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Breakdown Strength of Air and Air+SF_6 in Rod-Sphere Gap and Breakdown Voltage Estimation Using Artificial Neural Network

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Abstract: The breakdown strength of dry air and a mixture of dry air + SF_6 containing 1% of SF_6 in non-uniform field was studied in a pressure range of 50 to 450 kPa. For this purpose, 50 Hz AC breakdown voltages in a rod-sphere gap of 30 mm spacing were first measured and second estimated by means of an Artificial Neural Network (ANN). The results show that the addition of 1% of SF_6 to dry air increases considerably the breakdown voltage in a non-uniform field. By the aid of breakdown voltage versus pressure curves the relative breakdown strength of the mixture with respect to components was also calculated in 50 Hz AC. The comparison of measured and computed values show that there is a good agreement between two values.

Keywords: Sulphur Hexafluoride (SF_6), Air+SF_6 Gas Mixture, Breakdown Strength, Breakdown Voltage Estimation, Artificial Neural Network.

1. INTRODUCTION

In the past thirty years sulphur hexafluoride (SF_6) has been widely used in high voltage apparatus as an insulation as well as arc quenching media. In uniform field the dielectric strength of pure SF_6 is approximately three times that of air in the same conditions [1]. However in non-uniform fields it depends on many factors such electrode geometry, voltage waveshape, polarity, gas pressure etc. [2].

Recent investigations [3-4] show that the addition of a small amount of SF_6 to buffer gases as He, N_2, CO and CO_2 can considerably improve breakdown strength, particularly in non-uniform fields but the improvement seems to be less in uniform field geometry. Ryan et all. [5] found that, for switching overvoltages of positive polarity the addition of 1% of SF_6 to dry air can increase considerably (up to 2.5 times) 50% breakdown voltage (U_{50}) with respect to dry air or pure SF_6 alone.

Qiu and Kuffel [6] revealed that among the mixtures investigated the most promising is that of air + 1% SF_6 which in 60 Hz AC has the same dielectric strength as pure SF_6 and in positive lightning impulse voltage has a dielectric strength approximately 1.6 times that of pure SF_6. The main purpose of this work is first to study experimentally and second to estimate the breakdown strength of dry air and a mixture of dry air + 1% SF_6 using an artificial neural network [7-9]. Finally the measured and computed values are compared with previous investigations.

2. EXPERIMENTAL SETUP

Experiments were carried out using rod-sphere electrodes with a rod tip radius of 1 mm and sphere radius of 50 mm (Fig. 1). In this case gap spacing was kept at 30 mm in order to obtain a highly divergent field. Electrodes were mounted in an aluminium tank of 550 mm diameter and 883 mm length. In rod-sphere arrangement the hemispherically capped rod was connected to the high - voltage supply while the sphere electrode was earthed. Before each series of tests, the electrodes were polished and cleaned carefully. The vessel was first evacuated for at least two hours and than filled with the desired gas up to a relative pressure of 400 kPa.

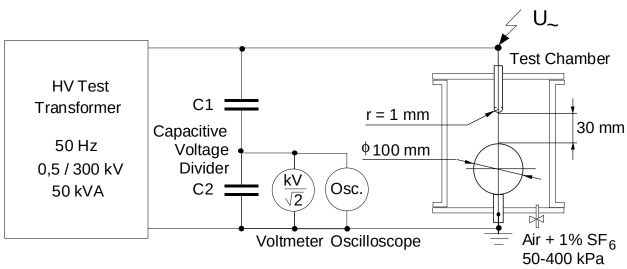

Figure 1. AC test circuit.

For the 50 Hz AC tests with voltages up to 300 kVrms a cascade high voltage transformer was employed. 50 Hz breakdown voltage was measured by means of a capacitive divider. The mean value of breakdown voltage and standard deviation were calculated by means of 20 voltage applications at 50 Hz AC.

3. TEST RESULTS

The breakdown voltages of dry air, and a mixture of dry air + 1% SF_6 was measured up to a relative pressure of 400 kPa in non-uniform field. Experiments have shown that AC breakdown voltage for dry air increases linearly up to 200 kPa and beyond that pressure the increase is very slow. The breakdown voltage of the mixture of dry air + 1% SF_6 increases with pressure up to 300 kPa where it reaches its maximum value and beyond that pressure decreases according to a negative slope.

The comparisons of these two curves show that in 50 Hz AC, the maximum breakdown strength of the mixture of dry air + 1% SF_6 is 50% higher than that of dry air (Fig. 2). In fact one may see that the breakdown strength of the mixture of dry air + 1% SF_6 is superior to dry air if pressure remains under 350 kPa.

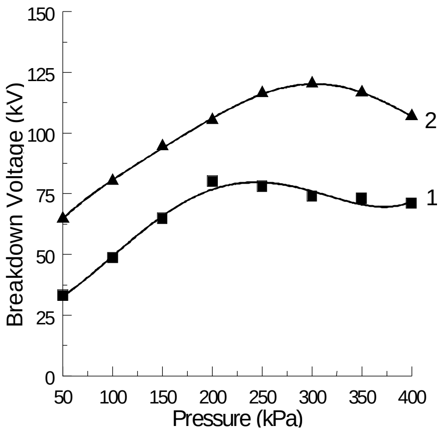

Figure 2. Breakdown voltage curves (50 Hz).
1: Dry air; 2: Dry air + 1% SF_6

Beyond this pressure it is seen that there is an improvement in the breakdown strength of dry air with respect to the mixture of dry air + 1% SF_6. Table 1 gives a comparison of the breakdown strengths of dry air and the mixture of dry air + 1% SF_6 with respect to pure SF_6. It can be seen that there is a good agreement between our test results and the work of Qiu and Kuffel.

Table 1. Comparison of dielectric strengths of dry air and dry air + 1% SF_6 with respect to pure SF_6.

	Dry air	Dry air+1% SF_6
50 Hz AC (Qiu and Kuffel)	-	0.94*
50 Hz AC (Present work)	0.60	0.90
Paschen curve (50 Hz AC)	0.39	0.51

* The dielectric strengths of pure SF_6 at 100 kPa were chosen as 1.0.

4. THE MODELING BASED ON ARTIFICIAL NEURAL NETWORK OF THE MEASUREMENT SYSTEM

The basic feedforward artificial neural network (ANN) contains three components: an input layer, one or more hidden layers, and an output layer as shown in Fig. 3.

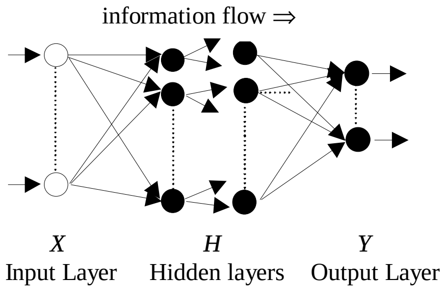

Figure 3. General structure of the multi-layer feedforward net.

Each network layer contains a set of processing units called *"nodes"* or *"neurons"*. Every node in a network layer sends its output to all the nodes of the next layer unit-directionally, but has no connection to the nodes in its own layer. The input layer of the neural network serves as an interface that takes information from the outside world and transmits it to the internal processing units of the network. The hidden layers are used to get the feature extraction during the information flow. The output layer presents the system output. In the using of the feedforward ANN, there are two stages. One of them is training and another one is the recalling or asking the input pattern corresponded with unknown output pattern to the ANN.

4.1. Mathematical Formulation

Let us define a system with inputs $x = [x_1, x_2, \ldots x_n]^T$ such as experimental measurements and corresponding outputs $y(x) = [y_1, y_2, \ldots y_m]^T$. It is convenient to represent the system as the relationship *AS* between the input space $X : \{x \in X \mid x \textit{ is the input to the system}\}$ and the output space $Y : \{ y(x) \in Y \mid y \textit{ is the output to the system with input } x\}$ as expressed in Eq. (1) and Fig. 4.

$$AS: X \rightarrow Y \tag{1}$$

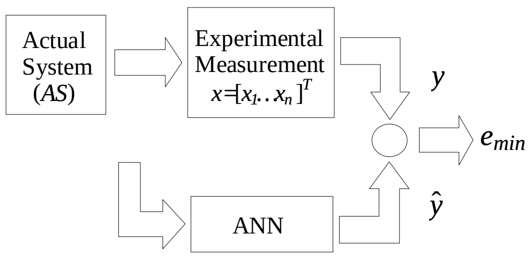

Figure 4. Schematic diagram of the input-output relation between *AS* and ANN

The network training process can be though of as training the network to present *AS* through the input-output relation as close as possible by adjusting the network internal parameters (or weights) *w*, represented mathematically as

$$\min_{w \in W} \left\| \hat{y}(x|w) - y(x) \right\| \quad , \quad \forall x \in X . \qquad (2)$$

Let us define e_p as the training error of training pattern p, Eq. (3).

$$e_p = e(x_p, w) = \left\| \hat{y}(x_p, w) - y(x_p) \right\| \qquad (3)$$

During the network training, the error is minimized for all training patterns as a quantity E as

$$E(w) = \frac{1}{P} \sum_{p=1}^{P} e(x_p, w) \qquad (4)$$

In this study, The back-propagation algorithm was used to minimize the error function in Eq. (4).

4.2. Back-propagation Algorithm

The back-propagation training algorithm is a commonly used steepest descent method of training that searches for an optimal *w* to minimize the error *E* in Equation (4). The general procedure is

1) Find $(\partial E/\partial w)$
2) Update the weight $w(n)$ to $w(n+1)$ as

$$w(n+1) = w(n) + \Delta w(n) \qquad (5)$$

where

$$\Delta w_{ji}(n+1) = \eta\, \delta_j\, o_j + \alpha\, \Delta w_{ji}(n) \qquad (6)$$

Equation (6) is called the delta rule. It is a commonly used method to adapt the network weights and has been derived. In this equation, η is called the learning rate and α is included in the momentum rate. The $\alpha\, \Delta w_{ji}(n)$ term is called the momentum term and is included in the weight update equation to try to avoid a local minimum.

5. APPLICATION

In this application, an artificial neural network (ANN) study is implemented in form of the back-propagation algorithm using the experimental measurement results which are subjected with breakdown voltage and pressure.

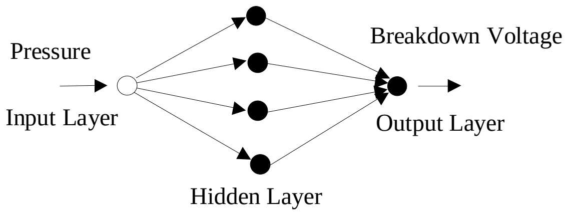

Figure 5. The neural network structure used in application.

For this aim, the ANN structure is established with one hidden layer which includes the 4 hidden nodes as Fig. 3. Hence, it can be used to estimate the extrapolation point for the given measurement values in the case of dry air.

In the Table 2, the measured values that are obtained from the experimental setup and computed values are named as the target values and actual output of the ANN respectively. Here, while the inputs denote the pressure values in units of [kPa], other outputs, which are the target and actual outputs, indicate the breakdown voltage in unit of [kV].

Table 2. Measured and estimated values for dry air.

Pressure (input) [kPa]	Breakdown Voltage (target value) [kV]	Computed Voltage by ANN (actual value) [kV]
50	33.26	33.18
100	48.68	48.76
150	64.85	64.75
200	80.16	80.31
250	79.80	79.58
300	74.42	74.74
350	75.55	75.19
400	77.24	77.38
450	unknown	79.17

During the training process of the ANN structure, the number of the training patterns, which are related to the input nodes of the ANN, is eight. At the same time, the number of target values is also eight.

After the 180000 training epochs, the training process provides a very high learning capability. Using the recall process, the value of 450 kPa that takes place at the out of the training set in the Table 2, that is 9 th pattern or unknown pattern, is asked to the ANN. The ANN gets a very good estimation according to the produced output.

In the training process, in order to have a good performance, 10% noise level is added to the input patterns. Here, this noisy pattern set provides more accuracy training process and it can also produce the high sensitive extrapolated value.

In order to test the accuracy of the ANN's performance, it is trained with the first seven training patterns and the next training pattern, 9 th input pattern that is the pressure value of 450 kPa, is asked to the ANN to get the 9 th breakdown voltage. With the using of this test, the relative error (*RE*) for dry air is calculated as 18E-4.

As a result, the using of multilayered feedforward – neural network procedure provides a very good performance to estimate the breakdown voltage value at the out of the measurement range. For this aim, the changes of the computed outputs and target (measured) values of the ANN versus to the pressure values are given as Fig. 6.

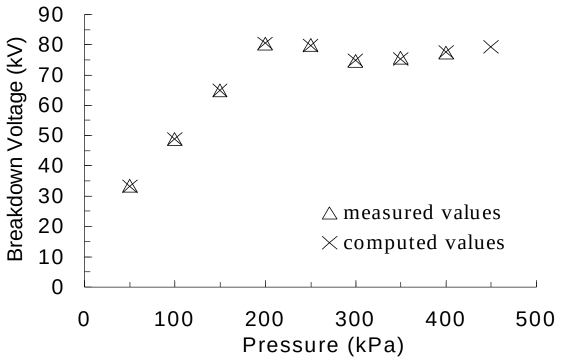

Figure 6. Estimated values for dry air using the ANN.

Where, symbols (×) and (Δ) denote the computed values by the ANN and target values gathered by the measurements respectively. From the Table 2 and Fig. 6, the extrapolated value, which is computed as 79.17 kV for input value of 450 kPa, give us the best predicted value in terms of the limited measurement possibilities.

With a similar way, Table 3 and Fig. 7 also show the measured and estimated values. According to second type application results, that is for dry air + 1% SF_6 mixture, very good results are observed again.

Table 3. Measured and estimated values for dry air + 1% SF_6 mixture.

Pressure (input) [kPa]	Breakdown Voltage (target value) [kV]	Computed Voltage by ANN (actual value) [kV]
50	64.85	64.97
100	80.42	80.37
150	94.67	94.34
200	105.29	105.93
250	116.32	115.83
300	120.30	120.33
350	116.55	116.58
400	107.04	107.03
450	unknown	104.56

Here the estimated breakdown voltage is 104.56 kV for 450 kPa pressure value. For this aim computed relative error is given as 35E-5. Thus, The results of two independent measurements are modeled on an ANN structure and their estimated values can be found easily in the manner of extrapolation. But the ANN approach will create different possibilities in terms of the real time applications specially.

Using this methodology, those results can be extended to the more large measurement range safely and it can be an alternative tool for the inadequate measurement capabilities.

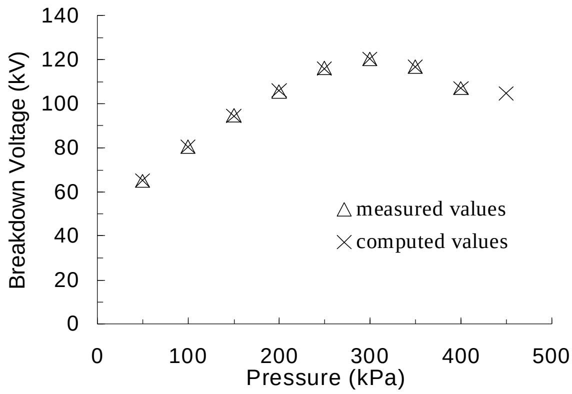

Figure 7. Estimated values for dry air + 1% SF_6 mixture using the ANN.

6. CONCLUSION

Experiments show that the mixture of dry air + 1% SF_6 with a maximum AC breakdown strength only 10% lower than that of pure SF_6 is the most promising among many others as a dielectric. The use of such a mixture in high voltage apparatus depends on many factors e.g. the working pressure of the apparatus because it is essential to have a sufficiently uniform field in order to guarantee a good dielectric strength as well as a good heat conductivity. And also, the using of the ANN plays very important role in terms of real-time applications to get the measurement values take place at the out of measurement range for pressure vessel and in extra high-voltage gas insulated substations with working pressures greater than 400 and up to 800 kPa.

7. REFERENCES

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