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STUDYING THE OPTIMAL PERFORMANCE OF THE ZnO BASED VARISTORS USING ARTIFICIAL INTELLIGENCE TECHNIQUES

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ABSTRACT
In this paper, the effect of some impurities (MnO_2, NiO, Ce_2O_3, La_2O_3) on the behavior of polycrystalline semiconductors (ZnO varistors) has been studied. We have built an experimental database between the concentration of these impurities and the value of non-linear coefficient α for each experiment. Number of experiences reached 400. Based on artificial intelligence techniques (neural networks) a neural non-linear model was built. This model expresses accurately the relationship between non-linear coefficient α and the concentrations of these impurities. According to the neural models, the value of mean square error of the model was $MSE = 0.1078$. Then the greatest values of non-linear coefficient were determined by using optimal solution algorithm based on Lagrange Newton algorithm in MATLAB. Then we determined the optimum values for the impurities that give the greatest value for the non-linear coefficient $\alpha = 99.6616$. The accuracy of the computational value of non-linear coefficient was practically confirmed; where the experimental value was $\alpha = 99.26$. The ratio of the relative error between the theoretical value and practical value was $RE = 0.004$. This result confirms the accuracy of the theoretical study.

***Keywords*:** Non-linear coefficient (α); Mean square error (MSE); Correlation factor (R).

I. INTRODUCTION

ZnO-based varistors are highly non-linear ceramic resistors that are used to sense and limit transient voltage surges and to do so repeatedly without being destroyed. They are composed of zinc oxide as the main component and some other metal oxides which are necessary to provide their desired characteristics. The non-linear coefficient (α) is the most important parameter in assessing the quality of the varistors. It is obtained from the nonlinear region in the I-V characteristic of ZnO-based varistors. It is represented by the following relationship:

$$\alpha = \frac{d \ln I}{d \ln V} \qquad (1)$$

If the value of this factor is great, this gives the best performance of the ZnO varistor [1,2,3]. The sensitivity of non-linear coefficient for some impurities was studied separately [4]. These impurities have been used to manufacture the ZnO varistors (La_2O_3, Ce_2O_3, NiO, MnO_2, Cr_2O_3, Co_3O_4, Nb_2O_5, and Bi_2O_3). In order to get the greatest value for non-linear coefficient, we built a non-linear mathematical model for the non-linear coefficient as a function of the concentration of each impurity separately. Depending on the optimal solution algorithms, we got the most influential impurities on the non-linear coefficient (MnO_2,NiO,Ce_2O_3,La_2O_3). It is represented by table 1. The objective of this research is to investigate the optimal ratios of the most sensitive impurities, in order to get the maximum value for the non-linear coefficient. The research depends on the artificial intelligence techniques -type neural network algorithms. The ratios of the rest impurities, which are the least influential (Cr_2O_3, Co_3O_4, Nb_2O_5, and Bi_2O_3) are given in table 1.

Table 1: Maximum values of (α) according to each impurity.

Impurity	Max (α)	C_i (mol%)
Bi_2O_3	17.0026	1.031
Nb_2O_5	27.9224	0.201
Co_3O_4	20.9448	1.005
Cr_2O_3	27.9659	0.507
MnO_2	49.0011	0.5
NiO	32.9541	0.515
Ce_2O_3	31.9071	0.405

La_2O_3	29.9395	0.598

II. EXPERIMENTAL PROCEEDURES

Research Steps for the proposed methodology are summarized in the following points:

- Building a database by performing experimental measurements for I-V characteristic. Then recording the values of the non-linear coefficient α corresponding to each change in ratios of these combined impurities (MnO_2, NiO, Ce_2O_3, La_2O_3).
- Building a non-linear mathematical model depending on artificial intelligence techniques. This model represents the relationship between ratios of the most influential impurities and the non-linear coefficient. $\alpha = f(MnO_2, NiO, Ce_2O_3, La_2O_3)$.
- Determining the values of the mean square error (MSE) and correlation factor (R) between the experimental values and the mathematical model. The objective of this step is to determine the accuracy of this model.
- Applying experimental tests using the optimal ratios of obtained impurities. Then measure the value of non-linear coefficient and compare it with the calculated value to assess the accuracy of the theoretical study.

III. BUILDING THE DATABASE

An experimental database has been built by changing the ratios of the following combined impurities (Cr_2O_3, Co_3O_4, Nb_2O_5, and Bi_2O_3). Then measuring the non-linear coefficient α of the varistor according to each change. The ratios of the impurities have been changed in the range between maximum value and minimum value.[Min,Max].

Number of experimental tests reached $N = 400$ (size of the database). As shown in table 2.

Table 2: Range of the most influential impurities.

Impurity	Min	Max
MnO_2	0.1	0.6
NiO	0.2	1.5
Ce_2O_3	0.2	0.8
La_2O_3	0.2	0.8

An experimental database will be used for training the neural network model according to the relationship:

$$\alpha = f(MnO_2, NiO, CeO_2, La_2O_3)$$

IV. BUILDING A MATHEMATICAL NEURAL MODEL

The network (model) that has been selected in our search is a multi-layered network [5]. It is compatible with our objective in building a non-linear mathematical model. This model is a supervised training network through the database. Each sample in this model is composed of a pair of values of input and output. Back-propagation algorithm has been chosen for its effectivity and accuracy. It depends on Levenberg - Marquardt algorithm. The general structure of this network that expresses the model which we aim to get is shown in figure 1.

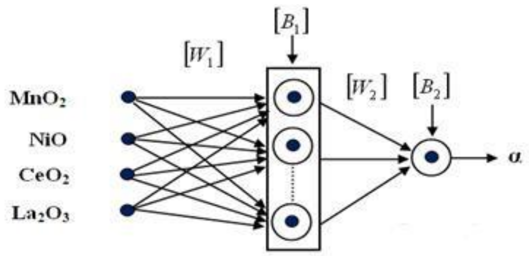

Fig. 1: The general structure of multi-layered neural network.

The network consists of:
(i) input layer which receives database,
(ii) hidden layers composed of several layers. Each layer is composed of (m) neurons. Number of neuron is determined based on the value of the desired error. By increasing the number of these neurons the mean square error (MSE) becomes smaller [6], and correlation factor (R) approaching the ideal value (one) [7,8]. The hidden layer is interrelated with the input layer and the following layer by the weights matrices $[W_1][W_2]$.

Figure 2 shows the general structure of each neuron which consists of two elements: First element called the summing function which adds the input signals after multiplying them with weights matrix $[W]$. The second element called the activation function. It receives two signals: output signal of collection function, and the displacement value B_k. In this research, conversional logarithmic function was chosen as an activation function for the hidden layers (logsig) $y = 1/(1+e^{-x})$.

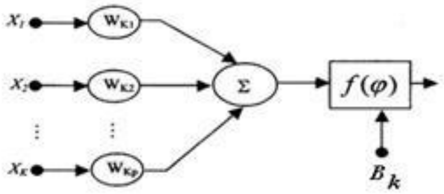

Fig. 2: The general structure of each neuron

Output layer: This layer gives the results after being processed in the network. Output layer represents the non-linear coefficient α in our study. We chose a linear function (Purelin) as an activation function for the output neuron in order to speed up the training process.

Mathematical relationship that represents the neural model, which we have adopted is:

$$\alpha = W_2\left[\frac{1}{1+e^{-(W_1 C_i + B_1)}}\right] + B_2 \qquad (2)$$

where:

C_i are the ratios of impurities C_i=[MnO_2, NiO, Ce_2O_3, La_2O_3]^T,

W_1, W_2, B_1, B_2 are matrices of the optimal values of the model weights.

V. RESULTS AND DISCUSSION

The mathematical model will be built depending on the trained model according to the practical experiences that have been prepared.

V.1. Building the neural model:

Using the program that we have created in MATLAB, we have trained the model according to the practical experiences that reached $N = 400$. In order to get the correlation factor (R≈1), and the smallest value of the mean square error (MSE), we increased the neurons of the hidden layer to six neurons.

As a result of the training, we got the value of the mean square error ($MSE = 0.1078$).This value is very small which means that the model is accurate. Number of training cycles was 286 cycles, as shown in figure 3.

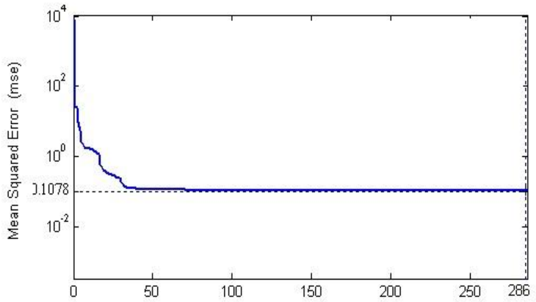

Fig. 3: Changes of mean square error (MSE).

Correlation factor (R) is also used to evaluate the accuracy of a model. The value of the correlation factor that we have got was $R = 0.99347$. This value is almost perfect because it is very close to the optimal value (R=1). Figure 4 shows the matching between the mathematical curve that we got and the experimental values.

Figure 5 illustrates the accuracy of the correspondence between the experimental values and the values of the neural model.

The mathematical relationship Eq (2) according to the neuron model is considered, and matrices for the optimal values of the model weights are:

$$W_1 = \begin{bmatrix} -0.4756 & 0.4153 & 0.1640 & -0.4223 \\ 0.1261 & -0.0896 & 5.3807 & -0.0704 \\ -0.0977 & -7.4618 & -0.0231 & 0.0445 \\ -0.7485 & -0.3254 & -0.2809 & 74.8431 \\ 22.8665 & -0.4312 & -0.1443 & 0.1796 \\ -0.0633 & -23.8466 & 0.0283 & -0.3361 \end{bmatrix}$$

$$W_2 = [-144.4848 \;\; 17.4873 \;\; -21.1652 \;\; -3.5766 \;\; -8.7266 \;\; 4.499]$$

$$B_1 = [0.2977 \;\; -0.7218 \;\; 2.3366 \;\; -40.5572 \;\; -15.899 \;\; 11.6115]^T$$

$$B_2 = [161.8614].$$

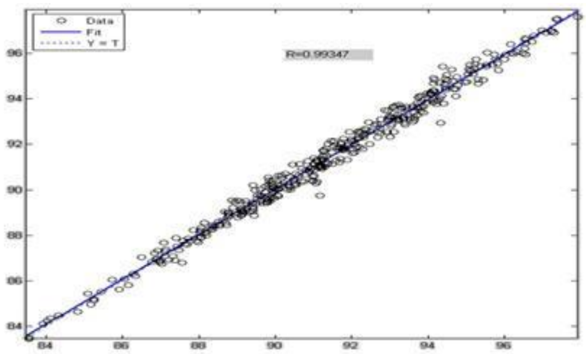

Fig. 4: Matching between the mathematical curve and the experimental values.

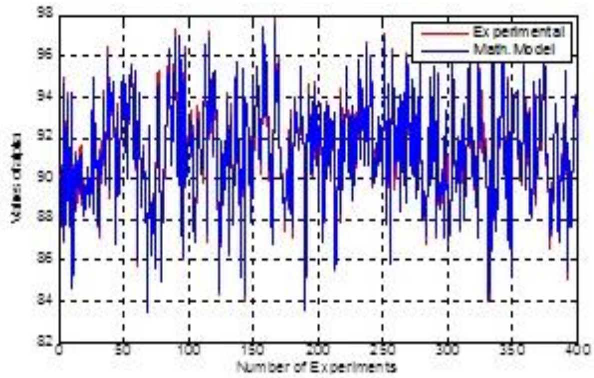

Fig. 5: Comparison between the experimental values and the values of the neural model.

V.2. Determining the optimal ratios of the impurities:

After we got the non-linear mathematical model; we can find the optimal ratios of impurities that give the greatest value of the non-linear coefficient. Depending on the optimal solution algorithm of the following form:

$$Max(\alpha = W_2\left[\frac{1}{1+e^{-(W_1C_i+B_1)}}\right]+B_2) \qquad (4)$$

subjected to:

$$0.1 \le MnO_2 \le 0.6$$

$$0.2 \le NiO \le 1.5$$

$$0.2 \le CeO_2 \le 0.8$$

$$0.2 \le La_2O_3 \le 0.8 \, .$$

The program was created in MATLAB. It depends on Lagrange Newton algorithm [9]. The results are shown in Table 3. The maximum value of the non-linear coefficient was $\alpha = 99.6616$.

Table 3: The optimal ratios of impurities.

C_i	MnO_2	NiO	Ce_2O_3	La_2O_3	α
Ratio	0.515	0.6336	0.4244	0.6068	99.6616

V.3. Comparing the theoretical results with the practical results:

To confirm the accuracy of the theoretical results, were $\alpha = 99.6616$. We have prepared a ZnO varistor according to the ratios obtained in table 3. Then we performed Practical measurements on the varistor. The practical value of the non-linear coefficient was $\alpha = 99.22$. This value shows that the computational results are very accurate according to the proposed method. The value of the relative error between the computational value and Practical value was $RE = 0.004$. This small value means that the proposed method has high accuracy and reliability.

IV. CONCLUSION

In this paper, a scientific methodology has been proposed. It has been depending on artificial intelligence techniques to determine the optimal values of some impurities $(MnO_2, NiO, Ce_2O_3, La_2O_3)$ in the ZnO varistors. This technique was proposed in order to get the best performance of the ZnO varistor. The maximum value of the non-linear coefficient was found depending on a mathematical methods rather than experimental methods. Non-linear mathematical relationship between the most sensitive combined impurities and the non-linear coefficient was created accurately $\alpha = f(MnO_2, NiO, Ce_2O_3, La_2O_3)$.

As a result of the study, the value of the mean square error was (MSE=1078), and the value of correlation factor was (R=0.99347). Depending on the optimal solution algorithm, the optimal ratios of the impurities that give the greatest value of the non- linear coefficient was found. The greatest value of the non-linear coefficient was $\alpha = 99.6616$. ZnO varistor was prepared according to the optimal ratios and practical measurements were performed. The practical value of the non-linear coefficient was $\alpha = 99.22$. Relative error between the practical value and calculated value was $RE = 0.004$. This value indicates that the proposed method has high accuracy and reliability.

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