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ANN Model to Predict Critical Flashover Voltages of Polluted Porcelain Disc Insulators

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Abstract

Assessment of pollution flashover voltage is key in the design of EHV/UHV transmission lines. In this paper, a multilayer fully connected feed forward neural network (FFNN) with Back propagation algorithm has been proposed for the assessment of critical flashover in artificially polluted porcelain insulators. The input parameters for the proposed model are the layer conductivity of pollution layer K_s (μS), critical arc length L_{arc} (cm), critical current i (A) and humidity h(kg/m^3) of a selected insulator profile. Three types of practical disc insulators are considered in the present work. The model is tested and the results show that, ANN structure with five nodes in the hidden layer is best-suited form. The results of the proposed model are compared with the present experimental and analytical result of earlier researcher. The comparisons indicate that the proposed ANN model gives better results compared to the analytical model suggested earlier.

INTRODUCTION

The need of electrical energy is increasing day by day because of enormous industrialization and changes in lifestyle of people. The gap created between the generation and demand is minimized by transmitting the electrical power at higher voltage level. The insulators which play a vital role in transmitting electrical energy are affected by pollution to a larger extent. As a result of pollution, the insulators fail to perform at working voltages only. The pollution flashover of insulators is a serious problem because some study revealed that 89% of outages were mainly due to pollution flashover, birds, lightning and fire. The pollution flashover of insulators had been identified in the early 20th century [1] The recent incidents of outages[2,3,4] due to pollution induced flashover of insulators have led to huge generation and load loss, clearly reveal that still the problem is persisting and is continued to be a serious problem in the safe and successful operation of transmission network.

Majority of earlier researchers adopted Ayrton's equation $[E(i)]= AI^{-n}$ "A" and "n" are arc constants and E(i) is the arc voltage gradient expressed as a function of arc current to model the initiation of the arc which may or may not lead to the final flashover. This equation is defined for the static arc, however to bring the dynamic behavior of the arc in the above static equation, the effect of change in the arc resistance with arc current is considered. As a result the current range and the arc constants A and n vary.

MuhsinTunay Gencoglu et al [5] have demonstrated the application of expert system such as Artificial Neural Network in the study of performance of porcelain insulators under pollution conditions. The model is to estimate the contamination flashover voltages of insulators has been developed using ANN. The ANN model has got six variables as inputs and one output. The input variables considered are height, diameter, total creepage length, Surface conductivity number of shed of the Insulator and finally the number of disc Insulators In the string the only output considered is the contamination flashover voltage.The model is given as Vc = f (H,D,L,σ,n,d)

Xingliang Jiang et al [6] have carried experiments on a string of three insulators of type lEC Ul60BL to develop a safety condition of insulator with the help of artificial tests and Artificial Neural Network method.

Dixit et al [7] have investigated the behavior of polluted porcelain insulators with help of experimental tests and mathematical model. Authors have carried out experiments on insulators to study the arc voltage and arc current behavior for the scintillations under different ESDDs. The experimental data of arc voltages and arc currents at different arc lengths for different ESDDs have been used in determining the Ayrton's arc constants A and n.

Chandrashekhar A Badachi et al [8] emphasizes on the development of a new mathematical model to estimate the contamination flashover voltages of ceramic string insulators under varying uniform and non-uniform pollution conditions subjected to AC voltages. The proposed model was developed based on dimensional analysis of the factors which commonly influence the process of contamination flashover of insulators. The new model for string insulators has been validated using previous authors both experimental and analytical results for total of fifteen string insulators including porcelain, glass string insulators and one porcelain long rod insulator. The validation of new model indicated that results of proposed model for string insulators are in good agreement with published experimental and model results.

In the present work three types of practical disc insulators are considered.. The model is tested and the results show that, ANN structure with five nodes in the hidden layer is best-suited form. The results of the proposed model are compared with the present experimental and analytical result of earlier researcher. The comparisons indicate that the proposed ANN model gives better results compared to the analytical model suggested earlier.

PROBLEM STATEMENT

The present work aims at finding the suitable value for Ayrton's arc constants A and n to predict the critical flashover voltage of polluted porcelain disc insulators. For this purpose the work has been divided in to three phases. Viz…, Monte Carlo technique based simulation (MCS) to estimate the values of A and n, experimental work and application of AI tools for the estimation of critical flashover voltages.

MONTE CARLO SIMULATION (MCS) TECHNIQUE IN THIS STUDY

The preamble to MCS is that the Ayrton's constants A and n used by different researchers are given in Table 1. There is no proof for A and n values of most of the researchers but Dixit et al[7] has substantiated the values of A and n obtained which is given in the subsequent section.

Table 1: Ayton's Arc contents A and n used by different researchers

Author's Name	Year[Ref.]	A(V/cm)	N
Obenus	1958[9]	100	0.7
Alston	1963[10]	63	0.76
Claverie et al	1973[11]	100	0.5
Jolly et al	1974[12]	296	0.397
Rumeli	1976[13]	518	0.273
Rahal & Hurraux	1979[14]	530	0.24
El-Arbaty et al	1979[15]	40	0.8
Verma M P	1983[16]	53045	0.5
Guan and Zhang	1990[17]	140	0.67
Topalis et al	1992[18]	131.5	0.374
R P Singh et al	1994[19]	31 to 100	0.43 to 0.98
Ghosh and Chaterjee	1995[20]	360	0.59
Farag et al	1997[21]	530	0.24
M Farzaneh et al	2000[22]	205	0.56
Holtzhausen	2001[23]	59	0.53
Gonos and Topalis	2002[24]	124.8	0.409
Boubakeur Zegnini et al	2007[25]	197.418	0.593
Dixit et al	2009[7]	68	0.65
Y Sabri et al	2010[26]	168	0.325
Yawei Li et al	2014[27]	112.1(T) 65.8(B)	0.82(T) 1.13(B)
Chandrashekhar Badachi et al	2016[8]	66	0.7

The author has taken Dixit mathematical model for comparison and his model explanation is given in section 3.2

In the present work Monte Carlo simulation technique has been adopted to estimate the appropriate values for Ayrton's arc constants A and n. For this purpose simulations have been carried out in two phases. In the phase I, the ranges for A, n and I were fixed based on the madel[28] and in the phase II, range of current I was fixed based on the experimental results reported in [28]. In both the phases, acceptance or rejection boundary were the voltage gradients obtained experimentally for 3 phases of arc growth, viz., inception gradient (E_{incp}), propagation gradient (E_{arc}) and flashover gradient (E_{fo}) reported in [28]. An in-house C-code has been developed for the computational work based on MCS technique. Simulations were carried out for different Monte Carlo runs. The flow chart of MCS technique adopted in the present work is shown in Fig.1.

Phase I: MCS based on literature

From Table 1, it is clear that there is a large variation in the values of current I and Ayrton's arc constants A & n. The ranges of A, n and I were fixed as, 534.5 V/m to 200000 V/m, 0.3 to 1.38 and 0.05 to 3.0A respectively{28}. Simulations were carried out from 1000 to 25000 Monte Carlo runs with 28000 V/m ≤ E_{incp} ≤ 60000 V/m, 61000 ≤ E_{arc} ≤ 144000 V/m and 145000 ≤ E_{fo} ≤ 200000 V/m as acceptance boundaries for the three arc growth stages. Table 1 shows the results obtained for different Monte Carlo runs.

Table 2: Result of Monte Carlo simulation

Monte Carlo runs	Mean AV/m	Mean n
1000	84845	0.794
2000	73920	0.710
5000	73685	0.714
10000	73770	0.713
15000	73690	0.714
20000	73574	0.715
25000	73877	0.715

The Table 2 shows that the average values of A and n are about 73700 V/m (737 V/cm) and 0.714 respectively.

Phase II: MCS based on experiments conducted

Based on the experimental results reported in [28], the minimum current for arc inception was 1.5mA and current just before the flashover was about 700mA was considered.. From this, the range for the three arc growth stages were fixed as,

- Arc inception and weak local arcs – 1.5 mA to 5 mA
- Current just before the flashover or strong continuous arc – 290 mA to 700 mA.

The ranges for scintillation inception and arc propagation ranges have been fixed to 28000 – 60000 V/m for arc inception, 61000 – 144000 V/m for arc propagation and 1.45 kV/cm to 2.8kV/cm for breakdown gradient.

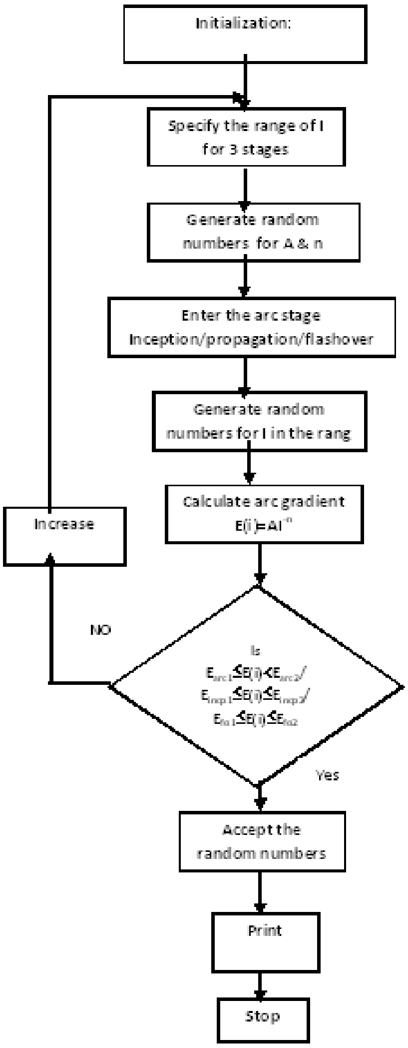
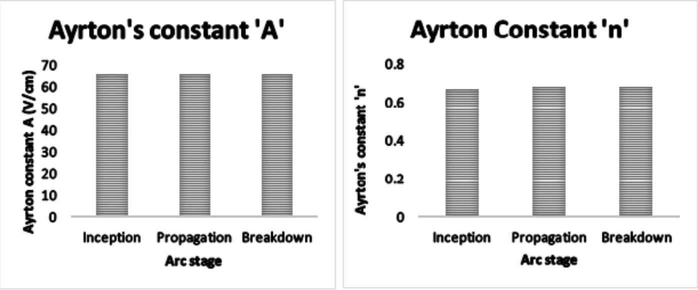


Figure. 1 Flow chart for the proposed MCS technique

The above current and three gradients ranges were used in MCS technique to estimate the appropriate values of Ayrton's arc constant A and n. The results of 30000 Monte Carlo runs are shown in Figures 2(a) and (b) for A and n respectively.



(a) (b)

Figure 2 (a) Monte Carlo result for Ayrton' constant A
(b) Monte Carlo result for Ayrton's constant n

Results of first and second phase of MCS technique gives the following,

- When the range for A, n and I were selected from the literature, MCS technique gives the values for A as 737 V/cm and 0.714 for n
- When the range for I was fixed from the experiments conducted on three disc insulator, MCS technique estimates the values of A and n as 65.8 V/cm and 0.68 respectively. The values obtained are nearer to those reported earlier when the type of contaminant is NaCl.

Further, to validate the values of A and n obtained from the MCS technique, the values used in the model reported in [7] to foretell the critical flashover voltage of three practical disc insulators.

DIXIT MODEL

Dixit et al [7] have investigated the behavior of polluted porcelain insulators with help of experimental tests and mathematical model. Authors have carried out experiments on insulators to study the arc voltage and arc current behavior for the scintillations under different ESDDs. The experimental data of arc voltages and arc currents at different arc lengths for different ESDDs have been used in determining the Ayrton's arc constants A and n. Authors have also conducted experiments on three different types of porcelain insulators to get critical current which is the current just before the flashover and pollution flashover voltages. Using these experimental data and dimensional analysis a mathematical model has been developed to predict the pollution flashover voltages of porcelain insulators. The developed model is of the form.

$$V_{FO} = \left\{\left[K_{MPF}\left(\frac{1}{d}\right)_{Min} e^{-0.03k,}\right] K_s\,(L_{arc})_c^2\; p^{\frac{3}{2}} h^{-\frac{1}{2}}\right\}^{-0.65} . (L_{arc})_c$$

$$\left\{\left[K_{MPF}\left(\frac{1}{d}\right)_{Min} e^{-0.03k,}\right] K_s\,(L_{arc})_c^2\; p^{\frac{3}{2}} h^{-\frac{1}{2}}\right\}^{-0.65} . R_p(L - (L_{arc})_c) \qquad (1)$$

where 68 and 0.65 are the Ayrton's arc constant A in V/cm and n respectively , (Larc)c is the critical arc length, p is the pressure, h is the humidity, K_s is the layer conductivity and R_p is the pollution resistance. $(l/d)_{min}$ is the minimum ratio of the creepage distance along the surface to air distance between the ribs. K_{MPF} is the modified profile factor defined as

$$K_{MPF}\; L_T + L_B \,/\, L'_P \qquad (2)$$

L_T - length of the top surface measured from the edge of the cap to tip of the last rib (from the pin), L_B-shortest distance (air path) from tip of last rib to the tip of the first rib (from the pin) & Lp' -protected creepage distance from the tip of the last rib to the tip of the first rib. To compare the flashover voltages estimated from the model have been compared with the results of present experimental and with the published data. The following section discusses the experimental details conducted in the present study.

Experiments to determine the flashover voltages

The experiment set up made is as shown in figure1.The dimension of the pollution chamber is 2.75m x 2.75m x 2.75m. The details of the transformer used is 400V/60kV,60kVA with R/X ratio 0.3. To pollute the test insulators (Type A, B and C) solid layer method is used and standard IEC507[30] procedure is followed.

Test preparation: The test insulator should be free from any contaminants and dried completely. The slurry composed of sodium chloride(to get conductivity and kaolin(binding agent) is prepared.as per IEC 507[30] with 90µS/cm tap water to pollute the insulator. With humidity of about 90-95%, the test insulator is exposed to steam for about twenty minutes.

Test procedure: For a required ESDD, the test insulator is artificially polluted uniformly and exposed to steam for 20 minutes. Then a low voltage is applied and increased gradually till flashover occurs. This procedure is repeated for three trials for the same ESDD. Note down the minimum flashover voltage and apply this minimum flashover voltage for 15 minutes. If the flashover occurs before 15 minutes then experiment is repeated by reducing 5% of the earlier voltage for 15 minutes. If insulator does not flashover then the voltage is increased by 2% and is appled for 15 minutes, this is repeated for 15 minutes for 5times for a given ESDD. The minimum flashover voltage in this process is treated as flashover voltage. The same procedure is repeated for different ESDD for the other two insulators

The different insulators used in the experiment along with their dimensional details are given in Table3. Figure 3 shows the experimental set up and figure4, figure5 and figure 6 represent the relation between flashover voltage and layer conductivity. The results of the present experiment is compared with the published results of other researchers for Type A, Type B and Type C insulators.

Table 3: Dimensional details of Type A, Type B and Type C insulators

Insulator type	Creepage distance cm	Protected creepage distance cm	Shed diameter cm	Total area cm^2
A	30.6	20	25.5	1455.94
B	30.1	18.7	24.6	1220.82
C	35.7	21	25.4	1736.42

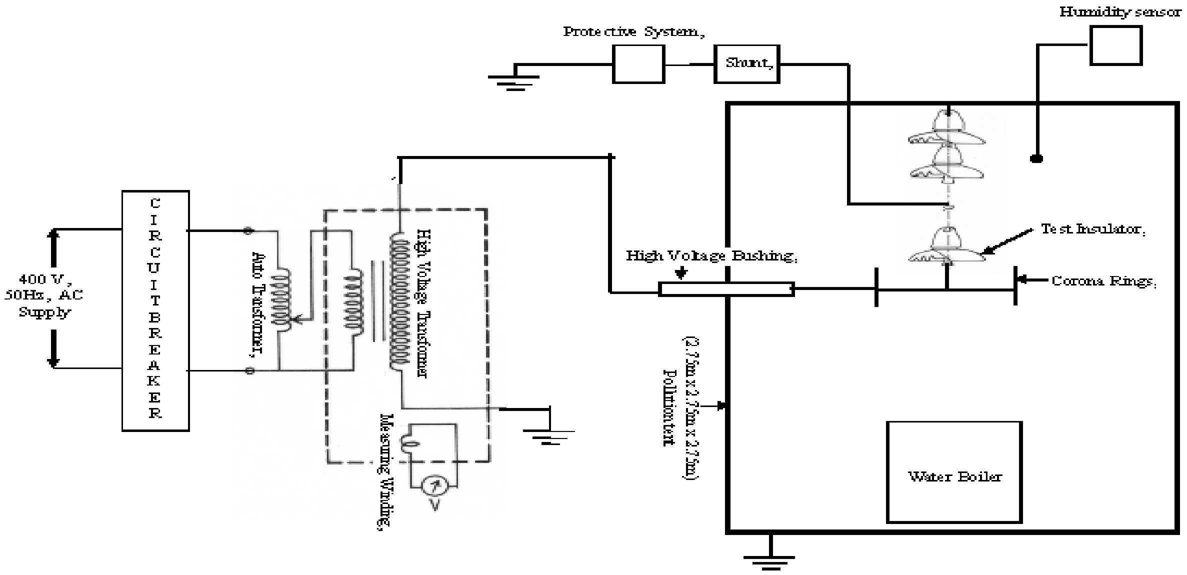


Figure 3. Experimental setup

Table 4: Flashover voltages obtained for Type A, B and C insulator

Type		A	B	C
ESDD mg/cm^2	K_s µS	Average Flashover voltage in kV	Average Flashover voltage in kV	Average Flashover voltage in kV
0.04	5	15.5	20.2	23.5
0.09	10	12.5	16.0	17.8
0.15	15	10.5	14.3	12.5
0.21	20	9.8	12.0	11.0
0.25	24	8.7	10.5	9.5
0.32	30	7.5	9.0	9.0
0.43	40	6.5	8.0	8.0

The results of present experiment are compared with other experimental results.

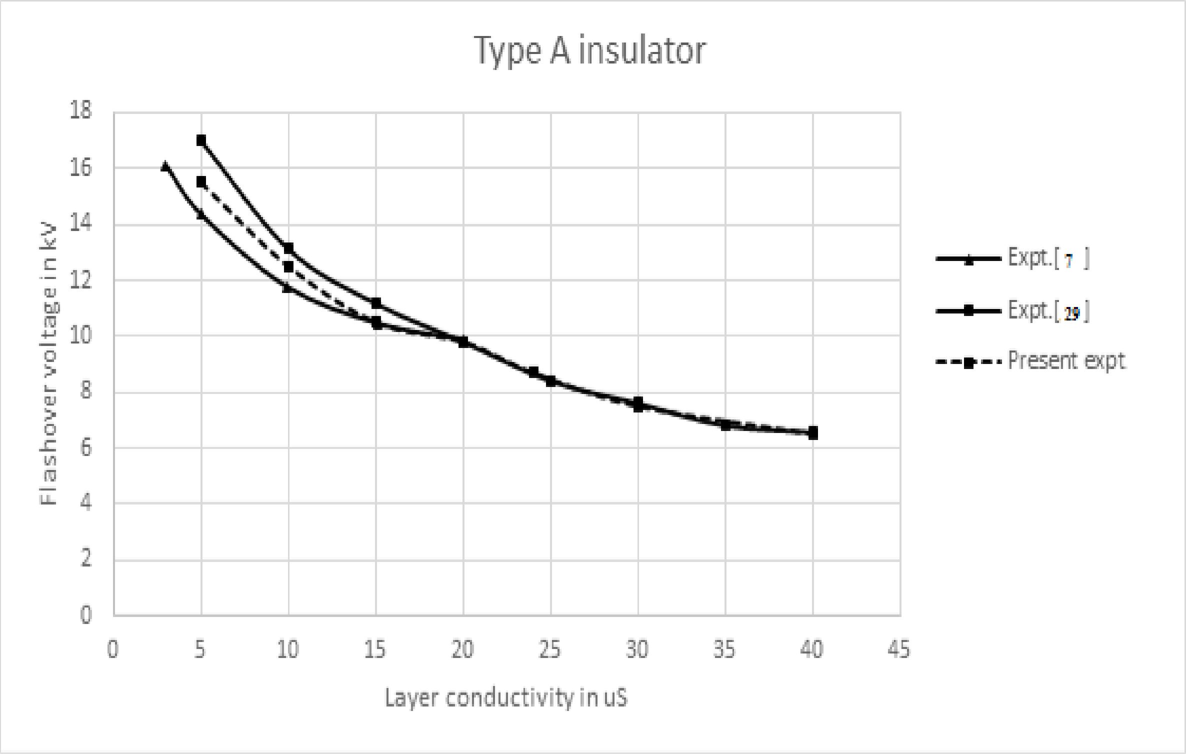


Figure 4. Graph representing the variation between critical flashover voltage and layer conductivity between present experiment and other experimental results.

From the comparison, it can be observed that the results calculated from proposed model are deviated with highest difference of 7.35% and lowest difference of -0.98% for type A insulator.

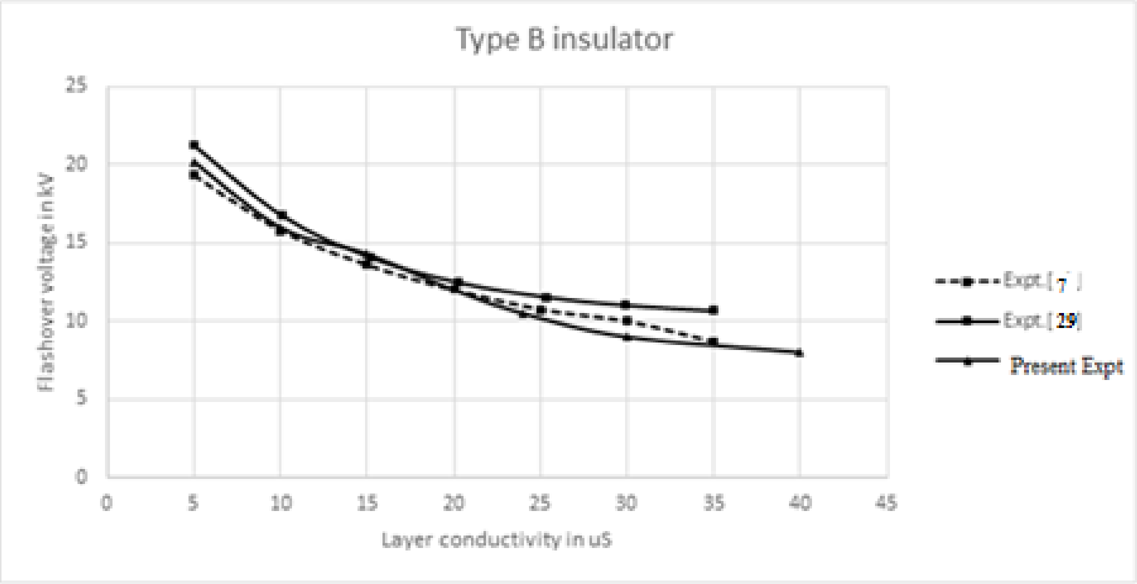


Figure 5. Graph representing the variation between critical flashover voltage and layer conductivity between present experiment and other experimental results.

From the comparison, it can be observed that the results calculated from proposed model are deviated f with highest difference of 4.25% and lowest difference of -11.11% for type B insulator.

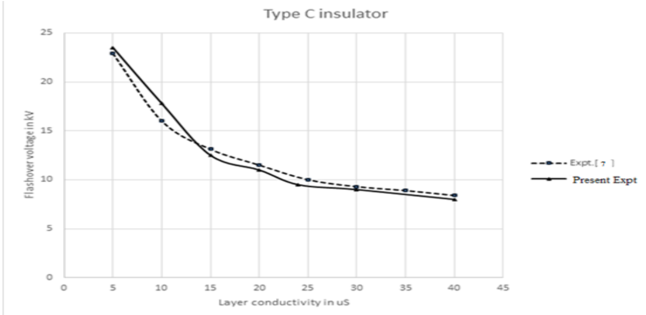


Figure 6. Graph representing the variation between critical flashover voltage and layer conductivity between present experiment and other experimental results

From the comparison, it can be observed that the results calculated from proposed model are deviated from the model [6] with highest difference of 2.59% and lowest difference of -4.76% for type C insulator.

Summary of Results

a) For practical disc insulators breakdown gradient varies between 1.45kV/cm to 2.0kV/cm

b) Arc inception gradient for disc insulators varies between .28kV/cm to 0.6kV/cm

c) Arcs initiates at the pin always invariably.

d) From the pin to first shed of the insulator the arc develops. Then abruptly shift to the bottom of the sheds(bridging two sheds

e) The arc (scintillation)current ranges between 1.5mA to 5 mA and strong arcing current ranges from 290 mA to 700 mA.

f) Increase in ESDD increases the energy required to develop dry band. Increase in ESDD implies more absorption of water.

g) From figures 5,6 and 7, it can be concluded that there will be reduction in flashover voltage on increasing the conductivity of the layer. There is a power function between flashover voltage and layer conductivity.

h) Results obtained experimentally are in exact concurrence with the other experimental results.

The results obtained for practical disc insulators were used in the MCS(Monte Carlo Simulation) technique and estimated the arc constants 'A' and 'n' (Ayrton) and the details of Monte Carlo Simulation technique was dealt in the previous section.

ANN MODEL FOR CRITICAL FLASHOVER VOLTAGES

In the present work ANN models have been developed [31] and used to model the relationship between critical flashover voltage (V_{cfo}) and given layer conductivity(K_s), critical current(i_c), arc length(L_{arc}) and humidity(h).A multilayer feed forward network shown in figure 7 was employed to model the critical flashover voltage of polluted disc insulators considered (Type A, Type B, and Type C). The input layer consists of four nodes corresponding to four input parameters viz., K_s, i_c, L_{arc} and h. The output layer composed of single node analogous to V_{cfo}. The one layer which was hidden with variable number of nodes to guarantee the dependency upon the correct estimation and repeatability in convergence was used. The output function of each unit in the hidden and output layers was non-linear (sigmoid).

Network training

Making use of error back propagation stepwise procedure for 1000 epochs and threshold on error fixing to a value 10^{-3}, the network was first trained. Using the present experimental data, the proposed ANN models for V_{cfo} for three insulators were trained. Here the learning rate parameter is 0.9 and the momentum factor is 0.9. The total sum of mean squares should reach either the desired error limit of 10^{-3} or till the completion of 1000 epochs. Until then the training was carried out.

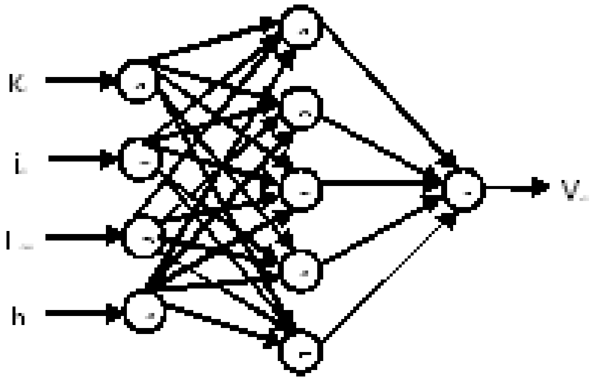


Figure 7. Multilayer FFNN model

With varying number of nodes in the hidden layer, the above network was trained. With five nodes in the hidden layer for three types of insulators, the smallest sum of squares error was obtained. All input and output variable in the training patterns were normalized before they were used for network training and testing. The details of the training, testing and network structure are as given in Table 5.

Table 5: Details of ANN model

Insulator Type	Number of patterns		Network structure		
	Training	Testing	No.of input nodes	No. of nodes in hidden layer	output node
A	69	18	4	5	1
B	72	26	4	5	1
C	74	37	4	5	1

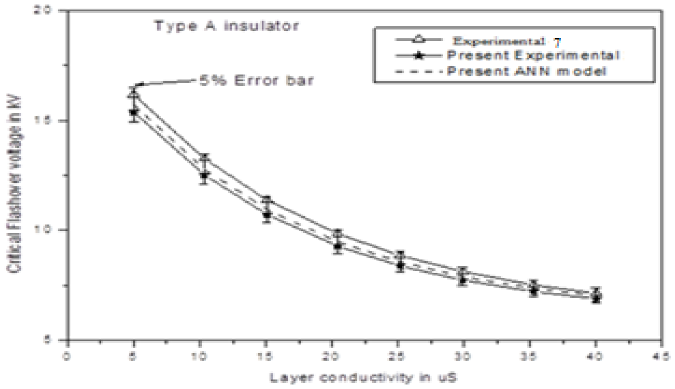
Once the Neural Network was trained, it was tested with the data obtained by the proposed model.

5. COMPARISON WITH OTHER EXPERIMENTAL RESULTS

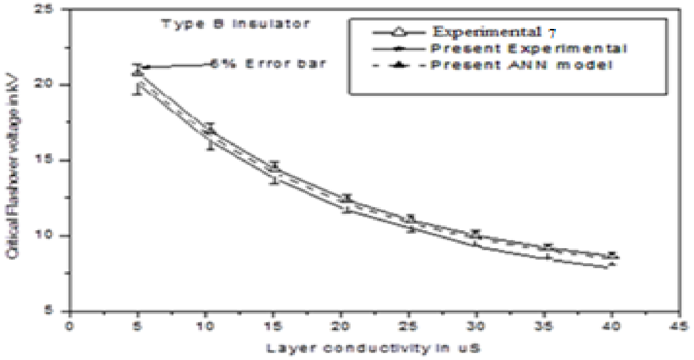
The results of the present ANN models of V_{cfo} have been compared with the results of present experimental and results obtained by Dixit mathematical model[7].The critical flashover voltages obtained for three insulators from the ANN models are plotted against K_s and are shown in Figures 8(a),(b) and 8(c) respectively for insulators Type A, B and C. From figures it can be observed that, the results of present ANN model is in correct concurrence with the current experimental and the model[7] results.

Validation of ANN results

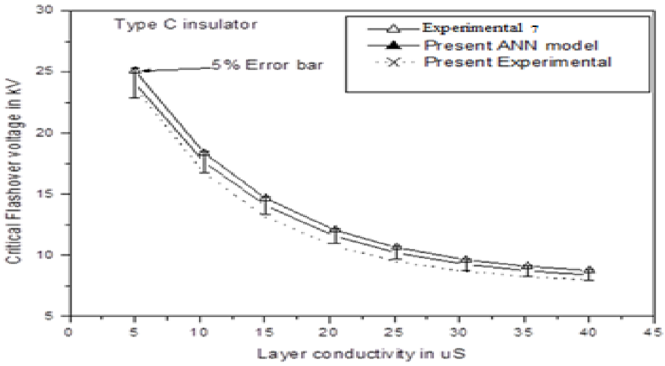
The validation of proposed of model to estimate the flashover voltages of contaminated porcelain disc insulator has been carried out for Type A, Type B and Type C insulator using ANN techniques. The proposed ANN model is compared with Experimental. Figures 8(a),(b) and 8(c) drawn for Type A, B and C insulators clearly indicates the validity of the proposed ANN model, where the results obtained are well within the experimental range (≤ ±5%).



8(a)



8(b)



8(c)

Figure 8 (a) (b) and (c) Critical Flashover Voltage vs layer conductivity for insulator Type A, Type B and Type C

Figure 8 (a),(b) and(c) relates the critical flashover voltage and the layer conductivity for Type A, Type B and Type C insulators. The flashover voltages estimated from the present ANN model is compared with present experimental, published experiential data and mathematical model[7]. It can be observed from the above figures that there is a maximum difference of 5% among the three methods.

CONCLUSIONS

The present paper discusses the Monte Carlo Simulation technique to find the appropriate values of Ayrton's arc constants A and n and a proposed multilayer fully connected feed forward neural network (FFNN) with Back propagation algorithm for the assessment of critical flashover in artificially polluted porcelain insulators. The results obtained in the present study leads to the following conclusions,

- MCS technique estimates the values of Ayrton's arc constants A and n as 65.8 V/cm and 0.68 respectively.
- ANN model proposed to predict the critical flashover voltages of contaminated insulators is highly flexible as the range of input variables can be extended simply by providing necessary additional training data. It is found that the convergence rate of the network training is significantly affected by the number of neurons in the hidden layer. The results obtained are ≤±5% with the present experimental and proposed mathematical model results and ≤±10% when compared to the results of earlier researchers.

On the whole, it is believed that the present work has resulted methodologies to estimate realistically and reliably the pollution performance of porcelain disc insulators.

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