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Application of fuzzy neural network for estimating the intensity of insulation aging of cable lines

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Abstract. The article considers the issues of forecasting the state of insulation of cable lines. It is shown that the insulation state is influenced by a large number of factors, some of which are indeterminate and can not be expressed in the quantitative form. It was proposed to use a fuzzy neural network for predicting the state of insulation, which ensures processing both quantitative and qualitative information, which makes it possible to obtain more valid results, in comparison with the use of only quantitative information.

Problem definition

In the initial state, the value of the breakdown voltage, which the insulation elements of the electrical equipment have, including cable lines, is quite high. The value of the probability of the insulation work without failures in this period of time is usually close to unity. As a result of insulation materials aging during the operation of equipment, the value of the breakdown voltage decreases, and the probability of the insulation work without failures also decreases. An important task to be solved in the operation process is to assess the intensity of the aging process of insulation.

Theory

In the insulation of the electrical equipment the aging processes are developing under the influence of the operating voltage. With the short lifetime of electrical installations (from units to 10^4 hours), the dependence [1] was experimentally established:

$$\tau = \frac{A}{U^n}, \quad (1)$$

where A – a constant, its value depends on the properties of the insulation; n – the exponent which is affected by the design features of the insulation and the type of voltage of the electrical equipment.

In case of the long service lives (τ is more than 10^4 hours), the amount of experimental data is rather small, which is explained by the considerable duration of the experiments; therefore, the course of the time dependence $\tau = f(U)$ is determined with the lower reliability.



Operating the electrical equipment, the following dependence is revealed: when the voltage U decreases, the service life τ increases faster than it follows from the expression (1), and below the certain voltage it becomes unlimitedly long.

The expression (2) corresponds to this course of the dependence $\tau = f(U)$:

$$\tau = \frac{A_1}{(U - U_{q.p.})^{n-1}}, \quad (2)$$

where U_{pD} — the voltage of partial discharges in the insulation, which is one of the main reasons for the electrical aging of electrical equipment insulation.

The intensity of the process of electrical aging of the insulating structure depends not only on the value of the operating voltage, but also on the number of factors which can not be quantified accurately [2-4]. Therefore, the evaluation of the intensity of the aging process of insulation and changes in its electrical properties is the task for the solution of which both quantitative and qualitative data should be used, some of which will inevitably have an indistinct or indeterminate character.

At present time the mathematical apparatus of fuzzy neural or hybrid networks is considered to be one of the most sought after solutions for such poorly or poorly structured problems [5, 6]. In general case a hybrid network is a multilayer neural network containing special structures which do not have feedbacks [7].

The usual (not fuzzy values) data, weights and functions of their activation are used for the operation of such network. The network performs the summation operation using an unchanged T-norm or some other continuous operation, for example, a T-conorm. In such network, all inputs, outputs and weights of the hybrid or fuzzy neural network are real numbers from the interval $[0, 1]$.

The basic idea used for the operation of hybrid networks is the following: to use the existing sample of the initial data to determine the constituents of the membership function which are the most suitable for the operation of the fuzzy inference system.

There is a class of hybrid networks which is functionally equivalent to the systems of fuzzy reasoning. This architecture is called ANFIS (Adaptive Network Based Fuzzy Inference System). ANFIS represents one of the first versions of the hybrid neural-fuzzy networks – a neural network of direct signal propagation of the special type. The architecture of the neural-fuzzy network is isomorphic to the fuzzy knowledge base.

The hybrid networks use the differentiable implementations of triangular norms (multiplication and probabilistic OR), as well as the smooth membership functions. It allows to use well-proven fast algorithms for neural networks training which use the method of the back propagation of the error.

The data about the variable for the certain time interval make up an image (time series), which is determined by its value at some time point outside the given interval, i.e. the value of the variable through the prediction interval. Let's assume that the current value of the time series is the dependent on the previous values or the process of changing of the insulation properties can be expressed as a regression model.

All the variables used to create such regression model can be expressed through the fuzzy sets $\{A\}$ and it is possible to specify the membership functions of these variables to these fuzzy sets. Therefore, it is necessary to find the set of fuzzy sets $\{A\}$ and determine the parameters of the membership functions to evaluate the intensity of the aging process.

Choosing the type of the membership functions, it is necessary to take into account that the degrees of the membership of the boundary values of the interval of variation of the variables to the extreme terms should be approximately equal to unity. In this case the visual rule will generally be carried out: the smaller or larger the value of the variable being considered, the more it will correspond to the extreme terms "very low" or "very high". Thus, for the membership function of the extreme terms, the trapezoidal forms were chosen.

Experimental results

The neural network which is being developed should have only one output, on which the estimate is formed, and as many inputs as the previous values we want to use for evaluation – for example, the last 5 values.

The training sample for the created network is compiled as follows: the input values for the network operation will be values for 5 selected time points, and the output value will be the known value at the next time point for the selected input quantities. To compose the training sample, it is necessary to copy the data into 4 columns and move the second column 1 cell up, the third column – 2 cells up, etc.

Hybrid or fuzzy neural networks have the advantages of the neural networks and the fuzzy inference systems. These networks provide the development and presentation of various research systems in the form of sets of rules for fuzzy products. Today, this mathematical apparatus is considered promising for obtaining solutions to weakly or poorly structured problems.

A hybrid network can be represented as a multilayer neural network which have a special structure without feedbacks. These networks use conventional (non-fuzzy) signals, weights and activation functions. The execution of the summation operations is based on the use of a fixed T-norm or some other similar continuous operation. Using these networks, it should be taken into account that all values of the inputs, outputs and weights of the hybrid network are expressed by real numbers from the interval [0, 1].

The work of the hybrid networks is based on the use of existing data sample to perform the operation of finding the parameters of the membership functions used in this network. These operations are performed on the basis of the known procedures for neural networks training. It should be noted that the use of hybrid networks ensures mutual strengthening of the positive sides and compensation of the disadvantages of fuzzy systems and neural networks.

The work of the hybrid network in performing of prediction tasks is to predict future values at the output of the system, based on its previous behavior. Having initial information on the values of the studied variable x at the certain time moments preceding the forecasting process, this network forms the most probable value of the predicted variable at the necessary time moment t .

Practical implementation of the fuzzy neural network for solving the problems of forecasting the state of isolation of the cable lines was carried out using the MATLAB Fuzzy Logic Toolbox expansion system. In this package fuzzy neural networks are represented in the form of adaptive systems of neuron-fuzzy output ANFIS. There are two the most commonly used algorithms for fuzzy inference which can be used for forecasting purposes: the Mamdani and the Sugeno algorithms. To develop the hybrid network the Sugeno algorithm is chosen, because the fuzzy neural network based on this Sugeno algorithm has the less error in both learning and predicting processes [7].

Figure 1 shows the structure of the ANFIS network, which uses two rules for its work [8]:

$$\begin{aligned} \text{If } x_1 = A_1 \text{ И } x_2 = B_1, \text{ then } y_1 &= c_{11}x_1 + c_{12}x_2; \\ \text{If } x_1 = A_2, \text{ И } x_2 = B_2, \text{ then } y_2 &= c_{21}x_1 + c_{22}x_2. \end{aligned}$$

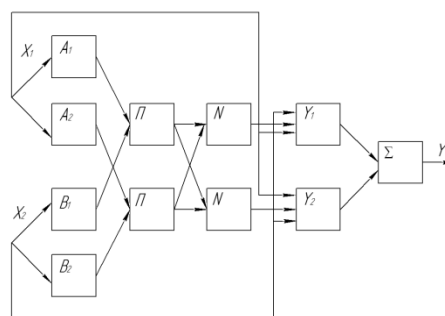


Figure 1. The ANFIS network structure

The output value of the network is determined by the formula:

$$y = \frac{\omega_1 y_1 + \omega_2 y_2}{\omega_1 + \omega_2}. \quad (3)$$

On the one hand, the ANFIS hybrid network can be represented as the neural network with one output and several inputs which work with the fuzzy linguistic variables. The terms of the input linguistic variables are formed by the standard membership functions, and the terms of the output variable are represented by the linear or the constant membership function. On the other hand, the ANFIS hybrid network is essentially an inference FIS system of the Sugeno type, in which each of the used fuzzy product rules has a constant weight equal to 1. Creating the network, the user has the ability to edit and configure the hybrid ANFIS network [9].

Consider the creating process of the fuzzy model of the hybrid network to solve the problem of assessing the insulation state of cable lines Q . The meaning of this problem is that, knowing the dynamics of Q changing over the certain time interval, to evaluate the value of this parameter at the certain time point in the future. As initial data we use information about the dynamics of the changes in Q over the certain time interval. For the convenience of the further work, we will present this information in the tabular form (Table 1). For the origin we take the time $t = 0$.

Table 1. The dynamics of the changes in Q

T , month	1	2	3	4	5	6	7	8	9	10	11	12
Q	90	89,8	89,8	89,7	89,6	89,4	89,3	89,2	89,1	89	88,9	88,8
T , month	13	14	15	16	17	18	19	20	21	22	23	24
Q	88,7	88,5	88,4	88,3	88,2	88,1	88,9	88,8	88,8	88,6	88,5	88,4

Suppose that the fuzzy model of the hybrid network will contain 4 input variables. In this case the first input variable will correspond to the Q for the current time, the second $-Q$ to the previous time, i.e., for the time $(i-1)$, where i denotes the current time. Then the third input variable will correspond to the Q for the time $(i-2)$, and the fourth one to the Q for the time $(i-3)$. The relevant training data is summarized in the separate table of the training sample (Table 2).

Save the training sample in the external file named proba_Q.dat. After that, open the ANFIS editor, in which we will load this file with the training data. The appearance of the ANFIS editor with the downloaded training data is shown in Figure 2.

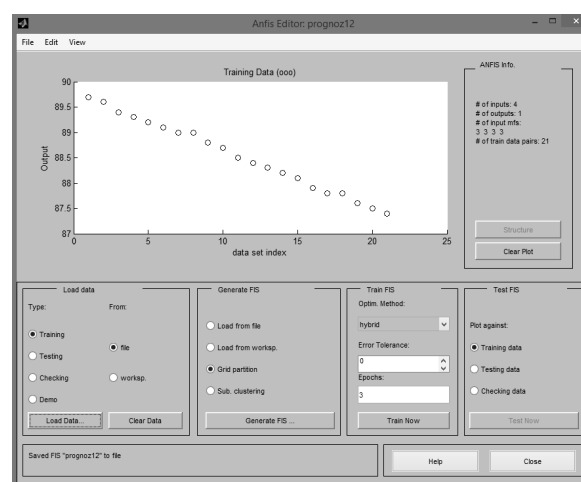


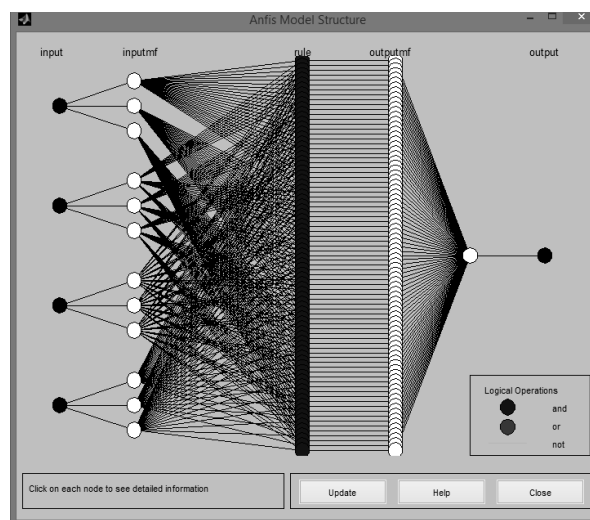
Figure 2. The graphical interface of the ANFIS editor after downloading the training sample

Table 2. The training sample

The values of the input variables				The value of the output variable
1	2	3	4	
89,7	89,8	89,8	90,0	89,7
89,6	89,7	89,8	89,8	89,6
89,4	89,6	89,7	89,8	89,4
89,3	89,4	89,6	89,7	89,3
89,2	89,3	89,4	89,6	89,2
89,1	89,2	89,3	89,4	89,1
89,0	89,1	89,2	89,3	89,0
88,9	89,0	89,1	89,2	89,0
88,8	88,9	89,0	89,1	88,8
88,7	88,8	88,9	89,0	88,7
88,5	88,7	88,8	88,9	88,5
88,4	88,5	88,7	88,8	88,4
88,3	88,4	88,5	88,7	88,3
88,2	88,3	88,4	88,5	88,2
88,1	88,2	88,3	88,4	88,1
87,9	88,1	88,2	88,3	87,9
87,8	87,9	88,1	88,2	87,8
87,8	87,8	87,9	88,1	87,8
87,6	87,8	87,8	87,9	87,6
87,5	87,6	87,8	87,8	87,5
87,4	87,5	87,6	87,8	87,4

Before generating the structure of the Sugeno type fuzzy inference system, after setting the properties of the dialog box we set three linguistic terms for each of the input variables. We select the triangular functions as the type of their membership functions which are set by the MATLAB system by default. We define the linear function as the type of the membership function of the output variable.

We use the hybrid training method with the error level 0 to train the hybrid network. The number of training cycles is set at 100. After learning the hybrid network, the structure of the constructed fuzzy model can visually evaluated (Figure 3).

**Figure 3.** The structure of the created fuzzy model

Conclusion

Perform the test of functioning of the constructed fuzzy hybrid network model. For this purpose we will make the retrospective forecast of the value of Q for the future, for example, for 25 months, counting for this case the current 24 month.

We use the function in the command line for this purpose: evalf. We indicate the vector of the values Q for the current time and 3 preceding ones as the arguments of this function. The full format for calling this function is:

$$q1 = \text{evalfis}([87.4 \ 87.5 \ 87.6 \ 87.8], \text{prognoz12}).$$

where $q1$ – the name of the output variable; 87.4 – the value of Q for 24 months; 87.5 – the value of Q for 23 months; 87.6 – the value of Q for 22 months; 87.8 – the value of Q for 21 months; prognoz12 - the name of the FIS structure preloaded into the working area of the MATLAB system.

The value of the output variable for the future time, equal to 87.2 will be obtained after executing this command with the help of the developed fuzzy model.

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