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A Metamodeling Approach for Leader Progression Model-based Shielding Failure Rate Calculation of Transmission Lines Using Artificial Neural Networks

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Abstract – The performance of transmission lines and its shielding design during a lightning phenomenon are quite essential in the maintenance of a reliable power supply to consumers. The leader progression model, as an advanced approach, has been recently developed to calculate the shielding failure rate (SFR) of transmission lines using geometrical data and physical behavior of upward and downward lightning leaders. However, such method is quite time consuming. In the present paper, an effective method that utilizes artificial neural networks (ANNs) to create a metamodel for calculating the SFR of a transmission line based on shielding angle and height is introduced. The results of investigations on a real case study reveal that, through proper selection of an ANN structure and good training, the ANN prediction is very close to the result of the detailed simulation, whereas the Processing time is by far lower than that of the detailed model.

Keywords: Shielding failure rate, Metamodel, Artificial neural network, Lightning performance, Leader progression model, Charge simulation method

1. Introduction

Many different mathematical models are used to deal with practical problems that are often hard to solve. Metamodeling is a mathematical technique usually used in conjunction with heuristic optimization methods to deal with complicated problems that may have multiple factors or that are too time consuming to find adequate answers for to fit the practical requirements [1-3]. This method is also utilized for solving problems in a power system and in the field of fast transient phenomena [3, 4]. The lightning performance of transmission lines is one of the major issues that come up during overhead line design and operation. Lightning performance is usually quantified by a shielding failure rate (SFR) index in strokes/100 km/year. The well-known electrogeometrical model (EGM) has long been used as a simple and effective method to investigate the lightning performance of transmission lines [5-7]. Nevertheless, leader progression models (LPMs), which consider the details of leader movement from cloud to line and upward leader inception criteria, are also proposed by investigators [8, 9]. These complicated models consider the geometrical configurations of towers, phase, and ground conductors and their sags, as well as earth effects. The lightning attachment to ground structures comprises a downward leader movement from cloud approaching the ground and an upward leader inception from "striking point." Tracking the leaders' paths toward each other requires electrical field calculation in the area under simulation for each step of advancement [8]. These simulations also require the changing the position of the downward leader starting from the clouds. As a result, the overall simulation time is quite long. In addition, these simulations may have to be repeated for different shielding angles and different height of wires to find the optimum angle, and so on. In such cases, direct simulation is simply not practical. The metamodeling approach is fitted to this problem. In this approach, a detailed simulation is performed for specified angles and heights, which are actually "samples" to be used to develop a metamodel. In the present paper, this higher-level model is an artificial neural network (ANN). A three-layer perceptron is used to learn the patterns of shielding angle-height and SFR. After training, this metamodel is to be manipulated to get the SFR of the line in all other shielding angles and heights. The prediction of this model is compared with the prediction of the detailed model, and shows acceptable coincidence. The required time to find the solution through the metamodeling approach is much lower than that of the detailed model, which makes it a more suitable method to be used.

The rest of the current paper is organized as follows. In Section 2, the leader progression model is described. Section 3 provides the meta-modeling details and training procedure. In Section 4, a case study for applying this approach for a transmission line and as the simulation

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results are presented. Finally, Section 5 concludes the paper.

2. Leader progression model

To calculate the SFR of transmission lines using the LPM approach, one span of the overhead line, including towers, wires, ground, and clouds, are modeled accordingly to consider their effects on the variation of electric field. Upward and downward lightning leaders are then modeled to travel in this space of simulations to identify a point where the lightning would finally attach [8]. In this section, the principles of the LPM-based SFR calculation of transmission lines are presented.

2.1 Cloud and structures model

Any simulation of lightning attachments to ground structures requires electric field calculation under the study environment to find other related parameters such as space charges, stable leader inceptions, decision on downward leader direction, and so on. In the present paper, a charge simulation method is used [10, 11], wherein the ring, point, and line charges are placed in any location to enforce the boundary conditions to meet the values specified by the problem definition. The overall equipment configuration is shown in Fig. 1.

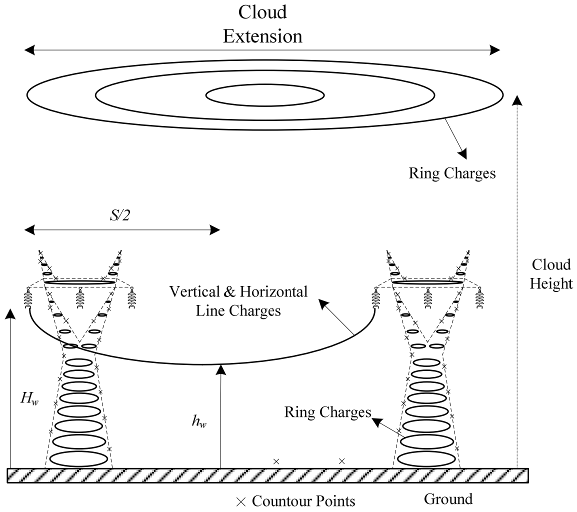

Fig. 1. Location of the charges for the field calculation using the charge simulation method

The model of clouds represents the charges during a thunderstorm and their distribution. Simplified unipolar negative ring charges are used to model the cloud charges. As seen in Fig. 1, at the height of 2000 m and with an extension of 5000 m, ring charges are placed with their centers above midspan axes. According to the field tests, the storm field produces an electrical field on ground level ranging from 1–20 kV/m [12]. Thus, cloud charges are calculated so that the electric field near ground level becomes 10 kV/m. Ring charges are also used to model the towers. According to Fig. 1, the exact shape and the arms of towers are modeled as such so that the main structure of ring charges is similar to the tower shape itself. By assuming that the contour points around the tower are in the middle of consecutive ring locations, the zero voltage boundary condition in three dimensions around the tower may be achieved. Short horizontal and vertical line charges are used to model the wires and their sag with hyperbolic function [8]:

$$z = h_w \cdot \cosh\left[k \cdot \left(\frac{S}{2} - x\right)\right] \tag{1}$$

$$k = \frac{2}{S}\cosh^{-1}\left(\frac{H_w}{h_w}\right) \tag{2}$$

where h_w is the height of the wire at mid-span, h_w is the wire height at connection point to the towers, and S is the span length, as shown in Fig. 1. The boundary conditions for ground wires and phase wires are zero voltage and peak positive nominal voltage, respectively. In a flat configuration of Fig. 1, the middle phase is assumed to be at its positive peak voltage, whereas the side phases are assumed to be at half-negative peak.

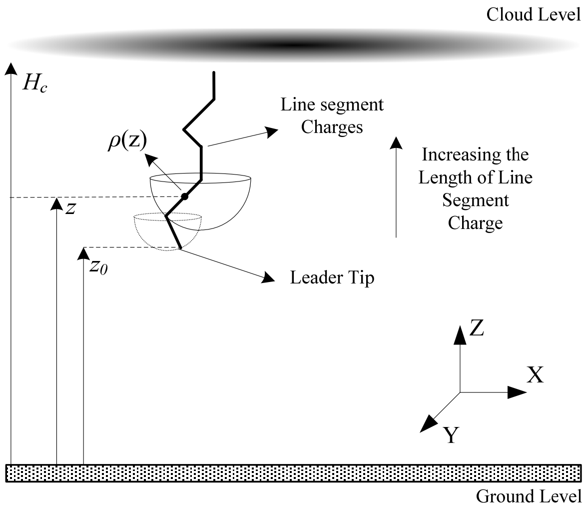

Fig. 2. Downward lightning leader, line charge segments, and contour points for finding the next jump point

2.2 Downward leader model

In the LPM, the downward leader starts from the clouds and approaches the earth; By accepting the principle that the more similar the model is to real phenomenon, the more accurate it is; the proposed model takes care of the physical behavior of downward leader based on physical observations [13]. The propagation of the downward leader is modeled by steps with lengths of 1/20 of the distance of the tip of the downward leader from the ground, which ensures that the step length is always lower than 100 m, in accordance with field observations [14]. Similarly, a lower bound of 10 m is also applied. In this stepping model, knowing the direction of leader movement toward the ground is important. The next leader jump is assumed to be a point where maximum voltage gradient may exist between the leader tip and the target point [8] [Fig. 2(a)]. The steps of the downward leader are modeled by horizontal and vertical line charges. The charge density of the downward leader line charges is computed by the following equation based on electrostatic considerations of measured waveforms of the return-stroke current [15]:

$$\begin{aligned}\rho(z) = I_p \Bigg\{ & m_0\left(1-\frac{z-z_0}{H_c-z_0}\right)\left(1-\frac{z_0}{H_c}\right) \\ & + \frac{m_1+m_2(z-z_0)}{1+m_3(z-z_0)+m_4(z-z_0)^2}\times \\ & \left[0.3e^{\frac{10-z_0}{75}}+0.75\left(1-\frac{z_0}{H_c}\right)\right]\Bigg\}\end{aligned} \tag{3}$$

where $m_0 = 1.476\times10^{-5}$, $m_1 = 4.857\times10^{-5}$, $m_2 = 3.9097\times10^{-6}$, $m_3 = 0.522$, $m_4 = 3.73\times10^{-3}$, z_0 is the height of the downward leader tip in m, H_c is the cloud height in m, I_p is the return stroke peak current in kA, ρ is the downward leader charge density in C/m, and z is the height variable of the point on the leader where the charge density is to be calculated (Fig. 2). In this figure, the length of line charges is increased from the tip of the downward leader to the base of the cloud.

2.3 Upward leader model

The most important stage of lightning stroke attachment to any structure on earth is the instance of a stable inception of an upward connecting leader, i.e., the discrimination time for the stroke to attach to the target point. Based on different laboratory and field observations in recent years, different stable upward leader inception criteria have been proposed [9, 15-17]. A simplified self-consistent model that tracks the leader–streamer system movement of positive upward leader by considering the space charge development in the streamer zone and the transition of the corona streamer to the leader–streamer system is selected to find the stroke target [15]. The upward leader model first calculates the initial streamer length and charge produced in the streamer zone of the local ionization region for each test point on ground structures according to (4) and (5):

$$L_s(0) = \frac{U_0}{E_{str}-E_1} \tag{4}$$

$$\Delta Q(0) = \frac{1}{2}K\cdot L_s^2(0)\cdot(E_{str}-E_1) \tag{5}$$

where U_0 and E_1 are the voltage and field on the fitted line of background electric field (which is calculated by charge simulation method), respectively; E_{str} is the constant streamer zone electric field, which is taken to be 450 kV/m for positive upward leaders; K is a geometrical factor that depends on the configuration and shape of the streamer and is taken to be 3.5×10-11 C/V•m; and $L_s(0)$ and $\Delta Q(0)$ are the initial length and the developed charge in the streamer zone. The criterion of $\Delta Q(0) > 1\mu C$ is checked for initial streamer charge transition to leader–streamer system. When this condition is fulfilled, leader–streamer system advancement mechanism is simulated by the following equations:

$$\begin{aligned}U_T(i) = {} & E_\infty\cdot L_l(i) \\ & + x_0\cdot E_\infty \ln\left[\frac{E_0}{E_\infty}-\frac{E_0-E_\infty}{E_\infty}e^{-L_l(i)/x_0}\right]\end{aligned} \tag{6}$$

$$L_s(i) = \frac{U_0+E_{str}\cdot L_l(i)-U_T(i)}{E_{str}-E_1} \tag{7}$$

$$\begin{aligned}\Delta Q(i) = {} & K\times[L_s(i-1)-L_l(i)]\times \\ & \{E_{str}[L_l(i)-L_l(i-1)]+U_T(i-1)-U_T(i)\}\end{aligned} \tag{8}$$

$$\Delta L_l(i) = \frac{\Delta Q(i)}{q} \tag{9}$$

$$L_l(i-1) = L_l(i)+\Delta L_l(i) \tag{10}$$

where $U_T(i)$ is the leader potential in step *i*; E_∞ and E_0 are the initial value and final quasi-stationary values of the leader gradient and taken to be 400 and 30 kV/m, respectively [16]; x_0 (=10 m) is a constant that depends on upward leader speed and leader channel conductance equation constant; and q is a constant that represents the charge per unit length necessary to achieve the thermal transition from the diffuse glow to the leader channel, which is assumed to be 50 μC/m [18]. The procedure is continued until $L_l(i)$ reaches a specified length (taken to be 5 m). If, during this advancement, any test point $\Delta Q(i)$ remains positive, it is approved that a stable upward leader is incepted from that point (i.e., target point is found). Ground strikes are assumed to occur if no stable leader is incepted from any test point on structures (towers, phase, and ground wires) until the downward leader reaches a height of 5 m above the ground level.

2.4 Simulation procedure using detailed model and SFR calculation

The simulation procedure is as follows:

(1) A one-span model of towers, wires, and ground is created considering practical dimensions. Charges are also placed properly according to the charge simulation method.

(2) The space above the span is divided into meshes. Owing to the symmetry that exists in the problem, performing the procedure of Fig. 3 on half of the

span length is sufficient. The width of the area in Y direction according to Fig. 3, where the simulation should be performed, is selected such that no flash to wires and towers occurs beyond it.

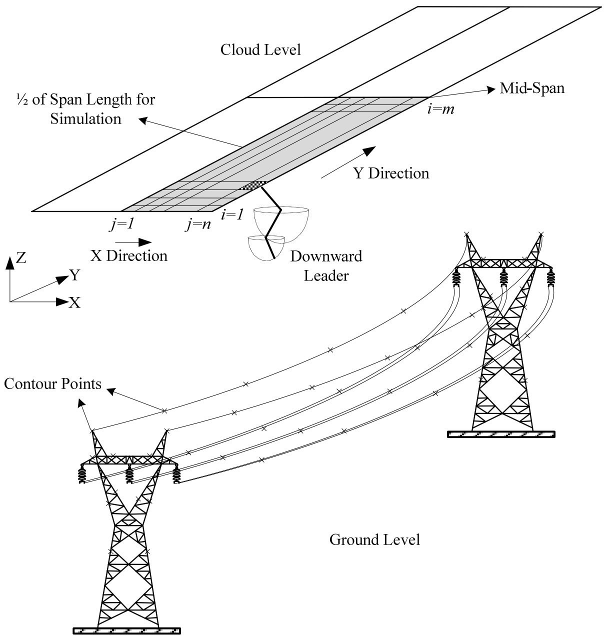

Fig. 3. One span of overhead line and starting meshes to start descending the downward lightning leader

(3) In a specified mesh, a downward leader is set to descend toward the ground. This procedure is repeated for all values of return stroke current in a reasonable range. In each downward leader step, the electric field at any test point is computed to identify the next jump of the downward leader. The electric field is also used to check for stable upward leader inception from the ground structures.

(4) In finding stable leader inception from phase wires for each mesh, a range of return stroke currents (I_{min}, I_{max}) where the lightning leaders strike the phase wires is extracted. Moreover, the height of the downward leader at discrimination instance and the statistical data of stroke inception are computed for different shielding angles.

(5) Steps 3 and 4 are repeated until a range of (I_{min}, I_{max}) is known for all meshes. The SFR on each mesh can be computed as follows:

$$SFR_{ij} = 0.1 \times GFD \times \frac{dx}{D} dy \times [P(I_{\max}) - P(I_c)] \tag{11}$$

where *dx* (m) and *dy* (m) are the mesh length and width, respectively, as shown in Fig. 5. Here, *D* (m) is the span length; SFR_{ij} is the shielding failure rate in strokes/100km/year of mesh *ij* for the currents exceeding I_c; and *P*(*I*) is the probability distribution function of the first stroke current exceeding *I* [19]:

$$P(I) = \frac{1}{1+\left(\frac{I}{31}\right)^{2.6}} \tag{12}$$

where *I* is the return stoke current in kA. Here, *GFD* is the ground flash density (flash/km^2/year) and is computed by [20]:

$$GFD = 0.04 \times T_d^{1.25} \tag{13}$$

where T_d is the number of thunderstorm days per year. In Table 2 and Fig. 6, the distances and dimensions are given for a 400 kV overhead line. Total SFR is then simply calculated by the following equation:

$$SFR = 4 \sum_{i=1}^{m} \sum_{j=1}^{n} SFR_{ij} \tag{14}$$

The SFR is a function of shielding angle and height of wires. To investigate the effects of the shielding angle, the above procedure should be repeated for different angles.

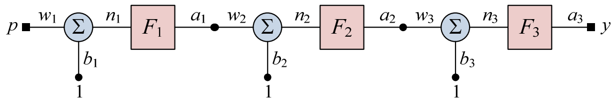

Fig. 4. Three-layer perceptron, the metamodel

3. Meta Modeling and ANN

A metamodel is simply a function that substitutes the real problem. The more precise the metamodel, the more accurate the final results. Metamodels are used to simplify the solution process of complex and time-consuming problems such as determining lightning performance of transmission lines, where the procedure requires detailed models. The metamodel, which is mostly used for such purposes, is a feedforward neural network called the three-layer perceptron, as illustrated in Fig. 4 [21, 22]. In this figure, *p* is the vector of inputs, *y* is the output, and *F* represents the neuron core function. Together, this neural net and backpropagation learning method produce a powerful approximator [22]. The hidden layer of the network normally has a sigmoid function (F_2). The backpropagation with momentum learning method, which is used to learn the pattern, is formulated as follows [23]:

$$\begin{aligned} & w_l^{k+1}(i,j) = w_l^k(i,j) - \\ & \alpha \cdot \frac{\partial R}{\partial w_l^k(i,j)} + \gamma \cdot \Delta w_l^{k-1}(i,j) \\ & b_l^{k+1}(i) = b_l^k(i) - \\ & \alpha \cdot \frac{\partial R}{\partial b_l^k(i)} + \gamma \cdot \Delta b_l^{k-1}(i) \end{aligned} \tag{15}$$

where $w_l^k(i,j)$ is the cell in row i and column j of weight matrix in layer l when learning the k th pattern;

R is the learning criterion function that is typically the square error of the output layer; $b_l^k(i)$ is the i th cell of bias array of layer l when learning the process of k th pattern; α is a learning rate factor and γ is the term of momentum; and $\Delta w_l^{k-1}(i,j)$ and $\Delta b_l^{k-1}(i)$ are (i,j) th weight and i th bias errors of layer l when learning the $k-1$ pattern.

Based on the LPM, which was described in the previous section, deriving sufficient samples by varying the shield angle and height of conductors is possible. These samples are used as learning patterns for the three-layer perceptron. After reaching the preset tolerance of the neural network learning process, it is tested against some test points that were not in the learning pattern set. If the prediction error of the neural net for test points is not acceptable, the learning process is restarted after changing the goal of learning, the number of patterns, or the number of neurons in the input or middle layer. If the predictions are acceptable, the metamodel is prepared and is investigated for different angles and heights. Fig. 5 shows the procedure of creating a reliable metamodel.

Combining the LPM and the met-modeling approach, the LPM results from detailed simulations are obtained for specific configuration of towers and environmental condition. The ANN is then trained with the abovementioned procedure up to an acceptable tolerance. Calculating the SFR in different shielding angles and so on becomes simple after the ANN is trained. Nevertheless, the ANN predictions can be verified by LPM. Therefore, the LPM and ANN are used in sequence to decrease the time required to obtain a specified result.

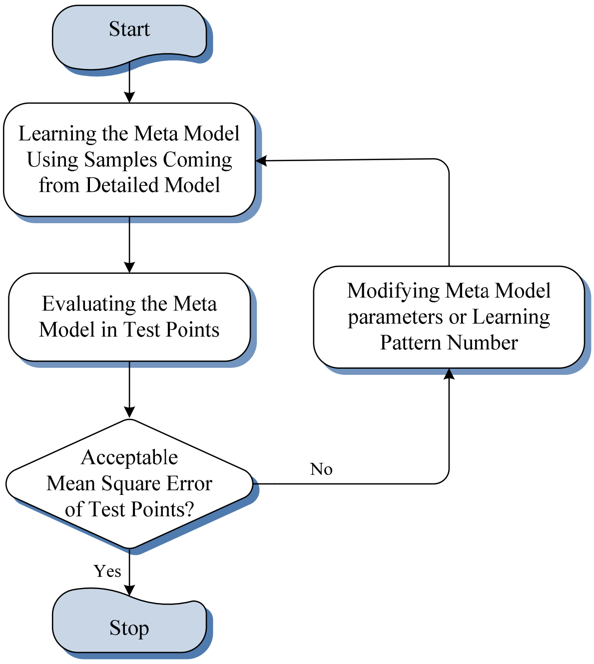

Fig. 5. Procedure for creating a reliable metamodel

4. Study Case: 400 kV Overhead Line

A 400 kV transmission line with flat configuration is investigated under a detailed model of LPM to extract the SFR index of the line for different shielding angles and height of conductors. The geometrical data of the transmission line and the data for the models of lightning leaders are listed in the Appendix. The derived SFR values are also listed in the Appendix, Table 3. For a height of 27.8 m of phase conductors, the variation of SFR values with respect to shielding angle is shown in Fig. 6. An optimum positive shielding angle exists where SFR takes its minimum for this configuration.

At this optimum angle, any increase in the shielding angle results in a sharp increase in SFR value, mainly because the strokes attach phase wires at the side. Similarly, by decreasing the shielding angle to negative values, the strokes would ping the phase wire at the middle, increasing the SFR value. Note that for deriving each SFR value, more than 20 hours is required, even with a powerful personal computer (CPU Clock 2.8 GHz, L1 Cash 32 kB, L2 Cash 2 MB, FSB 800 MHz and 1 GB RAM).

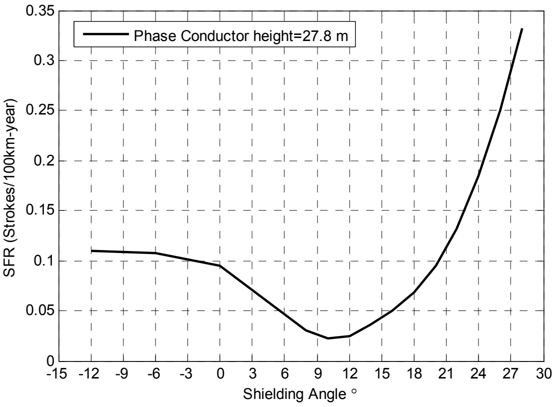

Fig. 6. SFR with respect to shielding angle extracted from detailed model

As seen in Fig. 6, the pattern of SFR versus the shielding angle is decreasing in positive angles below 10°, which is in contradiction with EGM predictions. In EGM, the path of the downward leader approaching the earth is not considered, whereas, in LPM, the stroke may have curved to impinge the phase wire. By changing the position of the shield wire and shifting it in, the electric field on the towers, wires, and ground changes on the span, which may decrease the SFR. However, this hypothesis needs to be further investigated in laboratories through experiments on small models.

A three-layer perceptron is trained by a backpropagation algorithm using the patterns of shielding angle and height as input and SFR values as output. From the data in Table 3 in the Appendix, one point is arbitrary chosen in each column to test the metamodel after training. The rest of the data are applied to ANN as learning patterns.

In the final stage, the three-layer perceptron comprises ten neurons in the first layer, three neurons in the second layer, and one neuron in the third layer. The first two layers have a sigmoid function, while the output layer function is set to be pure linear to achieve risk values higher than one. Fig. 7 shows the ANN performance after training. The maximum mean square error for this training is set at 10^{-5}, and the training procedure takes ~14 min. The mean square error for the test points (which are not used as learning patterns) is 0.096, which is acceptable.

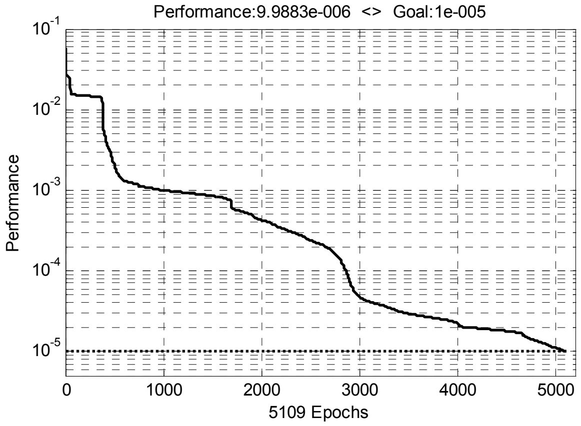

Fig. 7. Training performance of the metamodel

The metamodel prediction for SFR values for different heights of phase wires is shown in Fig. 8. Obviously, the simulated patterns are followed by the metamodel, and manipulating the metamodel to find the optimum position of shield wires in different heights is possible. In Fig. 9, the optimum shielding angle in different heights and the corresponding minimum SFR are plotted. In taller towers, the optimum shielding angle tends to decrease slightly. Minimum SFR increases with respect to the height of the phase wires.

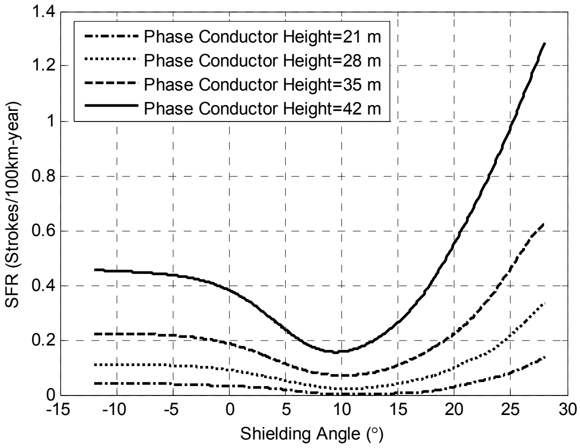

Fig. 8. SFR values predicted by the metamodel

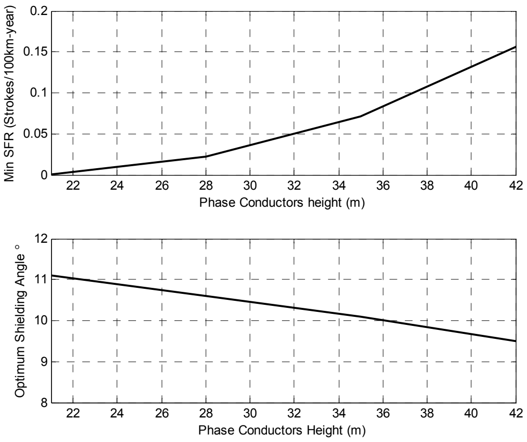

Fig. 9. Minimum SFR values at different phase wire heights (above) and optimum shielding angles (below)

Finally, the SFR of the transmission line from detailed model simulations is compared with the prediction of the meta-model at a height of phase wires of 42.8 m in Fig. 10. In higher shielding angles, the errors are higher. Note that this height is not used to train the metamodel, and the figure is an extrapolation. In practice, calculating the optimum shielding angle with high precision is useless; a precision of approximately one degree is sufficient. Therefore, the application of ANN at this height also produces good results. The pattern of SFR variation with respect to shielding angle is followed by the metamodel.

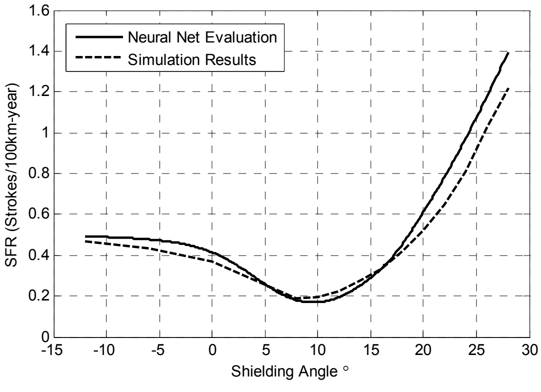

Fig. 10. Comparison between SFR values predicted by the metamodel and those predicted by detailed simulations

5. Discussion and Conclusion

In the present study, a metamodeling approach is introduced to calculate the SFR of a transmission line while studying its lightning performance. The approach is proven efficient in decreasing the time required to maintain precision for practical purposes. The meta-model used in the present study is a three-layer perceptron, which is essentially a good approximator.

In any practical situation, a contradiction always exists between the precision level (detailed models) and the time required for simulation. The more accurate the model, the more time consuming the simulation. For the lightning performance analysis of transmission lines, traditional models of shielding failure calculation with lower level of details have been used for years [5-7]. Higher-level details invoked recently for lightning performance analysis of transmission lines have increased the simulation volume dramatically [8]. The metamodeling approach is therefore a tool to overcome this drawback.

The advantage of LPM in comparison with traditional methods such as EGM is that, in LPM, the nature of lightning stroke and overhead line is considered as is (i.e., the downward stroke path, the upward leader–streamer system inception, the sag of conductors, the towers structure, and environmental conditions). Therefore, the effect of different factors is considered, resulting in higher precision. The most significant disadvantage of LPM is its long simulation time. The metamodeling approach has been proven to be effective in decreasing the overall simulation time.

Although Eq. (12) is used by many investigators to calculate probability of occurrence of stroke currents, different parameters and different distributions that may be more suitable for more recent measurements have also been suggested. The overall pattern of SFR would not change with a lower mean of stroke peak current in Eq. (12); however, the SFR values would be higher. Nevertheless, in practical studies, using the most recent measurement data and distribution functions available for lightning stroke peak current is recommended.

Several differences exist between the metamodel and the simulation optimization where a search algorithm after meta-model training is used [2, 3]. In the present paper and for SFR calculation, the manipulation of input–output is easier after ANN learned the patterns. Such phenomenon is rooted from the nature of the SFR calculation wherein two independent variables are used. Therefore, a direct search is suitable for finding the optimum shielding angle. In the case of mounting arresters in a high voltage network, the number of independent variables is significantly higher, and a direct search is not possible where heuristic optimization methods like genetic algorithms are needed [2].

Another issue that may arise is the possibility of using different metamodels such as multidimensional regression and so on. In fact, using any type of function to track the patterns identified by samples is mathematically possible. The criterion is that this function should be capable of producing good precision, and should have sufficient degree of freedom to be handled by the user. The ANN is a good approximator that learns fast, is capable of tracking the samples acceptably, and can be easily manipulated to fit the patterns better by changing the number of neurons of its layers. Nevertheless, increasing the quality of meta-modeling only by changing the metamodel itself is not possible. The number of samples and their scattering throughout the search space are also important. Trial and error is essentially needed to find the level of precision required by gradually increasing the number of samples.

Appendix

Table 1. Parameters of the positive upward leader model

Parameter	Value	Unit
E_{init}	400	kV/m
E_{inf}	30	kV/m
V	20×10^{4}	m/s
θ	50	μs
E_s	450	kV/m
K_Q	3.5×10^{-11}	C/V
q_l	50	μC/m

Table 2. Parameters for SFR calculation

Parameter	Value	Unit
D	430	m
Sag	9	m
dx	43	m
dy	20	m
T_d	15	thunderstorm days per year
Ground Wire Radius	0.0049	m
Phase Wire Radius	0.0158	m

Table 3. SFR values extracted from detailed LPM analysis (strokes/100 km/year)

	Height of phase conductor (m)			
Shielding angle (deg)	22.8	27.8	32.8	37.8
-12	0.0573	0.1101	0.174	0.298
-6	0.052	0.108	0.169	0.295
0	0.0387	0.095	0.153	0.245
8	0.0127	0.03	0.06	0.106
10	0.0073	0.022	0.047	0.1
12	0.004	0.025	0.052	0.113
14	0.0087	0.036	0.066	0.138
16	0.016	0.05	0.089	0.179
18	0.0267	0.068	0.122	0.245
20	0.044	0.095	0.172	0.32
22	0.0684	0.1316	0.24	0.419
24	0.0962	0.185	0.319	0.534
26	0.132	0.25	0.406	0.695
28	0.167	0.332	0.498	0.856

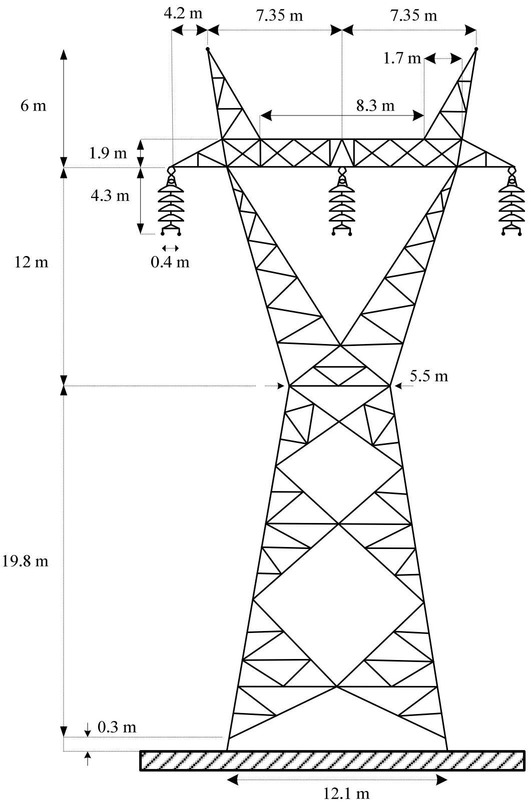

Fig. A1. 400 kV tower and dimensions

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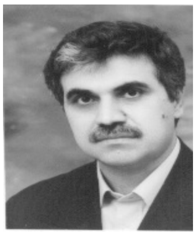

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