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Application and Comparison of Several Artificial Neural Networks for Evaluating the Lightning Performance of High Voltage Transmission Lines

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Abstract: Protecting overhead high voltage transmission lines from lightning strokes is one of the most important tasks to safeguard electric power systems. In order to achieve this effectively, the lightning performance of the lines has to be evaluated accurately. In the recent years Artificial Neural Networks (ANN) have attracted much attention and many interesting ANN applications have been reported in power system areas, due to their computational speed, the ability to handle complex non-linear functions, robustness and great efficiency, even in cases where full information for the studied problem is absent. In this paper, several ANN were addressed to identify the lightning performance of high voltage transmission lines. Each network has been constructed using different structures, learning algorithms and transfer functions in order best generalizing ability to be achieved. Actual input and output data, collected from Hellenic high voltage transmission lines, were used in the training, validation and testing process. A comparison among the developed neural networks was performed in order the most suitable network to be selected. Finally the selected ANN was applied on Hellenic transmission lines and the obtained results were compared with conventional methods' results and real records of outage rate.

INTRODUCTION

The design of transmission lines for a predetermined lightning performance requires a method of predicting the failure rates of the lines. Several methods around the globe, based on many different techniques such as analogue computers [1], geometrical models [2], Monte-Carlo simulation [3], travelling waves [4] and electrogeometric models [5] have been proposed in the last decades in order to predict the lightning performance. The current work demonstrates a novel approach for lightning performance evaluation of high voltage transmission lines based on Artificial Neural Networks (ANN), which have attracted much attention in the recent years. Many interesting ANN applications have been reported in power system areas [6-10], due to ANN's ability to learn, to handle complex non-linear functions, robustness, high computational speed and great efficiency, even in cases where full information for the studied problem is absent.

In this paper the feed-forward (FF) ANN method is used to identify the lightning performance of high voltage transmission lines. The FF method has been tested, by developing several models with different structures, learning algorithms and transfer functions in order the best generalizing ability to be achieved. Actual input and output data, collected from operating Hellenic high voltage transmission lines, were used in the training, validation and testing process. A comparison among the developed neural networks was performed in order the most suitable network to be selected. Finally the selected ANN was applied on operating Hellenic transmission lines of 150 kV and 400 kV in order to validate their accuracy and the obtained results are compared with these produced using conventional methods and with real records of outage rate.

ARTIFICIAL NEURAL NETWORKS

The ANNs represent a parallel multi layer information processing structure. The characteristic feature of these networks is that they consider the accumulated knowledge acquired during training and respond to new events in the most appropriate manner, giving the experience gained during the training process. The model of the ANN is determined according to the network architecture, the transfer function and the learning rule.

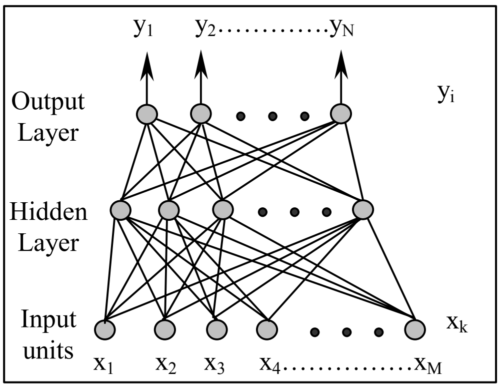

Fig. 1. A two layers feed-forward neural network.

The basic unit of an ANN is the neuron, which is represented as a node. A typical two layer feed-forward ANN is presented in figure 1. The name feed-forward implies that the flow is one way and there are not feedback paths between neurons. The initial layer, where the inputs come into the ANN is called the input layer and the last layer where the outputs come out of the ANN, is denoted as the output layer. All other layers between them are called hidden layers [11].

LIGHTNING FAILURE RATE

The total lightning failure rate N_T of a transmission line, is the arithmetic sum of the shielding failure rate N_{SF} and the backflashover failure rate N_{BF}:

$$N_T = N_{SF} + N_{BF} \tag{1}$$

Shielding failure rate N_{SF} is associated to a required minimum current I_{min} to cause a line insulation flashover [12]. N_{SF} is defined as follows:

$$N_{SF} = N_L \cdot \int_{I_{\min}}^{I_{\max}} f(I)\, dI \tag{2}$$

where:
N_L is the number of lightning flashes that are intercepted by a transmission line given from the equation [13]:

$$N_L = 0.004 \cdot T^{1.35} \cdot \left(b + 4 \cdot H^{1.09}\right) \tag{3}$$

T is the lightning level in the vicinity of the line,
H is the average height of the shielding wires,
b is the horizontal spacing, of the shielding wires,
$f(I)$ is the current density probability function,
I_{max} is the maximum lightning current,
I_{min} is the minimum current equal to $2U_a / Z_{surge}$ [12],
U_a is the insulation level of the transmission line,
Z_{surge} is the conductor line surge impedance, equal to:
$60\sqrt{\ln\frac{4h}{d} \cdot \ln\frac{4h}{D}}$ [13],
d is the equivalent conductor diameter without corona,
D is the equivalent conductor diameter with corona and
h is the conductor height at the tower in m.

Backflashover failure rate N_{BF} is estimated for transmission lines according to the method presented in [14, 15] and is given by the equation:

$$N_{BF} = N_L \cdot \int_0^{\infty} P(\delta)\, d\delta \tag{4}$$

where:
$P(\delta)$ is the probability distribution function of the random variable δ, which is a function of the two random variables I_{peak} and di/dt as shown in (5):

$$\delta\left(I_{peak}, di/dt\right) = R \cdot I_{peak}/2 - 0.85 \cdot U_a + L \cdot di/dt \tag{5}$$

R is the tower footing resistance in Ω,
L is the total inductance of the system in μH,
di/dt is a random variable denoting the lightning current derivative in kA/μs and
I_{peak} is a random variable denoting the peak lightning current in kA.

DESIGN OF THE PROPOSED ARTIFICIAL NEURAL NETWORK

The goal is to develop a neural network architecture that could identify the lightning performance of high voltage transmission lines. Five parameters that play important role to the lightning failure rate of a transmission line were selected as the inputs to the neural network, while as output the total lightning failure rate was considered. These data, which are presented in table I, constitute either actual collected data or estimated data based on actual measurements. More specifically, the tower footing resistance R and the insulation level U_a have been supplied by the Hellenic Public Power Corporation S.A. [16], the peak lightning current I_{peak} and the lightning current derivative di/dt, were estimated using the statistical lightning parameters distributions presented by Dr. Katz, based on his measurements in Israel [17], in combination with the geographical and meteorological data of the examined area, while the lightning level T has been supplied by the National Meteorological Authority of Hellas [18]. Finally the output, i.e. the total lightning failure rate N_T, consists of actual collected data provided also by the Hellenic Public Power Corporation S.A. [16].

Table I. ANN Architectures

Input Variables	Output Variables
- tower footing resistance R - insulation level U_a - peak lightning current I_{peak} - lightning current derivative di/dt - lightning level T	- total lightning failure rate N_T

As it has mentioned earlier each ANN model is determined according to its structure, the transfer function and the learning rule, which are used in an effort to learn the network the fundamental characteristics of the examined problem. The learning rules and the transfer functions are used to adjust the network's weights and biases in order to minimize the sum-squared error. The structure of the networks i.e. the number of hidden layers and the number of nodes in each hidden layer, is generally decided by trying varied combinations for selecting the structure with the best generalizing ability amongst the tried combinations. In general one hidden layer is adequate to distinguish input data that are linearly separable, whereas extra layers can accomplish nonlinear separations [19]. This approach was followed, since the selection of an optimal number of hidden layers and nodes for the FF network is still an open issue, although some papers have been published in these areas.

In this work, several FF ANN models were designed and tested. These were combinations of two learning algorithms, three transfer functions and five different structures selected among others due to their best generalizing ability in comparison with the all other tried combinations. The used learning algorithms were the Gradient Descent and the Levenberg-Marquardt, while the transfer functions were the hyperbolic tangent sigmoid the logarithmic sigmoid and the hard-limit (table II).

Table II. Designed ANN Models

Structure	Learning Algorithm	Transfer Function
- 5/5/10/1 - 5/10/10/1 - 5/10/15/1 - 5/10/5/10/1 - 5/10/15/10/1	- Gradient Descent - Levenberg-Marquardt	- Hyperbolic Tangent Sigmoid - Logarithmic Sigmoid - Hard-Limit

Finally a comparison among these neural networks was performed in order the most suitable network to be selected and to be applied on operating Hellenic transmission lines of 150 kV and 400 kV in order to validate its accuracy.

TRANSMISSION LINES' CHARACTERISTICS

The designed FF ANN models have trained, validated and tested using data collected from Hellenic operating transmission lines of 150 kV and 400 kV. These lines, which are presented in table III, were selected due to their high failure rates during lightning thunderstorms [16].

Each one of these five transmission lines are divided into regions, due to the different meteorological conditions and the different average values of tower footing resistance, which exist in each one region. It must be mentioned that the majority of the transmission lines in the Hellenic interconnected system present different characteristics through their length, since they run at the same time through plain regions, coastlines and/or mountainous regions. The number of regions and the different characteristics that exist in each one of these five lines, which are used in this study, are presented in table IV.

NEURAL NETWORK TRAINING, VALIDATION AND TESTING

The MATLAB neural network toolbox [20] was used to train the neural network models. Eight hundred forty values of each input and output data, referring to every one region of the examined transmission lines for every individual month of a five-year period, were used to train and validate the neural network model. In each training iteration 20% of random samples were removed from the training set and validation error was calculated for these data. The training process was repeated until a root mean square error between the actual output and the desired output reaches the goal of 1% or a maximum number of epochs (it was set to 7000) is accomplished. Finally, the number of the estimated lightning failures of the examined transmission lines was checked with the number obtained from situations encountered in the training, i.e. the five-year period, and others which have not been encountered.

TEST RESULTS

In order to evaluate the lightning performance of the examined Hellenic high voltage transmission lines, it was selected and used from the designed ANN models the model, which presented the best generalising ability, had a compact structure, a fast training process and consumed low memory. According to the training data presented in table V the ANN model, which been selected to be applied in the examined transmission lines was No. 18 (Levenberg-Marquardt - Logarithmic Sigmoid - 5/10/15/1).

The recorded lightning failures [16] of the examined transmission lines for the years 2002 and 2003 are presented in table VI, as well as the results obtained according to the simulation software program [15] and these obtained according to the proposed ANN model.

It is obvious that the results obtained according to the proposed ANN method are very close to the actual ones and the results obtained according to the simulation software program, something which clearly implies that the proposed ANN model is well working and has an acceptable accuracy.

CONCLUSIONS

The paper describes an artificial neural network method for the lightning performance evaluation of overhead high voltage transmission lines. Although several conventional analytical methods are published in the technical literature, which describe satisfactory the lightning performance of high voltage transmission lines, most of them are based on empirical and approximating equations. In contrast to these methods, the proposed ANN method is only using actual line data in its calculations, something that clearly presents its main advantage. Moreover the efficient and economic implementation of the ANN method with today's computer technology, constitute it as an alternative attractive tool.

The proposed method has been applied, on operating Hellenic transmission lines of 150 kV and 400 kV. The obtained results were almost identical to the field observation data collected from the Hellenic Public Power Corporation S.A. and these obtained using a conventional analytical method (simulation method). The presented methodology can be used by electric power utilities as a useful tool for the design of electric power systems.

Table III. Line parameters of the examined transmission lines [16]

No.	Line	Phase Voltage (kV)	Length (km)	No. of Towers	Insulation Level (kV)	Conductor Dimensions (ACSR MCM)	No. of Circuits
1	Thassaloniki-Kardia	400	109.908	305	1550	954	2
2	Thassaloniki-Amideo	400	90.589	249	1550	954	2
3	Arachthos-Igoumenitsa	150	75.802	239	750	336.4	1
4	Tavropos-Lamia	150	75.384	219	750	336.4	1
5	Megalopoli-Sparti	150	64.472	173	750	336.4	1

Table IV. Line design characteristics of the examined transmission lines [16, 18]

Line	Region	Towers	R (Ω)	N_T (Average lightning failures 1997-2001)	T (Average lightning level 1997-2001)
Thassaloniki-Kardia	I	1 - 195	1.93	0.80	29.80
	II	196 - 260	8.83	1.20	25.40
	III	261 - 305	18.24	2.00	27.20
Thassaloniki-Amideo	I	1 - 208	5.20	1.40	29.80
	II	209 - 249	11.40	3.60	32.50
Arachthos-Igoumenitsa	I	1 - 80	5.20	0.80	34.70
	II	81 - 163	13.00	1.80	31.00
	III	164 - 239	45.40	4.40	41.30
Tavropos-Lamia	I	1 - 74	2.44	1.60	24.40
	II	75 - 166	1.05	1.20	36.70
	III	167 - 219	6.45	3.20	31.90
Megalopoli-Sparti	I	1 - 45	5.10	0.20	28.00
	II	46 - 75	39.65	1.20	31.80
	III	76 - 173	11.18	2.60	30.10

Table V. Training data of the designed ANN models

Gradient Descent - Hyperbolic Sigmoid					**Levenberg-Marquardt - Hyperbolic Sigmoid**				
No.	**Structure**	**Epochs**	**Train Error**	**Validation Error**	**No.**	**Structure**	**Epochs**	**Train Error**	**Validation Error**
1	5/5/10/1	4091	0.010	14.75 %	6	5/5/10/1	6210	0.010	8.63 %
2	5/10/10/1	5238	0.010	11.41 %	7	5/10/10/1	5248	0.010	5.95 %
3	5/10/15/1	6172	0.010	12.36 %	8	5/10/15/1	5473	0.010	9.03 %
4	5/10/5/10/1	5643	0.010	9.15 %	9	5/10/5/10/1	7000	0.031	14.29 %
5	5/10/15/10/1	7000	0.023	19.99 %	10	5/10/15/10/1	7000	0.043	18.86 %
Gradient Descent - Logarithmic Sigmoid					**Levenberg-Marquardt - Logarithmic Sigmoid**				
No.	**Structure**	**Epochs**	**Train Error**	**Validation Error**	**No.**	**Structure**	**Epochs**	**Train Error**	**Validation Error**
11	5/5/10/1	6012	0.010	7.23 %	16	5/5/10/1	6378	0.010	9.54 %
12	5/10/10/1	5812	0.010	5.21 %	17	5/10/10/1	5591	0.010	7.72 %
13	5/10/15/1	7000	0.020	9.07 %	18	5/10/15/1	4924	0.010	4.08 %
14	5/10/5/10/1	7000	0.029	16.54 %	19	5/10/5/10/1	7000	0.026	17.10 %
15	5/10/15/10/1	7000	0.032	23.67 %	20	5/10/15/10/1	7000	0.030	21.16 %
Gradient Descent - Hard-Limit					**Levenberg-Marquardt – Hard-Limit**				
No.	**Structure**	**Epochs**	**Train Error**	**Validation Error**	**No.**	**Structure**	**Epochs**	**Train Error**	**Validation Error**
21	5/5/10/1	7000	0.027	19.64 %	26	5/5/10/1	7000	0.017	10.57 %
22	5/10/10/1	7000	0.035	22.37 %	27	5/10/10/1	6729	0.010	9.73 %
23	5/10/15/1	7000	0.028	15.14 %	28	5/10/15/1	6478	0.010	8.32 %
24	5/10/5/10/1	7000	0.045	26.41 %	29	5/10/5/10/1	7000	0.025	12.36 %
25	5/10/15/10/1	7000	0.058	28.76 %	30	5/10/15/10/1	7000	0.042	26.15 %

Table VI. Test results of the developed ANN model

Year	**2002**			**2003**		
Line	**Recorded Lightning Failures**	**Lightning Failures using Simulation Method**	**Lightning Failures using ANN Model**	**Recorded Lightning Failures**	**Lightning Failures using Simulation Methods**	**Lightning Failures using ANN Model**
Thassaloniki-Kardia	4.00	3.72	3.89	7.00	6.64	6.92
Thassaloniki-Amideo	5.00	5.17	4.94	4.00	3.81	4.07
Arachthos-Igoumenitsa	5.00	4.56	4.88	5.00	4.71	4.45
Tavropos-Lamia	6.00	6.34	5.99	5.00	5.01	5.19
Megalopoli-Sparti	5.00	4.80	4.93	3.00	2.72	3.01

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