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An optimal design method for improving the lightning performance of overhead high voltage transmission lines

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Abstract

This paper presents a method for the optimal design of high voltage transmission lines taking into consideration shielding and backflashover failure rates. The minimization of suitably defined performance indices, which relate the failures caused by lightning in a transmission line to both line insulation level and tower footing resistance, is aimed. Optimum values for both line insulation level and tower footing resistance are calculated. The method is applied on several operating Hellenic transmission lines of 150 and 400 kV, respectively, carefully selected among others, due to their high failure rates during lightning thunderstorms. Special attention has been paid on open loop lines, where a possible failure could bring the system out of service causing significant problems. The obtained design parameters, which reduce the failure rates caused by lightning, are compared with the existing design parameters of the transmission lines leading up to useful conclusions. The proposed optimization method can be proved a valuable tool to the studies of electric power systems designers, intending to reduce the failure rates caused by lightning.

Keywords: Lightning protection; Lightning performance; Optimal design method; Overhead transmission lines

1. Introduction

Lightning strikes to overhead high voltage transmission lines are a usual reason for unscheduled supply interruptions in the modern power systems. In an effort to maintain failure rates in a low level, providing high power quality and avoiding damages and disturbances, plenty of lightning performance estimation studies have been conducted [1–13] and several design methodologies have been proposed [14–19]. Designing appears to be the most important issue in the lightning performance of a transmission line, not only because differences in the design parameters values affect significantly the lightning performance but also because is practically impossible to make improvements and modifications in an existing transmission line.

Chang and Zinn [14] determined a minimum cost design of transmission lines. They demonstrated a methodology for the design of an electric transmission line system constructing a mathematical model, which represented the total cost of the system as a function of the system design variables. Grant and Clayton [15] developed a methodology, which used to explore the sensitivity of the required present worth of revenue, to several design variables in order to achieve design performance at minimum cost. Significant was also the study of Kennon and Douglass [16], who conducted an interesting study presenting a range of line optimization techniques which can be applied to decide whether standard or optimized line designs are appropriate, concluded that even simple methods of optimization can help the designer keep his costs to a minimum. Saied et al. [17] presented a method for the optimal design of overhead high voltage transmission lines with main objective the minimization of the line total annual cost, considering the relevant technical constraints and both fixed and running cost items. Katic and Savic [18] analysed the economical aspects of the overhead distribution line lightning performance taking into account customer and utility costs of line outages. An alternative design procedure for uncompensated overhead transmission lines introduced from Saied [19]. It was based on the derivation of two closed-form analytical expressions for both the line power and current ratings, in terms of the geometrical data of the line tower and its bundled conductors.

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Generally, two different methods exist in the design of a transmission line. The first method uses a good tower footing resistance and relatively low line insulation while the second one uses an average tower footing resistance but relatively high line insulation [8]. The current work presents in detail a design method for the optimum selection of the transmission line insulation level and the tower footing resistance. Suitable performance indices are defined in order to relate the line insulation level and the tower footing resistance cost values to the lightning failure costs. Using an iterative optimization algorithm, optimal values of these two design parameters are calculated in order to minimize the defined performance indices.

The developed method is applied on several operating Hellenic transmission lines, (including open loop lines), of 150 and 400 kV, with high lightning failure rates in order to validate its effectiveness. New values for the transmission line design parameters are proposed, which have as a result the reduction of the lightning failures. Useful conclusions are extracted from the comparison between the proposed values and the actual line design data.

2. Flashover rate of a transmission line

An approximation to the number of flashes to earth that are intercepted by a transmission line is calculated using the equation [8]:

$$N_{\mathrm{L}} = 0.004 \cdot T^{1.35} \cdot (B + 4 \cdot h^{1.09}) \tag{1}$$

where N_{L} is the number of lightning flashes to a line per 100 km/year, T the lightning level in the vicinity of the line, h the average height (in m) of the shielding wires and B is the horizontal spacing (in m) between the shielding wires.

The lightning parameters, i.e., the peak value and the lightning current derivative, are randomly selected from statistical distributions based on the measurements performed by Berger et al. in Monte San Salvatore [20] and the review conducted from the Lightning and Insulator subcommittee of the T&D Committee [21], with the 85% of the lightning strokes to be considered negative while the 15% of them to be considered positive.

The termination point of a lightning stroke to a transmission line can be either a shielding wire, phase conductor, tower or even ground. The electrogeometrical model using the concept of striking distance has got the ability to determine the termination point. In general, the striking distance r in m is given by the formula:

$$r = A \cdot I^{b} \tag{2}$$

where A and b are the constants dependent on the termination point and I is the prospective stroke current in kA.

Although there are several versions of electrogeometrical model [8,22–25], where each one uses different values for the constants A and b (see Table 1), all of them consider the following three concepts: (a) strokes arrive vertically, (b) the lightning leader develops unaffected by the existence of grounded objects until it arrives within striking distance from the grounded object and (c) the striking distance is related to the current of the return stroke.

Shielding failure flashover rate N_{SF} can be estimated according to several methods, such as electrogeometrical model [8,22–25], numerical analysis model [11], analytical [12], EMTP [13] and estimation methods [10]. In this paper, the shielding failure flashover rate N_{SF} is estimated according to the method presented in [8], where it is associated to a required minimum current $I_{\min}$ to cause a line insulation flashover and is defined as follows:

$$N_{\mathrm{SF}} = N_{\mathrm{L}} \cdot \int_{I_{\min}}^{I_{\max}} D_{\mathrm{c}} f(I)\,\mathrm{d}I \tag{3}$$

where $I_{\max}$ is the maximum lightning current in kA, $I_{\min}$ the minimum current equal to $2U_{\mathrm{a}}/Z_{\mathrm{surge}}$ [9], U_{a} the insulation level of the transmission line in kV, $f(I)$ the current density probability function, D_{c} the shielding failure exposure distance, Z_{surge} the conductor line surge impedance equal to $60\sqrt{\ln\frac{4h}{d} \cdot \ln\frac{4h}{D}}$ [9], d the equivalent conductor diameter without corona and D is the equivalent conductor diameter with corona.

It must be mentioned that adjacent towers and structures affect the shielding failure rates N_{SF}, as quantitatively shown by analytical models [26] and probabilistic estimation methods [10]. Taking into account this effect the shielding failures present a lower value but the estimation method becomes more complex and restrictive to every tower. However, in the proposed approach, this shielding failure reduction is neglected in order a common formula to be used for every tower and failure rates to be kept at safe side.

Backflashover failure rate N_{BF} is estimated for transmission lines, according to the method presented in [27] and is given

Table 1
Constants A and b of the striking distance equation: $r = A \cdot I^{b}$

Source	Striking distance to			
	Ground		Phase conductor and shielding wire	
	A	b	A	b
IEEE WG [8]	5.12, 6.4 or 8.0	0.65	8.0	0.65
Amstrong and Whitehead [22]	6.0	0.80	6.7	0.80
Brown and Whitehead [23]	6.4	0.75	7.1	0.75
Love [24]	10.0	0.65	10.0	0.65
Rizk [25]	na	na	$1.57\,\mathrm{h}^{0.45}$	0.69

from the following equation:

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

where $P(\delta)$ is the probability distribution function of δ, δ an auxiliary variable (in kV) given from the equation:

$$\delta = R \cdot \frac{I_{\mathrm{peak}}}{2} - 0.85 \cdot U_{\mathrm{a}} + L\frac{\mathrm{d}i}{\mathrm{d}t} \tag{5}$$

where R is the tower footing resistance, L the total inductance of the tower and grounding system and $\mathrm{d}i/\mathrm{d}t$ is the lightning current derivative.

Eqs. (3) and (4) show clearly that the variation of the transmission line insulation level and the tower footing resistance influence significantly the shielding failure and the backflashover failure rate. Therefore, it could be worthwhile to further investigate the most appropriate selection of these design parameters in order to reduce the lightning failure rates.

The total flashover failure rate N_{T} of a transmission line or the outage rate, is the arithmetic sum of the shielding failure N_{SF} and the backflashover failure rate N_{BF}:

$$N_{\mathrm{T}} = N_{\mathrm{SF}} + N_{\mathrm{BF}} \tag{6}$$

Using (3) and (4), total flashover failure rate results:

$$N_{\mathrm{T}} = N_{\mathrm{L}} \cdot \left(\int_{I_{\min}}^{I_{\max}} D_{\mathrm{c}}\, f(I)\,\mathrm{d}I + \int_0^{\infty} p(\delta)\,\mathrm{d}\delta \right) \tag{7}$$

The above equation has been applied on operating Hellenic high voltage transmission lines, giving quite satisfactory results in comparison with the real records of outage rate [28].

3. Formulation of the optimization problem

The examined transmission line is divided into N regions, due to the different meteorological conditions and the different average values of tower footing resistance, which exist in each one region of the line. For each region, an analysis is conducted and suitable values for the insulation level and the tower footing resistance are computed. The total flashover failure rate is also computed for each region, using (7).

A performance index is defined for each region of the examined transmission line in order to relate the annual cost of total flashover failure rate to the total investment cost of the regional values of the two design parameters, i.e., insulation level and tower footing resistance.

$$J_i = k_i(N_{Ti}) + g_{U_{\alpha i}}(U_{\alpha i}) + g_{R_i}(R_i) \tag{8}$$

where $i = 1, \ldots, N$ region number, J_i is the performance cost index of the ith region, $k_i(\cdot)$ the annual line failure cost, $g_{ji}(\cdot)$ the equivalent annual investment of the ith region line design characteristic j, N_{Ti} the total flashover failure rate of region i, $U_{\alpha i}$ the insulation level of region i and R_i is the grounding footing resistance of region i.

The annual line failure cost is given from the equation [18]:

$$k(\cdot) = C_{\mathrm{MEU}} + C_{\mathrm{RE}} + C_{\mathrm{FC}} \tag{9}$$

where C_{MEU} is the mean annual cost of undelivered energy for the utility, C_{RE} the mean costs of one permanent failure repair and C_{FE} is the equivalent annual line failure consumer cost.

The equivalent annual investment is calculated by the total cost of investment using:

$$g(\cdot) = \left(\frac{r(r+1)^t}{(r+1)^t - 1} + p \right) G(\cdot) \tag{10}$$

where $G(\cdot)$ is the total cost of investment of the transmission line's design parameters, r the annual interest rate, t the estimated line exploitation period in years and p is the empirical coefficient which defines the ratio of the annual maintenance cost to the total cost of investment.

3.1. Objective function

The design parameters, i.e., insulation level and tower footing resistance of each region, form a column vector x:

$$x = \{x_1, x_2, \ldots, x_{2N}\} = \{U_{a1}, U_{a2}, \ldots, U_{aN}, R_1, R_2, \ldots, R_N\} \tag{11}$$

Optimal selection of x_i's values minimize the set of the N performance indices defined in (8), i.e.,

$$\min_{Va_i, R_i} J_i = \min_{Va_i, R_i} [J_1, J_2, \ldots, J_N] \tag{12}$$

under the operating limits:

$$U_{\alpha i} \min \le U_{\alpha i} \le U_{\alpha i} \max$$

$$R_i \min \le R_i \le R_i \max$$

where $U_{\alpha i}$ min, $U_{\alpha i}$ max, R_i min and R_i max are limit values defined by electrical utilities.

Application of an optimization algorithm will determine the optimal values x_i.

3.2. Assumptions

Optimization procedure is applied to find optimal values of insulation level and tower footing resistance. For the rest of parameters, i.e.,

(a) the average height (in m) of the shielding wires, h,
(b) the horizontal spacing (in m) between the shielding wires, B,
(c) the total inductance of the system, L,
(d) the equivalent conductor diameter without corona, d,
(e) the equivalent conductor corona diameter, D,

typical values, which represent the usual equipment used from electrical utilities, were considered.

3.3. Optimization algorithm

The goal of the optimization is to minimize the objective vector function of several variables. Since the objective function

Table 2
Line design characteristics of the examined transmission lines [32]

No.	Line	Phase voltage (kV)	Length (km)	No. of towers	Insulation level (kV)	Conductor dimensions (ACSR MCM)	No. of circuits
1	Athina–Acheloos	400	250.557	717	1550	954	2
2	Thessaloniki–Kardia	400	109.908	305	1550	954	2
3	Kilkis–Serres	150	58.068	162	750	336.4	1
4	Arachthos–Igoumenitsa	150	75.802	239	750	336.4	1
5	Megalopoli–Sparti	150	64.472	173	750	336.4	1
6	Aktio–Argostoli	150	81.409	224	750	336.4	1

is not quadratic, linear regression cannot be used and the minimum cannot be reached in a full step, but requires a step analysis, namely an iteration technique. Many algorithms exist to perform, such as the gradient methods [29,30], i.e., Newton–Raphson, Levenberg–Marquardt and quasi-Newton methods, and the direct search methods [31], i.e., simplex of Nelder and Mead.

According to these recursive methods, the optimal solution vector can be found after the iteration of a formula of the form:

$$X_{n+1} = X_n - \lambda_n \cdot \mathrm{col}\, M_n \qquad (13)$$

where X_n is the value of the design characteristic vector at the nth iteration, λ_n the coefficient vector, which accelerates the convergence, col M_n the column vector formed from the Jacobian matrix M_n and M_n is the Jacobian matrix, defined as:

$$M_n(x_1, x_2, \ldots, x_{2N}) = \begin{bmatrix} \dfrac{\partial J_1}{\partial x_1} & \cdots & \dfrac{\partial J_1}{\partial x_{2N}} \\ \vdots & \vdots & \vdots \\ \dfrac{\partial J_N}{\partial x_1} & \cdots & \dfrac{\partial J_N}{\partial x_{2N}} \end{bmatrix} \qquad (14)$$

This method computes the first partial derivatives of the objective function in reference to the dependent variables [31]. It is internally made, by writing a suitable approximation of the objective function up to a desired degree.

The following algorithm based on quasi-Newton method has been implemented.

Step 1: Determine J_i 's function in reference to meteorological and tower structure data, from (8).
Step 2: Set initial values for insulation level U_{a} and tower footing resistance R.
Step 3: Calculate N_{Ti} from (7), J_i from (8), M_n from (14) and X_{n+1} from (13).
Step 4: As long as $||x_{n+1} - x_n|| < \varepsilon$, repeat Step 3, where ε is a positive parameter, which defines the desired convergence precision.
Step 5: Display converged values X_n.

4. Application of the method

4.1. Transmission lines parameters

The method presented in this paper has been applied and tested on 150 and 400 kV operating transmission lines of the Hellenic interconnected system [32]. These lines, which are presented in Table 2 (Fig. 1), were carefully selected among others, due to: (a) their high failure rates during lightning thunderstorms [33], (b) their consistent construction for at least 90 present of their length and (c) their sufficient length and their sufficient time in service in order to present a reasonable exposure to lightning.

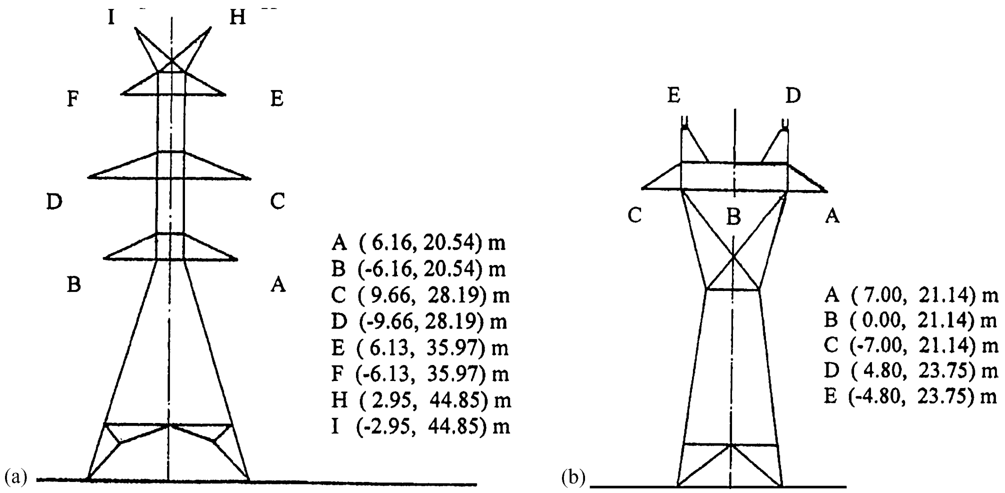

Fig. 1. Typical towers of the analyzed (a) 400 kV (lines 1–2) and (b) 150 kV (lines 3–6) Hellenic transmission lines.

Table 3
Analytical line parameters of the examined transmission lines [32,33]

Line	Region	Towers	R (Ω)	N_T (Average lightning failures 1994–1999)	T (Average lightning level 1994–1999)	J (€)
Athina–Acheloos	I	1–130	28.92	1.33	12.17	748770
	II	131–318	6.51	0.50	21.83	651960
	III	319–578	26.77	2.67	33.50	1495200
	IV	579–717	5.42	0.67	37.83	569460
Thessaloniki–Kardia	I	1–195	1.93	0.83	31.20	769650
	II	196–260	8.83	1.33	28.76	572550
	III	261–305	18.24	1.83	27.60	669150
Kilkis–Serres	I	1–46	1.99	1.00	29.45	396600
	II	47–106	4.40	2.17	28.90	777000
	III	107–162	1.78	0.33	27.20	216600
Arachthos–Igoumenitsa	I	1–80	5.20	0.66	37.33	366000
	II	81–163	13.00	1.83	38.25	723300
	III	164–239	45.40	4.33	44.10	1456500
Megalopoli–Sparti	I	1–45	5.10	0.17	28.00	145500
	II	46–75	39.65	0.67	31.67	264000
	III	76–173	11.18	1.50	30.17	655800
Aktio–Argostoli	I	1–55	4.75	0.00	37.50	115500
	II	56–137	64.93	0.83	34.17	421200
	III	138–224	126.25	2.00	35.33	782700

It must be mentioned that lines 5 and 6 are open loop lines and they have attracted lots of this analysis attention, since a possible failure in them could bring the system out of service, causing significant problems to the customers and the local societies, which they serve in general.

According to the proposed optimization method, each of the above lines are divided into regions, due to the different meteorological conditions and the grounding resistance, which exist in each one of them. The performance cost indices, which have been used in the analysis have calculated based on economical data supplied from the Hellenic Public Power Corporation S.A. [32]. The regions, the different parameters in each one of them as well as the calculated performance cost indices are shown in Table 3 [32,33].

4.2. Results of the optimization method

Table 4 clearly present the results obtained from the application of the proposed optimal design method to the Hellenic 150 and 400 kV transmission lines.

Table 4
Proposed optimum parameters and performance cost indices for the examined transmission lines

Line	Region	Insulation level (kV)	R (Ω)	N_T (No. of lightning failures)	J (€)
Athina–Acheloos	I	1820	9.56	0.23	456655
	II	1780	2.47	0.15	559199
	III	1840	5.45	1.31	1156802
	IV	1630	1.86	0.18	429940
Thessaloniki–Kardia	I	1590	1.12	0.21	587414
	II	1710	2.40	0.34	281290
	III	1800	3.91	0.54	290358
Kilkis–Serres	I	830	1.10	0.22	163515
	II	860	1.67	0.76	356640
	III	770	0.65	0.23	187597
Arachthos–Igoumenitsa	I	830	1.45	0.14	214160
	II	900	2.70	0.32	281090
	III	1010	6.56	0.92	467550
Megalopoli–Sparti	I	840	1.78	0.05	111795
	II	760	6.50	0.11	107895
	III	860	2.34	0.45	351756
Aktio–Argostoli	I	750	4.75	0.00	115500
	II	790	8.82	0.20	285443
	III	960	12.65	0.37	403538

Optimum values for the average insulation level and tower footing resistance of each one region of the transmission lines are calculated. It is obvious that the proposed combined values of these two design parameters reduce the total lightning failures of the examined transmission lines resulting also in a significant reduction of the performance cost indices.

5. Conclusions

The paper describes in detail an optimal design method for improving the lightning performance of overhead high voltage transmission lines taking into consideration both shielding and backflashover failure rates. The method calculates and proposes the most suitable line insulation level and tower footing resistance values, for each one region of the examined lines, in an effort to minimize the total failures caused by lightning. Suitable performance indices are defined in order the line insulation level and the tower footing resistance cost values to be related to the lightning failure costs.

The developed optimal design method has been applied on several operating Hellenic transmission lines of 150 and 400 kV. The obtained results for each one region of the examined lines, i.e., new selected design parameters, have significantly reduce the failure rates caused by lightning, something really important in the case of the open loop lines. Although, any modifications or improvements to the insulation level or to the tower footing resistance of these lines is practically impossible this method can be valuable to electric power utilities in the design of new transmission lines reducing significantly failures from lightning.

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Ioannis A. Stathopulos was born in Volos, Greece in 1951. He studied in the Faculty of Electrical and Mechanical Engineering of the National Technical University of Athens (1969–1974). He carried out his doctor thesis at the Technical University of Munich (1974–1978). He become teaching assistant at the Technical University of Munich (1974–1978), production engineer in the company "Vianox–Franke" (1979–1980), teaching assistant at the National Technical University of Athens (1979–1983) and thereafter lecturer (1983–1987), assistant professor (1987–1991), associate professor (1991–1995) and professor (since 1995) in the High Voltage Laboratory of the NTUA. He is the author of 8 books and more than 90 papers in scientific journals and conferences proceedings. He is lead assessor of the Hellenic Accreditation Council.