;5.0;3.0];
% (Breakdown voltage)
bve1=[2.0;2.1;2.0;2.3;2.2;2.4;2.1];
%Fuzzification (thickness of material)
for z=1:7
ftL1(z)=trapmf(t3(z),[0 at at+0.07 0.13]);
ftML1(z)=trapmf(t3(z),[0.05 at+0.05 at+0.12 0.18]);
ftM1(z)=trapmf(t3(z),[0.10 at+0.10 at+0.17 0.23]);
ftMH1(z)=trapmf(t3(z),[0.15 at+0.15 at+0.22 0.28]);
ftH1(z)=trapmf(t3(z),[0.20 at+0.20 at+0.27 0.33]);
%Fuzzification (thickness of void)
ft1L1(z)=trapmf(t4(z),[0 at1 at1+0.03 0.07]);
ft1H1(z)=trapmf(t4(z),[0.08 at1+0.08 at1+0.11 0.15]);
%Fuzzification (diameter of void)
fdL1(z)=trapmf(d3(z),[1.0 ad ad+1 3.0]);
fdML1(z)=trapmf(d3(z),[1.7 ad+0.7 ad+1.7 3.7]);
fdM1(z)=trapmf(d3(z),[2.4 ad+1.4 ad+2.4 4.4]);
fdMH1(z)=trapmf(d3(z),[3.1 ad+2.1 ad+3.1 5.1]);
fdH1(z)=trapmf(d3(z),[3.8 ad+2.8 ad+3.8 5.8]);
% Mamdani Rule Based Inference(MRBI)
for k=1:size(B)
% Fired1st rule
fBM11(z,k,:)=[ftH1(z),ft1L1(z),fdL1(z),fBM(k)];
fBM1(z,k)=min(fBM11(z,k,:));
% Fired2nd rule
fBM21(z,k,:)=[ftH1(z),ft1H1(z),fdML1(z),fBM(k)];
fBM2(z,k)=min(fBM21(z,k,:));
% Fired3rd rule
fBM31(z,k,:)=[ftMH1(z),ft1L1(z),fdL1(z),fBM(k)];
fBM3(z,k)=min(fBM31(z,k,:));
% Fired4th rule
fBMH11(z,k,:)=[ftH1(z),ft1H1(z),fdL1(z),fBMH(k)];
fBMH1(z,k)=min(fBMH11(z,k,:));
```

```
% Fired5th rule
fBH11(z,k,:)=[ftM1(z),ft1L1(z),fdM1(z),fBH(k)];
fBH1(z,k)=min(fBH11(z,k,:));
% Fired6th rule
fBH21(z,k,:)=[ftML1(z),ft1H1(z),fdML1(z),fBH(k)];
fBH2(z,k)=min(fBH21(z,k,:));
% Fired7th rule
fBMH21(z,k,:)=[ftL1(z),ft1L1(z),fdL1(z),fBMH(k)];
fBMH2(z,k)=min(fBMH21(z,k,:));
% Fired8th rule
fBM41(z,k,:)=[ftML1(z),ft1H1(z),fdL1(z),fBM(k)];
fBM4(z,k)=min(fBM41(z,k,:));
% Fired9th rule
fBMH31(z,k,:)=[ftM1(z),ft1L1(z),fdML1(z),fBMH(k)];
fBMH3(z,k)=min(fBMH31(z,k,:));
% Fired10th rule
fBM51(z,k,:)=[ftMH1(z),ft1H1(z),fdH1(z),fBM(k)];
fBM5(z,k)=min(fBM51(z,k,:));
% Fired11th rule
fBM61(z,k,:)=[ftML1(z),ft1L1(z),fdML1(z),fBM(k)];
fBM6(z,k)=min(fBM61(z,k,:));
% Fired12th rule
fBM71(z,k,:)=[ftM1(z),ft1H1(z),fdML1(z),fBM(k)];
fBM7(z,k)=min(fBM71(z,k,:));
% Fired13th rule
fBM81(z,k,:)=[ftH1(z),ft1L1(z),fdM1(z),fBM(k)];
fBM8(z,k)=min(fBM81(z,k,:));
% Fired14th rule
fBM91(z,k,:)=[ftH1(z),ft1H1(z),fdMH1(z),fBM(k)];
fBM9(z,k)=min(fBM91(z,k,:));
% Fired15th rule
fBM101(z,k,:)=[ftH1(z),ft1L1(z),fdH1(z),fBM(k)];
fBM10(z,k)=min(fBM101(z,k,:));
% Fired16th rule
fBMH41(z,k,:)=[ftMH1(z),ft1H1(z),fdML1(z),fBMH(k)];
fBMH4(z,k)=min(fBMH41(z,k,:));
% Fired17th rule
fBM111(z,k,:)=[ftL1(z),ft1L1(z),fdMH1(z),fBM(k)];
fBM11(z,k)=min(fBM111(z,k,:));
% Fired18th rule
fBM121(z,k,:)=[ftM1(z),ft1H1(z),fdH1(z),fBM(k)];
fBM12(z,k)=min(fBM121(z,k,:));
% Fired19th rule
fBM131(z,k,:)=[ftML1(z),ft1L1(z),fdL1(z),fBM(k)];
fBM13(z,k)=min(fBM131(z,k,:));
% Fired20th rule
```

```
fBMH51(z,k,:)=[ftM1(z),ft1H1(z),fdMH1(z),fBMH(k)];
fBMH5(z,k)=min(fBMH51(z,k,:));
```
% Fired21st rule
```
fBM141(z,k,:)=[ftL1(z),ft1L1(z),fdH1(z),fBM(k)];
fBM14(z,k)=min(fBM141(z,k,:));
```
% Fired22nd rule
```
fBMH61(z,k,:)=[ftL1(z),ft1H1(z),fdMH1(z),fBMH(k)];
fBMH6(z,k)=min(fBMH61(z,k,:));
```
% Fired23rd rule
```
fBH31(z,k,:)=[ftL1(z),ft1L1(z),fdML1(z),fBH(k)];
fBH3(z,k)=min(fBH31(z,k,:));
```
% Fired24th rule
```
fBM151(z,k,:)=[ftM1(z),ft1H1(z),fdL1(z),fBM(k)];
fBM15(z,k)=min(fBM151(z,k,:));
```
% Fired25th rule
```
fBM161(z,k,:)=[ftML1(z),ft1L1(z),fdH1(z),fBM(k)];
fBM16(z,k)=min(fBM161(z,k,:));
```
% Fired26th rule
```
fBM171(z,k,:)=[ftML1(z),ft1H1(z),fdMH1(z),fBM(k)];
fBM17(z,k)=min(fBM171(z,k,:));
```
% Fired27th rule
```
fBM181(z,k,:)=[ftM1(z),ft1L1(z),fdL1(z),fBM(k)];
fBM18(z,k)=min(fBM181(z,k,:));
```
% Fired28th rule
```
fBM191(z,k,:)=[ftMH1(z),ft1H1(z),fdL1(z),fBM(k)];
fBM19(z,k)=min(fBM191(z,k,:));
```
% Fired29th rule
```
fBMH71(z,k,:)=[ftMH1(z),ft1L1(z),fdML1(z),fBMH(k)];
fBMH7(z,k)=min(fBMH71(z,k,:));
```
% Fired30th rule
```
fBM201(z,k,:)=[ftH1(z),ft1H1(z),fdH1(z),fBM(k)];
fBM20(z,k)=min(fBM201(z,k,:));
```
% Fired31st rule
```
fBMH81(z,k,:)=[ftH1(z),ft1L1(z),fdMH1(z),fBMH(k)];
fBMH8(z,k)=min(fBMH81(z,k,:));
```
% Fired32nd rule
```
fBM211(z,k,:)=[ftMH1(z),ft1L1(z),fdMH1(z),fBM(k)];
fBM21(z,k)=min(fBM21(z,k,:));
```
% Fired33rd rule
```
fBMH91(z,k,:)=[ftML1(z),ft1H1(z),fdH1(z),fBMH(k)];
fBMH9(z,k)=min(fBMH91(z,k,:));
```
% Fired34th rule
```
fBM221(z,k,:)=[ftL1(z),ft1H1(z),fdM1(z),fBM(k)];
fBM22(z,k)=min(fBM221(z,k,:));
```
% Aggregated Membership function(taking the maximum of all 34
% outputs for each value of input& each value of

```
fB2(z,k,:)=[fBM1(z,k);fBM2(z,k);fBM3(z,k);fBMH1(z,k);fBMH1(z,k);fBH2(z,k);
fBMH2(z,k);fBM4(z,k);fBMH3(z,k);fBM5(z,k);fBM6(z,k);fBM7(z,k);fBM8(z,k);
fBM9(z,k);fBM10(z,k);fBMH4(z,k);fBM11(z,k);fBM12(z,k);fBM13(z,k);fBMH5(z,k);
fBM14(z,k);fBMH6(z,k);fBH3(z,k);fBM15(z,k);fBM16(z,k);fBM17(z,k);fBM18(z,k);
fBM19(z,k);fBMH7(z,k);fBM20(z,k);fBMH8(z,k);fBM21(z,k);fBMH9(z,k);
fBM22(z,k)];
fB3(z,k)= max(fB2(z,k,:));
end;
end;
% Defuzzification(Centroidal Method)
for z=1:7
bve2(z,:)= defuzz(B,fB3(z,:),'centroid');
end;
% MAE
MAE=0;
for z=1:7
MAE = MAE+abs((bve2(z,:)-bve1(z))/(bve1(z)))*(100/7);
end;
subplot(3,3,1); plot(B, [fB3(1,:) ]);
subplot(3,3,2); plot(B, [fB3(2,:) ]);
subplot(3,3,3); plot(B, [fB3(3,:) ]);
subplot(3,3,4); plot(B, [fB3(4,:) ]);
subplot(3,3,5); plot(B, [fB3(5,:) ]);
subplot(3,3,6); plot(B, [fB3(6,:) ]);
subplot(3,3,7); plot(B, [fB3(7,:) ]);
```

APPENDIX 3

MATLAB Code for BDV modeling under DC conditions using fuzzy logic

and triangular MF

```
clear all;
% Three Inputs (thickness of material, thickness of void and diameter of
% void)
% To model the BDV under DC conditions using fuzzy logic
% and triangular MF (Mamdani Rule Based Inference
% & Centroid Defuzzification)
% MF of the thickness of the dielectric
t= (0:0.005:0.33)';
at=0.05;
ftL=trimf(t,[0 at 0.13]);
ftML=trimf(t,[0.05 at+0.05 0.18]);
ftM=trimf(t,[0.10 at+0.10 0.23]);
ftMH=trimf(t,[0.15 at+0.15 0.28]);
ftH=trimf(t,[0.20 at+0.20 0.33]);
ft=[ftL,ftML,ftM,ftMH,ftH];
% MF of the thickness of the void
t1= (0:0.005:0.15)';
at1=0.03;
ft1L=trimf(t1,[0 at1 0.07]);
ft1H=trimf(t1,[0.08 at1+0.08 0.15]);
ft1=[ft1L,ft1H];
% MF of the diameter of the void
d= (1.0:0.1:5.8)';
ad=1.6;
fdL=trimf(d,[1.0 ad 3.0]);
fdML=trimf(d,[1.7 ad+0.7 3.7]);
fdM=trimf(d,[2.4 ad+1.4 4.4]);
fdMH=trimf(d,[3.1 ad+2.1 5.1]);
fdH=trimf(d,[3.8 ad+2.8 5.8]);
fd=[fdL,fdML,fdM,fdMH,fdH];
% MF of the breakdown voltage
B= (17:1:30)';
a1=18;
```

```
fBL=trimf(B,[17 a1 21]);
fBML=trimf(B,[19 a1+2 23]);
fBM=trimf(B,[21 a1+4 25]);
fBMH=trimf(B,[23 a1+6 27]);
fBH=trimf(B,[26 a1+9 30]);
fB=[fBL,fBML,fBM,fBMH,fBH];

% Program for using the Fuzzy Logic System to evaluate the MAE
% (Thickness of material)
t3=[0.125;0.125;0.125;0.125;0.18;0.18;0.26];
% (Thickness of void)
t4=[0.025;0.025;0.025;0.025;0.025;0.125;0.025];
% (Diameter of the void)
d3=[1.5;2.0;3.0;4.0;3.0;1.5;4.0];
% (Breakdown voltage)
bve1=[23.44;22.88;23.22;24.44;24.44;23.00;23.77];
%Fuzzification (thickness of material)
for z=1:7
ftL1(z)=trimf(t3(z),[0 at 0.13]);
ftML1(z)=trimf(t3(z),[0.05 at+0.05 0.18]);
ftM1(z)=trimf(t3(z),[0.10 at+0.10 0.23]);
ftMH1(z)=trimf(t3(z),[0.15 at+0.15 0.28]);
ftH1(z)=trimf(t3(z),[0.20 at+0.20 0.33]);
%Fuzzification (thickness of void)
ft1L1(z)=trimf(t4(z),[0 at1 0.07]);
ft1H1(z)=trimf(t4(z),[0.08 at1+0.08 0.15]);
%Fuzzification (diameter of void)
fdL1(z)=trimf(d3(z),[1.0 ad 3.0]);
fdML1(z)=trimf(d3(z),[1.7 ad+0.7 3.7]);
fdM1(z)=trimf(d3(z),[2.4 ad+1.4 4.4]);
fdMH1(z)=trimf(d3(z),[3.1 ad+2.1 5.1]);
fdH1(z)=trimf(d3(z),[3.8 ad+2.8 5.8]);
% Mamdani Rule Based Inference(MRBI)
for k=1:size(B)
% Fired 1st rule
fBM11(z,k,:)=[ftH1(z),ft1L1(z),fdL1(z),fBL(k)];
fBM1(z,k)=min(fBM11(z,k,:));
% Fired 2nd rule
fBMH11(z,k,:)=[ftH1(z),ft1H1(z),fdML1(z),fBML(k)];
fBMH1(z,k)=min(fBMH11(z,k,:));
% Fired 3rd rule
fBH11(z,k,:)=[ftMH1(z),ft1L1(z),fdL1(z),fBL(k)];
fBH1(z,k)=min(fBH11(z,k,:));
% Fired 4th rule
fBM21(z,k,:)=[ftH1(z),ft1H1(z),fdL1(z),fBM(k)];
```

```
fBM2(z,k)=min(fBM21(z,k,:));
% Fired 5th rule
fBML11(z,k,:)=[ftM1(z),ft1L1(z),fdM1(z),fBMH(k)];
fBML1(z,k)=min(fBML11(z,k,:));
% Fired 6th rule
fBMH21(z,k,:)=[ftML1(z),ft1H1(z),fdML1(z),fBH(k)];
fBMH2(z,k)=min(fBMH21(z,k,:));
% Fired 7th rule
fBL11(z,k,:)=[ftL1(z),ft1L1(z),fdL1(z),fBL(k)];
fBL1(z,k)=min(fBL11(z,k,:));
% Fired 8th rule
fBL21(z,k,:)=[ftML1(z),ft1H1(z),fdL1(z),fBML(k)];
fBL2(z,k)=min(fBL21(z,k,:));
% Fired 9th rule
fBML21(z,k,:)=[ftM1(z),ft1L1(z),fdML1(z),fBMH(k)];
fBML2(z,k)=min(fBML21(z,k,:));
% Fired 10th rule
fBM31(z,k,:)=[ftMH1(z),ft1H1(z),fdH1(z),fBM(k)];
fBM3(z,k)=min(fBM31(z,k,:));
% Fired 11th rule
fBMH31(z,k,:)=[ftML1(z),ft1L1(z),fdML1(z),fBH(k)];
fBMH3(z,k)=min(fBMH31(z,k,:));
% Fired 12th rule
fBM41(z,k,:)=[ftM1(z),ft1H1(z),fdML1(z),fBMH(k)];
fBM4(z,k)=min(fBM41(z,k,:));
% Fired 13th rule
fBH21(z,k,:)=[ftH1(z),ft1L1(z),fdM1(z),fBML(k)];
fBH2(z,k)=min(fBH21(z,k,:));
% Fired 14th rule
fBMH41(z,k,:)=[ftH1(z),ft1H1(z),fdMH1(z),fBH(k)];
fBMH4(z,k)=min(fBMH41(z,k,:));
% Fired 15th rule
fBM51(z,k,:)=[ftH1(z),ft1L1(z),fdH1(z),fBL(k)];
fBM5(z,k)=min(fBM51(z,k,:));
% Fired 16th rule
fBML31(z,k,:)=[ftMH1(z),ft1H1(z),fdML1(z),fBMH(k)];
fBML3(z,k)=min(fBML31(z,k,:));
% Fired 17th rule
fBL31(z,k,:)=[ftL1(z),ft1L1(z),fdMH1(z),fBML(k)];
fBL3(z,k)=min(fBL31(z,k,:));
% Fired 18th rule
fBH31(z,k,:)=[ftM1(z),ft1H1(z),fdH1(z),fBML(k)];
fBH3(z,k)=min(fBH31(z,k,:));
% Fired 19th rule
fBM61(z,k,:)=[ftML1(z),ft1L1(z),fdL1(z),fBL(k)];
fBM6(z,k)=min(fBM61(z,k,:));
```

% Fired 20th rule
fBML41(z,k,:)=[ftM1(z),ft1H1(z),fdMH1(z),fBM(k)];
fBML4(z,k)=min(fBML41(z,k,:));
% Fired 21st rule
fBL41(z,k,:)=[ftL1(z),ft1L1(z),fdH1(z),fBM(k)];
fBL4(z,k)=min(fBL41(z,k,:));
% Fired 22nd rule
fBM71(z,k,:)=[ftL1(z),ft1H1(z),fdMH1(z),fBMH(k)];
fBM7(z,k)=min(fBM71(z,k,:));
% Fired 23rd rule
fBML51(z,k,:)=[ftL1(z),ft1L1(z),fdML1(z),fBM(k)];
fBML5(z,k)=min(fBML51(z,k,:));
% Fired 24th rule
fBMH51(z,k,:)=[ftM1(z),ft1H1(z),fdL1(z),fBM(k)];
fBMH5(z,k)=min(fBMH51(z,k,:));
% Fired25th rule
fBMH61(z,k,:)=[ftML1(z),ft1L1(z),fdH1(z),fBL(k)];
fBMH6(z,k)=min(fBMH61(z,k,:));
% Fired 26th rule
fBM81(z,k,:)=[ftML1(z),ft1H1(z),fdMH1(z),fBM(k)];
fBM8(z,k)=min(fBM81(z,k,:));
% Fired 27th rule
fBMH71(z,k,:)=[ftM1(z),ft1L1(z),fdL1(z),fBMH(k)];
fBMH7(z,k)=min(fBMH71(z,k,:));
% Fired 28th rule
fBMH81(z,k,:)=[ftMH1(z),ft1H1(z),fdL1(z),fBH(k)];
fBMH8(z,k)=min(fBMH81(z,k,:));
% Fired 29th rule
fBH41(z,k,:)=[ftMH1(z),ft1L1(z),fdML1(z),fBM(k)];
fBH4(z,k)=min(fBH41(z,k,:));
% Fired 30th rule
fBMH91(z,k,:)=[ftH1(z),ft1H1(z),fdH1(z),fBML(k)];
fBMH9(z,k)=min(fBMH91(z,k,:));
% Fired 31st rule
fBM91(z,k,:)=[ftH1(z),ft1L1(z),fdMH1(z),fBM(k)];
fBM9(z,k)=min(fBM91(z,k,:));
% Fired 32nd rule
fBMH101(z,k,:)=[ftMH1(z),ft1L1(z),fdMH1(z),fBML(k)];
fBMH10(z,k)=min(fBMH101(z,k,:));
% Fired 33rd rule
fBM101(z,k,:)=[ftML1(z),ft1H1(z),fdH1(z),fBL(k)];
fBM10(z,k)=min(fBM101(z,k,:));
% Fired34th rule
fBML61(z,k,:)=[ftL1(z),ft1H1(z),fdM1(z),fBML(k)];
fBML6(z,k)=min(fBML61(z,k,:));
% Aggregated Membership function(taking the maximum of all 34

```
% outputs for each value of input& each value of
fB2(z,k,:)=[fBM1(z,k);fBMH1(z,k);fBH1(z,k);fBM2(z,k);fBML1(z,k);fBMH2(z,k);fBL1(z,);
fBL2(z,k);fBML2(z,k);fBM3(z,k);fBMH3(z,k);fBM4(z,k);fBH2(z,k);fBMH4(z,k);fBM5(z,k);
fBML3(z,k);fBL3(z,k);fBH3(z,k);fBM6(z,k);fBML4(z,k);fBL4(z,k);fBM7(z,k);fBML5(z,k);
fBMH5(z,k);fBMH6(z,k);fBM8(z,k);fBMH7(z,k);fBMH8(z,k);fBH4(z,k);fBMH9(z,k);
fBM9(z,k);fBMH10(z,k);fBM10(z,k);fBML6(z,k)];
fB3(z,k)= max(fB2(z,k,:));
end;
end;
% Defuzzification(Centroidal Method)
for z=1:7
bve2(z,:)= defuzz(B,fB3(z,:),'centroid');
end;
% MAE
MAE=0;
for z=1:7
MAE = MAE+abs((bve2(z,:)-bve1(z))/(bve1(z)))*(100/7);
end;
subplot(3,3,1); plot(B, [fB3(1,:) ]);
subplot(3,3,2); plot(B, [fB3(2,:) ]);
subplot(3,3,3); plot(B, [fB3(3,:) ]);
subplot(3,3,4); plot(B, [fB3(4,:) ]);
subplot(3,3,5); plot(B, [fB3(5,:) ]);
subplot(3,3,6); plot(B, [fB3(6,:) ]);
subplot(3,3,7); plot(B, [fB3(7,:) ]);
```

Appendix 4

Matlab Code for BDV modeling under DC conditions using fuzzy logic and trapezoidal membership function

```
clear all;
% Three Inputs (thickness of material, thickness of void and diameter of
% void)
% To model the BDV under DC conditions using fuzzy logic
% and trapezoidal MF (Mamdani Rule Based Inference
% & Centroid Defuzzification)
% MF of thickness of the dielectric
t= (0:0.005:0.33)';
at=0.05;
ftL=trapmf(t,[0 at at+0.04 0.13]);
ftML=trapmf(t,[0.05 at+0.04 at+0.09 0.18]);
ftM=trapmf(t,[0.10 at+0.09 at+0.14 0.23]);
ftMH=trapmf(t,[0.15 at+0.14 at+0.19 0.28]);
ftH=trapmf(t,[0.20 at+0.19 at+0.24 0.33]);
ft=[ftL,ftML,ftM,ftMH,ftH];
% MF of the thickness of the void
t1= (0:0.003:0.12:0.15)';
at1=0.02;
```

```
ft1L=trapmf(t1,[0 at1 at1+0.03 0.07]);
ft1H=trapmf(t1,[0.08 at1+0.08 at1+0.11 0.15]);
ft1=[ft1L,ft1H];
```

% MF of the diameter of the void

```
d= (1.0:0.1:5.8)';
ad=1.5;
fdL=trapmf(d,[1.0 ad ad+1 3.0]);
fdML=trapmf(d,[1.7 ad+0.7 ad+1.7 3.7]);
fdM=trapmf(d,[2.4 ad+1.4 ad+2.4 4.4]);
fdMH=trapmf(d,[3.1 ad+2.1 ad+3.1 5.1]);
fdH=trapmf(d,[3.8 ad+2.8 ad+3.8 5.8]);
fd=[fdL,fdML,fdM,fdMH,fdH];
```

% MF of the breakdown voltage

```
B= (17:1:30)';
a1=18;
fBL=trapmf(B,[17 a1 a1+2 21]);
fBML=trapmf(B,[19 a1+2 a1+4 23]);
fBM=trapmf(B,[21 a1+4 a1+6 25]);
fBMH=trapmf(B,[23 a1+6 a1+8 27]);
fBH=trapmf(B,[25 a1+8 a1+10 30]);
fB=[fBL,fBML,fBM,fBMH,fBH];
```

% Program for using the Fuzzy Logic System to evaluate the MAE

% (Thickness of material)

```
t3=[0.125;0.125;0.125;0.125;0.18;0.18;0.26];
```

% (Thickness of void)

```
t4=[0.025;0.025;0.025;0.025;0.025;0.125;0.025];
```

% (Diameter of the void)

```
d3=[1.5;2.0;3.0;4.0;3.0;1.5;4.0];
```

% (Breakdown voltage)

```
bve1=[23.44;22.88;23.22;24.44;24.44;23.00;23.77];
```

%Fuzzification (thickness of material)

```
for z=1:7
ftL1(z)=trapmf(t3(z),[0 at at+0.04 0.13]);
ftML1(z)=trapmf(t3(z),[0.05 at+0.04 at+0.09 0.18]);
ftM1(z)=trapmf(t3(z),[0.10 at+0.09 at+0.14 0.23]);
ftMH1(z)=trapmf(t3(z),[0.15 at+0.14 at+0.19 0.28]);
ftH1(z)=trapmf(t3(z),[0.20 at+0.19 at+0.24 0.33]);
```

%Fuzzification (thickness of void)

```
ft1L1(z)=trapmf(t4(z),[0 at1 at1+0.03 0.07]);
ft1H1(z)=trapmf(t4(z),[0.08 at1+0.08 at1+0.11 0.15]);
```

%Fuzzification (diameter of void)

```
fdL1(z)=trapmf(d3(z),[1.0 ad ad+1 3.0]);
fdML1(z)=trapmf(d3(z),[1.7 ad+0.7 ad+1.7 3.7]);
fdM1(z)=trapmf(d3(z),[2.4 ad+1.4 ad+2.4 4.4]);
fdMH1(z)=trapmf(d3(z),[3.1 ad+2.1 ad+3.1 5.1]);
fdH1(z)=trapmf(d3(z),[3.8 ad+2.8 ad+3.8 5.8]);
```

% Mamdani Rule Based Inference(MRBI)

```
for k=1:size(B)
```

% Fired1st rule

```
fBM11(z,k,:)=[ftH1(z),ft1L1(z),fdL1(z),fBL(k)];
fBM1(z,k)=min(fBM11(z,k,:));
```

% Fired2nd rule

```
fBMH11(z,k,:)=[ftH1(z),ft1H1(z),fdML1(z),fBML(k)];
fBMH1(z,k)=min(fBMH11(z,k,:));
```

% Fired3rd rule

fBH11(z,k,:)=[ftMH1(z),ft1L1(z),fdL1(z),fBL(k)];

fBH1(z,k)=min(fBH11(z,k,:));

% Fired4th rule

fBM21(z,k,:)=[ftH1(z),ft1H1(z),fdL1(z),fBM(k)];

fBM2(z,k)=min(fBM21(z,k,:));

% Fired5th rule

fBML11(z,k,:)=[ftM1(z),ft1L1(z),fdM1(z),fBMH(k)];

fBML1(z,k)=min(fBML11(z,k,:));

% Fired6th rule

fBMH21(z,k,:)=[ftML1(z),ft1H1(z),fdML1(z),fBH(k)];

fBMH2(z,k)=min(fBMH21(z,k,:));

% Fired7th rule

fBL11(z,k,:)=[ftL1(z),ft1L1(z),fdL1(z),fBL(k)];

fBL1(z,k)=min(fBL11(z,k,:));

% Fired8th rule

fBL21(z,k,:)=[ftML1(z),ft1H1(z),fdL1(z),fBML(k)];

fBL2(z,k)=min(fBL21(z,k,:));

% Fired9th rule

fBML21(z,k,:)=[ftM1(z),ft1L1(z),fdML1(z),fBMH(k)];

fBML2(z,k)=min(fBML21(z,k,:));

% Fired10th rule

fBM31(z,k,:)=[ftMH1(z),ft1H1(z),fdH1(z),fBM(k)];

fBM3(z,k)=min(fBM31(z,k,:));

% Fired11th rule

fBMH31(z,k,:)=[ftML1(z),ft1L1(z),fdML1(z),fBH(k)];

fBMH3(z,k)=min(fBMH31(z,k,:));

% Fired12th rule

```
fBM41(z,k,:)=[ftM1(z),ft1H1(z),fdML1(z),fBMH(k)];
fBM4(z,k)=min(fBM41(z,k,:));
```

% Fired13th rule

```
fBH21(z,k,:)=[ftH1(z),ft1L1(z),fdM1(z),fBML(k)];
fBH2(z,k)=min(fBH21(z,k,:));
```

% Fired14th rule

```
fBMH41(z,k,:)=[ftH1(z),ft1H1(z),fdMH1(z),fBH(k)];
fBMH4(z,k)=min(fBMH41(z,k,:));
```

% Fired15th rule

```
fBM51(z,k,:)=[ftH1(z),ft1L1(z),fdH1(z),fBL(k)];
fBM5(z,k)=min(fBM51(z,k,:));
```

% Fired16th rule

```
fBML31(z,k,:)=[ftMH1(z),ft1H1(z),fdML1(z),fBMH(k)];
fBML3(z,k)=min(fBML31(z,k,:));
```

% Fired17th rule

```
fBL31(z,k,:)=[ftL1(z),ft1L1(z),fdMH1(z),fBML(k)];
fBL3(z,k)=min(fBL31(z,k,:));
```

% Fired18th rule

```
fBH31(z,k,:)=[ftM1(z),ft1H1(z),fdH1(z),fBML(k)];
fBH3(z,k)=min(fBH31(z,k,:));
```

% Fired19th rule

```
fBM61(z,k,:)=[ftML1(z),ft1L1(z),fdL1(z),fBL(k)];
fBM6(z,k)=min(fBM61(z,k,:));
```

% Fired20th rule

```
fBML41(z,k,:)=[ftM1(z),ft1H1(z),fdMH1(z),fBM(k)];
fBML4(z,k)=min(fBML41(z,k,:));
```

% Fired21st rule

fBL41(z,k,:)=[ftL1(z),ft1L1(z),fdH1(z),fBM(k)];

fBL4(z,k)=min(fBL41(z,k,:));

% Fired22nd rule

fBM71(z,k,:)=[ftL1(z),ft1H1(z),fdMH1(z),fBMH(k)];

fBM7(z,k)=min(fBM71(z,k,:));

% Fired23rd rule

fBML51(z,k,:)=[ftL1(z),ft1L1(z),fdML1(z),fBM(k)];

fBML5(z,k)=min(fBML51(z,k,:));

% Fired24th rule

fBMH51(z,k,:)=[ftM1(z),ft1H1(z),fdL1(z),fBM(k)];

fBMH5(z,k)=min(fBMH51(z,k,:));

% Fired25th rule

fBMH61(z,k,:)=[ftML1(z),ft1L1(z),fdH1(z),fBL(k)];

fBMH6(z,k)=min(fBMH61(z,k,:));

% Fired26th rule

fBM81(z,k,:)=[ftML1(z),ft1H1(z),fdMH1(z),fBM(k)];

fBM8(z,k)=min(fBM81(z,k,:));

% Fired27th rule

fBMH71(z,k,:)=[ftM1(z),ft1L1(z),fdL1(z),fBMH(k)];

fBMH7(z,k)=min(fBMH71(z,k,:));

% Fired28th rule

fBMH81(z,k,:)=[ftMH1(z),ft1H1(z),fdL1(z),fBH(k)];

fBMH8(z,k)=min(fBMH81(z,k,:));

% Fired29th rule

fBH41(z,k,:)=[ftMH1(z),ft1L1(z),fdML1(z),fBM(k)];

fBH4(z,k)=min(fBH41(z,k,:));

% Fired 30th rule

fBMH91(z,k,:)=[ftH1(z),ft1H1(z),fdH1(z),fBML(k)];

fBMH9(z,k)=min(fBMH91(z,k,:));

% Fired31st rule

fBM91(z,k,:)=[ftH1(z),ft1L1(z),fdMH1(z),fBM(k)];

fBM9(z,k)=min(fBM91(z,k,:));

% Fired32nd rule

fBMH101(z,k,:)=[ftMH1(z),ft1L1(z),fdMH1(z),fBML(k)];

fBMH10(z,k)=min(fBMH101(z,k,:));

% Fired33rd rule

fBM101(z,k,:)=[ftML1(z),ft1H1(z),fdH1(z),fBL(k)];

fBM10(z,k)=min(fBM101(z,k,:));

% Fired34th rule

fBML61(z,k,:)=[ftL1(z),ft1H1(z),fdM1(z),fBML(k)];

fBML6(z,k)=min(fBML61(z,k,:));

% Aggregatedoutpt. Membership function(taking the maximum of all 34

% outputs for each value of
inputfB2(z,k,:)=[fBM1(z,k);fBMH1(z,k);fBH1(z,k);fBM2(z,k);fBML1(z,k);fBMH2(z,k);fBL1(z,);

fBL2(z,k);fBML2(z,k);fBM3(z,k);fBMH3(z,k);fBM4(z,k);fBH2(z,k);fBMH4(z,k);

fBM5(z,k);fBML3(z,k);fBL3(z,k);fBH3(z,k);fBM6(z,k);fBML4(z,k);fBL4(z,k);fBM7(z,k);

fBML5(z,k);fBMH5(z,k);fBMH6(z,k);fBM8(z,k);fBMH7(z,k);fBMH8(z,k);fBH4(z,k);

fBMH9(z,k);fBM9(z,k);fBMH10(z,k);fBM10(z,k);fBML6(z,k)];

fB3(z,k)= max(fB2(z,k,:));

end;

end;

% Defuzzification(Centroidal Method)

for z=1:7

```
bve2(z,:)= defuzz(B,fB3(z,:),'centroid');
end;
```

% MAE

```
MAE=0;
for z=1:7
MAE = MAE+abs((bve2(z,:)-bve1(z))/(bve1(z)))*(100/7);
end;
subplot(3,3,1); plot(B, [fB3(1,:) ]);
subplot(3,3,2); plot(B, [fB3(2,:) ]);
subplot(3,3,3); plot(B, [fB3(3,:) ]);
subplot(3,3,4); plot(B, [fB3(4,:) ]);
subplot(3,3,5); plot(B, [fB3(5,:) ]);
subplot(3,3,6); plot(B, [fB3(6,:) ]);
subplot(3,3,7); plot(B, [fB3(7,:) ]);
```