

A Methodology for Optimal Design of Transmission Lines Protection against Lightning Surges in the Presence of Arresters

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Abstract

In this paper, a methodology for determining the optimal value of protection design parameters of transmission lines (TLs) is presented. The proposed method calculates the shielding failure flashover rate (SFFOR) and back flashover rate (BFR) of transmission lines based on the Electro-geometric model of TLs and the Monte Carlo simulation method, respectively. The accuracy of the proposed method is verified by comparing the associated results with those obtained with the IEEE FLASH program. The proposed method can be used to achieve the minimum lightning flashover rate (LFOR) of TLs by the minimum investment cost. Indirectly, it can be used for determining the appropriate value of the footing resistance, insulation strength, and arrester rating to satisfy a specified number of LFOR that might be given by the power utilities.

1. Introduction

The transmission lines (TLs) are exposed to lightning strokes in which the resultant overvoltages may lead to insulation failure and hence the transmission line outage [1]. The outages result in the financial loss of utilities and consumers. Therefore, many researchers have paid great attention to find an approach to improve TL performance against lightning strokes.

A detailed assessment of lightning surge and its parameters have been presented in [2]. In [3], a study is carried out on the shield wire placement and its effect on the protection of the transmission lines against lightning strokes. In [4, 5], the iso-keraunic level has been introduced, and the shield wire effect on the back flashover rate (BFR) has been studied. In [6], the EMTP software is used to estimate the lightning performance of TLs. In [7], an optimization approach is presented to minimize lightning-related failure. The effect of non-vertical strokes on lightning performance has been investigated in [8]. In [9], a method has been presented to evaluate arrester failure rates using the fault current flowing through it. However, in the literature, the arrester rating is not considered as a design parameter to select the appropriate protection scheme.

In this paper, an analytical method for investigation of the TLs performance against lightning strokes is presented. The proposed approach is a rough-straight method to evaluate the lightning performance of TLs considering the effect of the

surge arresters installation along with TLs in addition to the conventional parameters, i.e., the footing resistance and insulation strength of insulator strings. The presented method could be useful for optimal placement of surge arresters along with TLs considering economic criteria. Also, it is helpful for selecting the appropriate value of footing resistance, insulation strength, and arrester rating as protection design parameters in the planning stage of TLs.

2. Lightning Analysis

The behavior of each lightning parameter x follows a log-normal distribution which is defined by the following mathematical equation [10]:

$$f(x) = \frac{1}{\sqrt{2}\beta x} e^{-\frac{1}{2} \left[\frac{\ln(\frac{x}{M})}{\beta} \right]^2} \quad (1)$$

where M is the median value, and β is the log-standard deviation of the x parameter.

2.1. Electro-Geometrical model

The transmission line performance can be estimated based on the electro-geometrical model (EGM) of the overhead line, as shown in Fig. 1. The EGM is drawn considering tower dimensions, conductors' arrangement, and the distance between the lightning stroke and phase or shield wire conductor or adjacent ground [11].

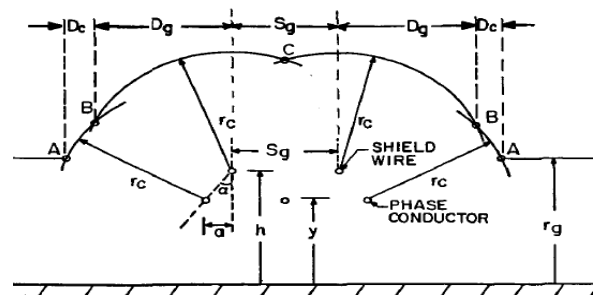


Figure 1: The EGM model of transmission line

According to the EGM model of Fig. 1, if a vertical lightning stroke reached D_c , it hits the phase conductor. If the lightning stroke reached S_g or D_g , it hits the shield wire. Otherwise, the lightning hits the adjacent ground.

2.2. Shielding failure

The lightning stroke that passes through the striking distance of shield wires hits the phase conductor and may cause shielding failure if the dielectric strength of the insulator string is less than the generated overvoltage across the insulator. Considering Fig. 2, the shielding failure flashover rate (SFFOR) is given by [12]:

$$SFFOR = N_L \int_{I_c}^{I_{max}} D_c f(I) dI \quad (2)$$

where $f(I)$ is the log-normal distribution of lightning current and is given by (1). The N_L is the ground flash density [13]:

$$N_L = 0.004T^{1.25}(b + 4h^{1.09}) \quad (3)$$

where T represents thunder days per year, b is the horizontal distance between guard wires, and h is the average height of guard wires.

The D_c is given by [15]:

$$D_c = R_c[\cos(\theta) - \cos(\alpha + \beta)] \quad (4)$$

where R_c is calculated for each peak current magnitude I_p by the following [15]:

$$R_c = 8 \times I_p^{0.65} \quad \& \quad R_g = \beta \times R_c \quad (5)$$

Also, I_c and I_{max} can be estimated by [16]:

$$I_c = \frac{2 \times U_a}{Z_{surge}} \quad (6)$$

$$I_{max} = \frac{Y_g + Y_c}{2K_0} \left[1 + \sqrt{1 - K_0 \left[1 + \left(\frac{d}{Y_g + Y_c} \right)^2 \right]} \right] \quad (7)$$

where

$$K_0 = 1 - \gamma^2 \sin^2 \alpha \quad , \quad \gamma = \frac{R_c}{R_g} \quad (8)$$

where U_a is the insulation level of insulator string, and Z_{surge} is phase conductor surge impedance.

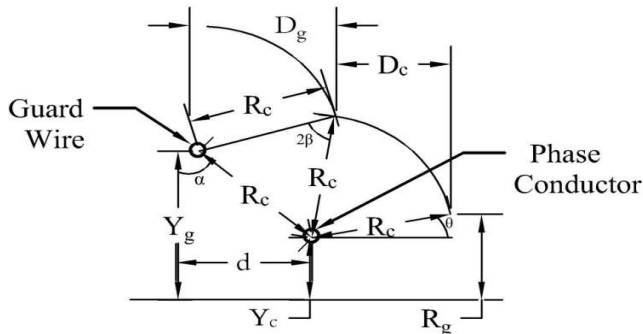


Figure 2: The arrangement of the protected area of the guard conductor [14].

2.3. Back-flashover failure

If a lightning surge of a peak current I_p hits the shield wires or tower, divides into two half-waves with the amplitude of $I_p/2$ and propagates in two opposite directions. As a result, the following voltage is created across the insulator string:

$$V_{ms} = R \frac{I_p}{2} + L \frac{di}{dt} \quad (9)$$

where R is tower footing resistance, L is tower inductance, and di/dt is lightning current derivative. However, the flashover occurs, if:

$$V_{ms} \geq 0.85U_a \quad (10)$$

where U_a is the insulation level of transmission line that is multiplied by 0.85 to achieve the conservative results.

The BFR of transmission lines is calculated by [7]:

$$\begin{aligned} BFR &= N_L \int_0^{\infty} P(\beta) d\beta \\ &= N_L \iint P\left(\beta\left(I_p, \frac{di}{dt}\right)\right) dI_p d\left(\frac{di}{dt}\right) \end{aligned} \quad (11)$$

where $P(\beta)$ is the probability distribution function of the random variable β . The variable β is defined as follows [7]:

$$\beta = R \frac{I_p}{2} + L \frac{di}{dt} - 0.85U_a \quad (12)$$

It can be seen that β is a function of I_p and di/dt that are random variables of the lightning current waveform. It is understood that the back flashover occurs if the value of β is greater than zero.

Assuming surge arresters of rated voltage U_r are installed along with TLs, the random variable β would change into the following form:

$$\beta = R \frac{I_p}{2} + L \frac{di}{dt} - 0.85U_a - U_r \quad (13)$$

The equation (13) shows that the presence of arresters causes the β to become more negative, which in turn reduces the BFR of the transmission line. However, by using (13), the effect of arrester installation can be involved in the calculation of BFR.

2.4. LFOR Calculation

The lightning flashover rate (LFOR) of the transmission line as a function of the design parameters is specified by summing the BFR and SFFOR:

$$LFOR(R_i, U_a, U_r) = SFFOR + BFR \quad (14)$$

The SFFOR and BFR should be evaluated separately when the lightning strikes the TLs equipped with the shield wires.

Once the EGM model has been constructed, the I_{max} and I_c can be calculated by equations (6) and (7) and, hence, the SFFOR is estimated by Eq. (2). If surge arresters are installed along with TLs, the shielding failure rate would be zero.

It must be mentioned the calculation of BFR is performed based on the Monte Carlo method. The Monte Carlo procedure for this purpose consists of generation of random numbers to obtain the parameters of the lightning strokes, of which the statistical parameters are known, calculation of the overvoltage generated by each stroke across the insulator string, and calculation of the BFR.

The steps of the proposed method that is executed by a computer program are summarised below:

Step 1: Specification of transmission line parameters such as the average height of guard wires h , thunder days per year T , the horizontal distance between guard wires b , insulation level U_a , footing resistance R , and voltage rating of arrester U_r .

Step 2: Constructing the EGM model of transmission line and calculation of the SFFOR.

Step 3: Calculating the BFR based on Monte Carlo simulation.

It should be mentioned that the transmission line must be divided into some regions based on the tower footing resistance. In this case, Step 1 to 3 must be performed for each region, separately.

In the proposed method, the lightning peak current

magnitude I_p and the current derivative of the lightning waveform (di/dt) are variables that are generated randomly based on their log-normal distribution in the MATLAB environment. The standard values of lightning parameters are shown in Table 1.

Table 1: Standard parameters of lightning waveform [17]

Parameters	M	β
I_p (kA)	31.1	0.48
t_r (μ sec)	3.83	0.55
t_p (μ sec)	77.5	0.58
di/dt (kA/ μ sec)	24.3	0.6

The process of generation of random values goes on until the difference between the generated values of parameters and those of the theoretical distribution function match within an error margin of 3%. In this paper, the convergence occurred after 30000 iterations. As an example, the distribution of generated values of lightning current magnitude is shown in Fig. 3.

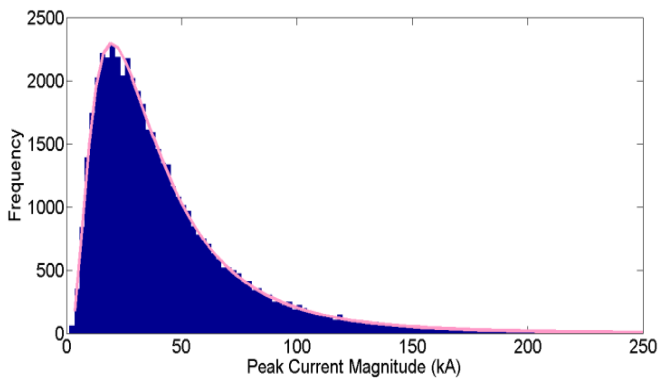


Figure 3: Distribution of generated values of lightning current.

The proposed method has been applied to a test line of 400 kV rated voltage. Table 2 presents the line parameters that were taken from the data from a real transmission line of Iranian Power Utility. The test line is divided into three regions based on the average value of footing resistance along the transmission line. For example, Fig. 4 presents the calculated BFR probability by the proposed method for the region with the grounding resistance of 18.24 Ω , in the case of non-presence of arrester along the transmission line.

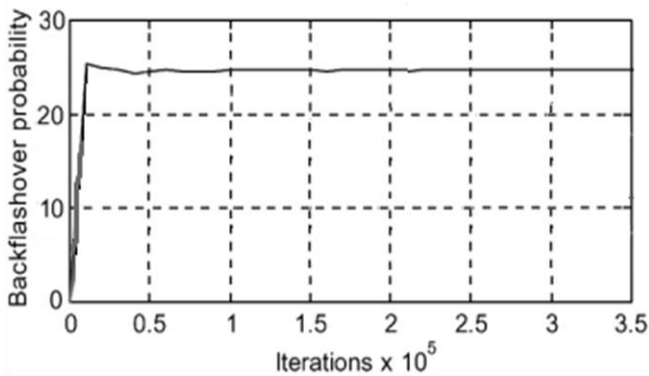


Figure 4: Convergence of Monte Carlo simulation, $R=18.24\Omega$

The evaluated LFOR of the test line by the proposed method is presented in Table 2. It must be mentioned that to verify the proposed methodology, the LFOR is also calculated with the IEEE FLASH program (Version 2) [18]. The results show that the obtained results by the proposed method (P.M.) are very close to those calculated by the Flash program, as the benchmark.

Table 2: Characteristics of the 400 kV TL

Region		1	2	3	
Average R (Ω)		1.93	8.83	18.24	
U_a (kV)		1150			
Length (km)		110			
LFOR (WOA*)		P.M.	1.9	7.72	37.15
		FLASH program	1.85	7.70	36.64
LFOR (WA**)	$U_r = 390$ kV	P.M.	0.49	3.85	19.18
		FLASH program	0.49	3.82	19.09
	$U_r = 420$ kV	P.M.	0.24	2.79	15.05
		FLASH program	0.23	2.71	15.04

*Without Arrester, **With Arrester

Owing to the results of Table 2, the LFOR of TLs depends on the insulation strength of insulator strings, the footing resistance, and the arrester rating voltage. In other words, an engineer can determine the appropriate value of each of the design parameters to achieve a specified number of LFOR.

3. Numerical Analysis

As the transmission lines are divided into N regions, an analysis is performed for each region along with TLs, and suitable values for design parameters are computed. In order to go through this, an optimization can be performed, based on the genetic algorithm (GA), with and without the presence of surge arresters to achieve the minimum LFOR with the minimum investment cost. The investment cost of the design parameters of each region is determined as a percent of the total investment cost of the transmission line [19].

3.1. GA Algorithm

The GA has been receiving a large amount of attention because of its versatile optimization capabilities for both continuous and discrete problems and hence has much more potential in power system analysis [20].

The GA consists of a population of bit strings transformed by selection, crossover, and mutation genetic operators. The solutions are classified by an evaluation function giving better values to better solutions [21]. The principles of the GA can be explained briefly as follows (see [14] for more detail):

(a) Encoding: The chromosomes in the population are presented as strings of binary digits.

(b) Evaluation: A chromosome should be evaluated to examine its fitness for being a solution. The chromosomes which have better fitness should be selected as parents. Because of minimization nature of the problem, the roulette wheel was used to select the chromosomes with the proper probability [21], in which the probability of selecting the i th chromosome is:

$$P_s(i) = \frac{fitness(i)}{\sum_{k=1}^S fitness(k)} \quad (15)$$

where $fitness(i)$ is a fitness number attributed to the i th chromosome, and S is the total number of individuals in the generation. Two chromosomes are selected in each generation to produce offspring. One is the best individual and the other is chosen randomly.

(c) Crossover: A single point crossover can be used, and a point can be chosen randomly in the parents' string of genes. Once the first part of one parent is joined to the last part of the other one, holding the order of the genes, two offspring are generated.

(d) Mutation: Mutation is used to prepare the chance for the algorithm to produce out of order the individuals who maybe better or not. In the proposed method, there are two groups of individuals.

3.2. Objective function

The total investment cost C_{Ti} is defined for each region i th of the transmission line as an index to be minimized:

$$C_{Ti} = C_I + C_{LFOR} \quad (16)$$

where C_{LFOR} is the cost of undelivered energy to customers caused by the lightning outage, and C_I is the investment cost related to the transmission line design parameters.

C_I can be calculated using the following equation [14]:

$$C_I = \frac{r(r+1)^t}{(r+1)^t - 1} C_{TI} \times L \quad (17)$$

where C_{TI} is the total cost considering the cost of insulators, tower footing resistance, and arrester per km of the region, L (km) is region length, r is the interest rate, and t (years) is the operation period. In this paper, the r is assumed to be 0.12 and t is 20 years.

The C_{LFOR} is also determined as follows:

$$C_{LFOR} = LFOR(R_i, U_a, U_r) \times P_{line} \times T_{CF} \times C_E \quad (18)$$

where LFOR is given by (14), P_{line} (kW) is the transferred power, T_{CF} (hours) is mean time to repair and C_E is energy price in kWh.

If the transmission line is divided into N regions, the objective function (O.F.) is defined as:

$$O.F. = \underset{R_i, U_{a_i}, U_{r_i}}{Min} [C_{T_1}, C_{T_2}, \dots, C_{T_N}], i = 1, 2, \dots, N \quad (19)$$

However, the constraints of the design parameters are as follows:

$$\begin{aligned} R_{i,min} &\leq R_i \leq R_{i,max} \\ U_{a,min} &\leq U_{a_i} \leq U_{a,max} \\ U_{r,min} &\leq U_{r_i} \leq U_{r,max} \end{aligned} \quad (20)$$

where R_i is tower footing resistance, U_{a_i} is insulator strength, and U_{r_i} is the rated voltage of arrester, all of the region i . The min and max value associated with each parameter are the limits that are defined by the utility.

Fig. 5 shows the flowchart of the optimization procedure based on the proposed method.

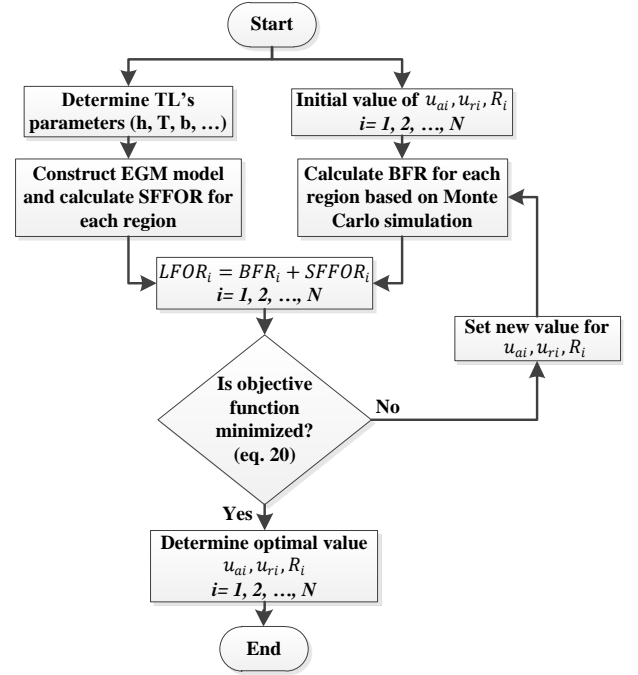


Figure 5: Flowchart of the optimization procedure.

3.3. Results and discussion

This section provides an economic assessment of three TEs with voltage levels of 132, 230, and 400 kV that are selected from the Iranian southeast power system grid. According to the proposed method, at first, each transmission line is divided into some regions, as shown in Table 3. The investment costs in Table 3 are adapted from data supplied by the Iranian southeast power grid [22].

Table 3: The characteristics of the test lines

Name	Length (km)	Investment cost (\$/km)	Line configuration				Analytical line parameters		
			No. of Circuits	No. of Shield wires	No. of Towers	Transferred power (MW)	Region	Towers	Altitude (m)
Line I:									
Sirjan-Neiriz (400 kV)	156	100000	1	2	600	1000	1	1~310	1711
							2	311~395	1872
							3	396~500	1565
							4	501~600	1597
Line II:									
Kerman-Zarand (230 kV)	66	86000	2	2	180	460	1	1~18	1847
							2	19~108	2049
							3	109~180	1727
Line III:									
Baft-Shahmaran (132 kV)	96	57000	1	2	300	180	1	1~30	2221
							2	31~264	1949
							3	265~300	1190

The LFOR of the test lines in the current operating condition is shown in Table 4. The LFOR of each region is calculated, based on the procedure described in Section 2.4.

Table 4: LFOR of test lines with non-presence of arresters

Name	Region	Footing resistance (Ω)	LFOR
Line I: 400 (kV)	1	40	3.669
	2	47	4.387
	3	33	2.707
	4	36	3.091
Line II: 230 (kV)	1	46	6.811
	2	53	7.463
	3	40	6.236
Line III: 132 (kV)	1	60	19.565
	2	51	18.225
	3	20	12.749

Due to the results, compared with the higher voltage levels, the higher footing resistances have a more terrible effect on the lightning performance of lower voltage levels. For example, region 3 of Line 2 has more outage with the same footing resistance and approximately similar conditions with the region 1 of Line I.

In the next step, an optimization process based on the genetic algorithm (GA) is performed to determine the optimal value of design parameters to minimize the line outage LFOR. Table 5 presents the limits of insulation strength U_a , footing resistance R_i and the mean-time to repair (MTTR) of the lightning-related failure for the test lines. The power utilities specify the desirable footing resistance based on ground hardness, humidity and soil type of under the study region for different voltage levels. The mean time to repair of lightning-related failure is also determined by access to the road and distance from metropolitan or power stations.

Table 5: Line parameters for the optimization process [22]

Name	Region	U_a (kV)	R_i (Ω)	MTTR (hr)
Line I	1	1000~1400	5~10	2
	2		5~10	4
	3	3~8	2	
	4	3~8	3	
Line II	1	650~950	5~10	2
	2		8~13	4
	3		5~10	3
Line III	1	400~600	8~13	3
	2		5~10	4
	3		5~10	3

The rated voltage of arrester U_r is also selected based on the power system voltage level and available arresters from the manufacturers inside Iran. The arresters' characteristic of different voltage levels is presented in Table 6.

Table 6: Available arresters for each voltage level

Voltage level (kV)	U_r (kV)	Price ($\times 1000\$$)
132	96, 108, 120, 138, 144	10~12
230	180, 192, 210, 219, 228	13~15.5
400	330, 336, 360, 372, 420	20~25

However, Tables 5 and 6 present the range of variation of

the design parameters of equation (20). The initial population size of GA is 50, the crossover operator rate is 1, the mutation operator rate is 0.1, and the epoch is determined to be 50.

The results of the optimization process are presented in Table 7, in which the optimal value of the design parameters for each region is determined so that the minimum LFOR ($LFOR_{min}$) is achieved with a minimum investment cost (C_{Tmin}).

Table 7: Optimal value of design parameters and LFOR.

Name	Region	R_i (Ω)	U_a (kV)	U_r (kV)	$LFOR_{min}$	C_{Tmin} ($\times 10^5\$$)
Line I: (400kV)	1	5	1395	420	0	18.03
	2	5	1395	400	0	4.926
	3	3.1	1385	400	0	5.940
	4	3.2	1390	415	0	5.920
Total investment cost needed for Line I:						34.816
Line II: (230kV)	1	5	950	225	0.012	1.287
	2	8	950	230	0.058	6.271
	3	5	950	230	0.011	5.131
Total investment cost needed for Line II:						12.689
Line III: (132kV)	1	8	600	144	1.098	1.517
	2	5	600	144	0.365	8.797
	3	5	600	144	0.355	1.528
Total investment cost needed for Line III:						11.842

Compared with the results of Table 4, it is clear that installing surge arresters results in complete protection of 400 kV line (Line I) against lightning strokes and significantly improves the performance of TLs at lower voltage levels. Besides, the arrester installation would be cost-effective only in the 132 kV transmission line (Line III) as the $LFOR_{min}$ is achieved with the lowest total investment cost of $11.842 \times 10^5 \$$.

The proposed method, indirectly, can be used to determine the appropriate value of design parameters to meet a certain number of LFOR as the target value. The target value is specified by power utility or standard. For example, assuming a target value of 3 for LFOR of the 132 kV line of Table 3, the obtained value of design parameters with the investment cost (C_T) needed for the protection of each region is presented in Table 8.

Table 8: Specified value for design parameters to satisfy a value of $LFOR=3$ for 132 kV test line (see Table 3)

Region	1	2	3
R_i (Ω)	7	7	6
U_a (kV)	400	400	400
U_r (kV)	120	96	96
C_T ($\$$)	2.581×10^5	8.794×10^5	1.736×10^5

4. Conclusion

The paper presents a probabilistic methodology to analyze the lightning performance of TLs at the planning stage in the presence of the surge arresters. The method can be used to improve the lightning performance of transmission lines by determining the optimal value of the most critical design parameters to the protection that are the tower footing resistance, insulation strength and the rating of surge arresters.

The proposed method calculates the SFFOR, based on the

EGM model, and the BFR, based on the Monte Carlo method, and can be directly used to achieve the minimum LFOR by spending the minimum investment cost.

In general, the cost-effective being of arrester installation depends on the footing resistance, insulation level of insulator string, and transmitted energy through the transmission line. The planning engineer can analyze this issue by the procedure illustrated in the paper.

The presented method can be used, indirectly, to determine the appropriate value of the footing resistance, insulation strength, and arresters' rating to satisfy a target number of LFOR that might be specified by the utilities or standards.

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