# Optimization of surge arresters location in transmission line due to lightning surges


O. Hajiloo
Shiraz University
Email: omid_hjl@yahoo.com

M. Allahbakhshi
Shiraz University
Email: allahbakhshi@shirazu.ac.ir

A. Seifi
Shiraz University
Email: seifi@shirazu.ac.ir



*Abstract*— **Lightning surges are one of the main causes of unscheduled supply interruptions in overhead transmission lines since they may lead to the failure of the insulation. Employing shield wires is the typical strategy used to protect the transmission lines against lightning. However, it is associated with the risk of insulation failure due to back flashover, especially in the regions with high ground resistance. Therefore, surge arrester is the best protection element to control overvoltages caused by lightning which increases the network reliability. Ideally, to eliminate all of the stresses caused by lightning on each of the electricity towers, surge arrester should be installed. However, there is no requirement to do this since the engineering designs are done with a certain acceptable value of risk. Furthermore, there are also investment restrictions. As a result, optimization of surge arrester's location should be considered which achieves some advantages such as less cost, higher efficiency as well as improving the network performance. The purpose of this paper is the optimization of surge arresters location to minimize the global risk of network failure in case of lightning surges in the transmission lines.**



***Keywords- Lightning surges; shield wire; risk of failure; back flashover; surge arrester***


## I. INTRODUCTION

Commonly, lightning surges are one of main causes of power outages in the transmission lines. Thus protecting overhead transmission lines against lightning strokes is very important and achieved by using shield wires and surge arresters. Shield wires are grounded conductors installed above phase conductors to arrest lightning strokes. So they can not directly strike to phases. Surge arresters installation improve the lightning performance of overhead transmission lines with reducing the insulation risk of failure.

The installation of a large number of surge arresters require enormous costs that is not economical and on the other hand, installing of a small number of them cause lack of protection coverage of the power network. As a result, optimization of surge arresters location should be considered, in addition to less cost, more efficient in order to improve network performance.

So far, several researches have been carried out for optimization of surge arresters[1-4]. In [1] the problem is considered as continuous which is not suitable for large networks. In [2-4] has used Genetic algorithm for optimization and the problem is defined in discrete manner.

The proposed algorithm can determine minimum global failure risk of the network depending on the type and a certain number of surge arresters.

In this paper, at first, a statistical method based on Monte Carlo simulation is used to calculate the parameters of lightning surges, overvoltages caused by lightning strikes and the energy absorbed by the surge arresters in transmission line of the network and then based on its results, insulation failure risk and surge arrester failure risk are calculated. Finally, using two methods of Genetic algorithm (GA) and Binary Particle swarm optimization (BPSO), specified optimum location of surge arresters in the studied network and the results of the two algorithms are compared with each other.

As insulation equipments, surge arresters are also exposed to failure and therefore, in this paper, in addition to the insulation failure risk, the risk of failure of surge arresters is also considered in the objective function.

There are a wide range of softwares such as EMTP, PSCAD and MATLAB & Simulink for simulating power system which can give a graphical representation and transient analysis of the systems [5]. In this study, MATLABfile and Simulink are used for coding and simulations.

## II. THEORY

### A. Lightning

The main parameters of the lightning waveform are the peak current magnitude $I_P$ , front (or rise) time $T_{Front}$ and time to half value $T_{Tail}$.

Information collected from several experiments have shown that the statistical behavior of each of the lightning variables can be approximated with a log-normal function [6]-[7]-[8]

$$p(x) = \frac{1}{\sqrt{2\pi}\sigma_{\ln x} x} \cdot \exp\left\{ -\frac{1}{2}\left(\frac{\ln x - \ln \bar{x}}{\sigma_{\ln x}}\right)^2 \right\} \quad (1)$$

Where $\bar{x}$ and $\sigma_{lnx}$ are the median and standard deviation of the variable, respectively.

Because of the random nature of lightning phenomenon, its study should be based on statistical methods such as Monte Carlo [9]-[10].

There are several models for display lightning waveform which is one of the most common of them, display as the sum of two terms exponential that is shown in Fig. 1 [7]-[11].

The Fig. 1 waveform equation are expressed by [7]

$$I(t) = k_c \cdot I_p \,(e^{-\alpha t} - e^{-\beta t}) \quad (2)$$

Where $k_C$ is the correction factor, $\alpha$ and $\beta$ are constant coefficients that they determine $T_{Front}$ and $T_{Tail}$.

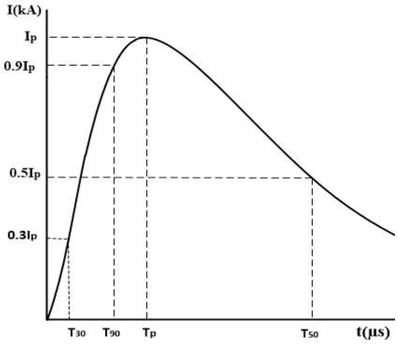


Fig. 1. Lightning waveform

As shown in Fig. 1, $T_P$ is the time that derivative of the curve is zero. The $T_P$ and $k_C$ are calculated by

$$T_p = \frac{1}{\beta-\alpha} \ln \frac{\beta}{\alpha} \quad (3)$$

$$k_c = 1/(e^{-\alpha Tp} - e^{\beta Tp}) \quad (4)$$

Using simple geometric relationships, $T_{Front}$ and $T_{Tail}$ are obtained by

$$T_0 = (3/2)T_{30} - (1/2)T_{90} \quad (5)$$

$$T_{Front} = (7/6)T_{90} - (1/6)T_{30} - T_0 \quad (6)$$

$$T_{Tail} = T_{50} - T_0 \quad (7)$$

Where $T_0$ is virtual zero time. Virtual zero time is defined because of in a laboratory high-pressure, as soon as apply the impulse wave, the current does not begin to rise, but after a few swings, will rise. Therefor zero moment of produced current waveform is considered shortly after applying impulse wave. $T_{30}$ and $T_{90}$ are the times which the current wave reaches 30% and 90% its maximum value, respectively.

According to equations (5), (6) and (7), to obtain $T_{Front}$ and $T_{Tail}$ , should be calculated $T_{30}$ , $T_{50}$ and $T_{90}$ by means of placing the points of 30%, 50% and 90% in equation (2).

### B. *Surge Arrester*

Surge arresters are installed between phase conductor and ground as shown in Fig. 2 in order to improve the lightning performance and reduce insulation failure risk.

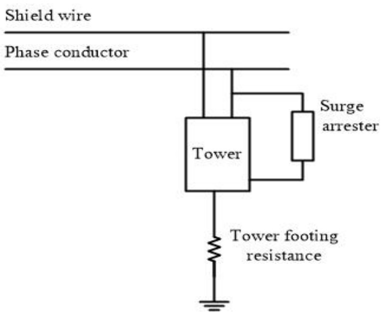


Fig. 2. Surge arrester representation

Surge arresters are nonlinear resistance which its values change between a few ohm and several Mohm. Various types of surge arresters are existent and all of them perform in a similar method. They act as high-impedance at normal operating voltages of the network and become low-impedance during surge occurrence [12].

It should be noted that the surge arrester acts only against overvoltage with high-energy and never will be against voltage fluctuations around operating point.

The principal characteristics of surge arresters are [13]

- Maximum continuous operating voltage (MCOV), which should be greater than the maximum operating voltage of the network with 5% safety margin.
- Energy withstand capacity for transient overvoltages
- Rated voltage, which should be 1.25 x MCOV.

The absorbed energy by a surge arrester (E) is calculated by

$$E = \int v(t) \cdot i(t)\, dt \quad (8)$$

Where v(t) and i(t) are the values of residual voltage and discharge current of the surge arrester.

## III. RISK OF FAILURE

### A. *Insulation Failure Risk*

It is assumed that lightning overvoltages distribution is the normal density function [14]

$$f(V) = \frac{1}{\sigma.\sqrt{2\pi}} . \exp\left[ -\frac{(V - V_{50\%})^2}{2\sigma^2} \right] \quad (9)$$

Where f(V) is the probability density of overvoltage occurrence, $V_{50\%}$ is the overvoltage which the probability density of its occurrence is 50% and σ is standard deviation.

It is considered that the probabiliy of insulation disruptive discharge is a Normal cumulative probability function

$$P(V) = \frac{1}{\sigma.\sqrt{2\pi}} \int_{-\infty}^{V} \exp\left[ -\frac{(V - V_{50\%})^2}{2\sigma^2} \right] \cdot \mathrm{d}V \quad (10)$$

Where p(V) is probability of disruptive discharge, $V_{50\%}$ is insulation voltage which has a 50% probability to flashover and σ is standard deviation.

Finally, failure risk of each node in the network is obtained by [15]

$$R = \int_{0}^{\infty} f(V) \cdot P(V) \cdot \mathrm{d}V \quad (11)$$

Where R is the risk of failure and f(V) and p(V) already been defined.

### B. *Surge Arrester Failure Risk*

With installing surge arresters on the network may be the absorbed energy by them exceeds of their maximum acceptable energy level, therefore, they will be also exposed to failure. The risk of failure of surge arresters is obtained by

$$R_A = \int f(E).F(E)\, dE \qquad (12)$$

Where $R_A$ is surge arrester failure risk, f(E) is the probability density of energy occurrence and p(E) is the energy absorption capability of surge arrester which can be approximated by a Weibull cumulative distribution [7]

$$p(E)= 1 - 0.5^{(((E/ER - 2.5)/1.5) + 1)^\wedge 5} \qquad (13)$$

Where $E_R$ is rated energy capability of surge arrester.

## IV. PSO

PSO algorithm is simulation of social behavior of birds. Consider a group of birds that are looking for food in the environment. None of the birds do not have information about the location of food; but at every stage, know his distance until food location. On this basis, the best approach to find food is following the nearest bird to food. PSO simulate this behavior at optimization problems. In thes algorithm, each bird that is called particle, represents a possible solution in search space of the function to be optimized.

In the first stage, particles are produced with random positions and velocities. During the implementation of PSO, the position and velocity of each particle in the new stage of the algorithm (t+1) are made from information of previous stage (t).

In this algorithm, velocity equation is the guarantee for the movement of particles into optimum region and usually based on three main elements is presented that as follows:

- Initial velocity
- Personal best : The best location that particle had so far.
- Global best : The best location that all particles have found it so far.

The new position of each particle in the population calculated by the sum of the same particle velocity with its present position

$$V_i(t+1)=wV_i(t)+c_1r_1(P_{bi}-P_i(t))+c_2r_2(P_g-P_i(t)) \qquad (14)$$

$$P_i(t+1)=P_i(t)+V_i(t+1) \qquad (15)$$

Where $P_i$ represents the position of i th particle, v is the velocity, w is inertia coefficient, $r_1$ and $r_2$ are random numbers in the range of [0,1] with uniform distribution and $c_1$ and $c_2$ are learning coefficients. The number of repetitions is also shown as t. The movement of each particle in the search space of PSO is shown in Fig. 3.

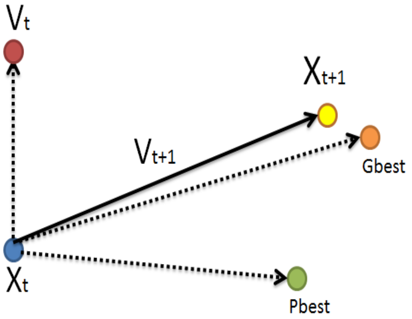


Fig. 3. Movement of each particle in PSO

## V. THE PRINCIPLES OF DETERMINING OPTIMAL LOCATION OF SURGE ARRESTER

Considering the number of repetitions of the optimization algorithm, it may be necessary to exchange information between Matlabfile and Simulink and required data be called from a MATLAB environment to the other hundreds or thousands times.

In the following, explain the steps of the optimization algorithm and determine the optimal location of surge arresters in the network.

### A. *Collect Statistical Information*

The required statistical information at any time of lightning stroke are the maximum value of the overvoltage across the insulator ($|V|_{max}$) at each tower (or so-called node) and absorbed energy (E) by surge arresters of the network which collected and stored for related calculations. Fig. 4 shows insulator and its voltage.

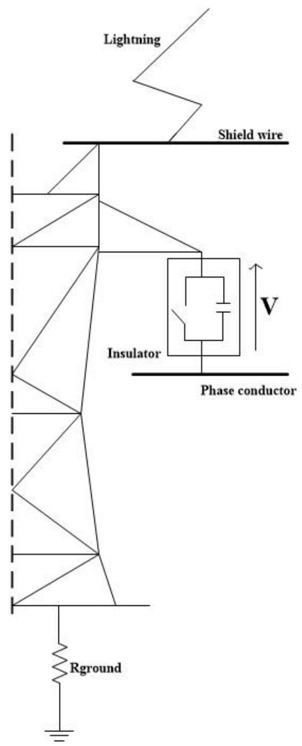


Fig. 4. Insulator voltage

### *B. Calculate the Risks of Failure*

Through statistical data obtained by simulation, insulation failure risk and surge arrester failure risk are computed according to values of $|V|_{max}$ and E, respectively.

### *C. The Definition of the Objective Function*

Both the failure risks of the insulation and the surge arreser are considered as objective function. The objective function is defined to compare solutions and optimize them.

$$\text{Min } F = C_{Ins} \cdot R_{G.Ins} + C_A \cdot R_{G.A} \quad (16)$$

Where $R_{G.Ins}$ and are $R_{G.A}$ global risks of failure of insulations and surge arresters of the network, respectively. Also $C_{Ins}$ and $C_A$ are coefficients that represent the percentage of power outages caused by failure of insulations and surge arresters, respectively.

## VI. EXAMPLE

### *A. Specifications of the Considered Network and Its Component*

The considered network is as a 400 kV transmission line. The length of this line is 18 kilometers which consists of 40 electricity towers and the distance between each of them is 450 meters. Tables 1 and 2 represent the characteristics of shield wire and phase conductor of the network, respectively.

The surge arrester model of sim power systems toolbox of Simulink is used for simulation. The rated voltage and the energy absorption capacity of this surge arrester are 410 kV and 1000 kJ, respectively.

Grounding impedance or tower footing resistance is considered as a linear resistance.

Table 1 Characteristics of phase conductors

| Phase conductors | R [ohm/km] | $X_L$ [ohm/km] | $X_C$ [Mohm*m] |
|---|---|---|---|
| + Sequence | 0.00618 | 0.0624 | 55.48 |
| 0 Sequence | 0.05447 | 0.168 | 91.16 |

Table 2 Characteristics of shield wires

| | Type | Diameter [cm] | Resistance [ohm/km] |
|---|---|---|---|
| Shield wires | 7N8 AW | 0.98 | 1.490 |

### *B. Results and Discussion*

The proposed method is implemented for determining optimum location of surge arresters with the aim of minimizing the objective function or global failure risk of the network.

In order to test the proposed method, it was compared with GA in 3 different cases. Figures 5, 6 and 7 show the results of these comparisons.

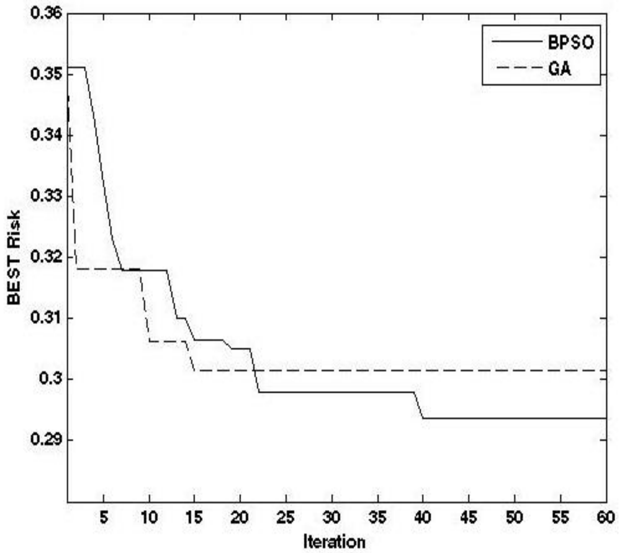


Fig.5. Results for the first case. Objective function = $0.65R_{G.Ins} + 0.35R_{G.A}$ , Number of surge arresters= 14, BIL= 500 kV, Median of Ip = 144.436 kA. Results of the proposed BPSO in compare to GA.

| Tower | 1-5 | 6-12 | 13-20 | 21-26 | 27-30 | 31-37 | 38-40 |
|---|---|---|---|---|---|---|---|
| Tower footing resistance | 97 | 100 | 104 | 106 | 102 | 99 | 95 |

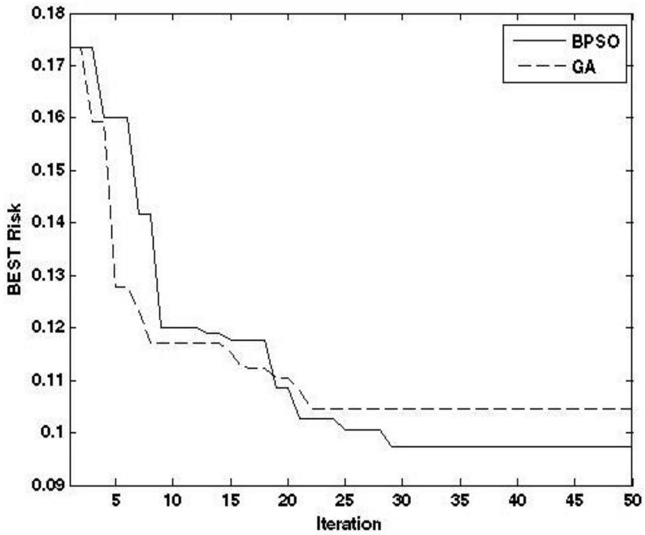


Fig.6. Results for the second case. Objective function = $0.6R_{G.Ins} + 0.4R_{G.A}$ , Number of surge arresters= 11, BIL= 500 kV, Median of Ip = 100.016 kA. Results of the proposed BPSO in compare to GA.

| Tower | 1-4 | 5-10 | 11-14 | 15-20 | 21-28 | 29-35 | 36-40 |
|---|---|---|---|---|---|---|---|
| Tower footing resistance | 80 | 85 | 83 | 78 | 75 | 77 | 79 |

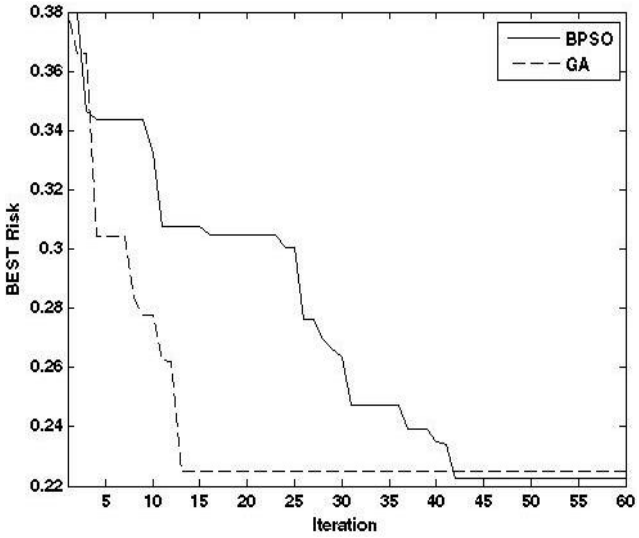


Fig.7. Results for the first case. Objective function = $0.65R_{G.Ins}$ + $0.35R_{G.A}$ , Number of surge arresters= 13, BIL= 500 kV, Median of Ip = 187.012 kA. Results of the proposed BPSO in compare to GA.

| Tower | 1-5 | 6-13 | 14-18 | 19-21 | 22-30 | 31-33 | 34-40 |
|---|---|---|---|---|---|---|---|
| Tower footing resistance | 80 | 82 | 79 | 76 | 81 | 85 | 83 |

The values of the objective functions obtained by BPSO and GA are presented in Table 3.

In accordind to figures 5, 6 and 7 the convergence process of the proposed BPSO is better in comparison to GA.

Table 3 Comparing the results of 2 method

| Objective function | Case 1 | Case 2 | Case 3 |
|---|---|---|---|
| BPSO | 29.356% | 9.734% | 22.274% |
| GA | 30.145% | 10.449% | 22.521% |

As it can be seen in the results, the proposed method is superior to GA, both in time efficiency and in giving a more optimized solution. This method is an alternative solution in relation to expensive suggestions and of course quite ordinary for general protection of power networks including the indiscriminate installation of surge arresters.

To continue the work can be paid to cases where the following:

- Lightning struck to the ground around lines and considered induced voltages caused it.
- In addition to the failure risks of the insulations and the surge arresters, the risk of failure of other equipment of the network is also considered.

## VII. CONCLUTION

This paper presents an optimization method based on BPSO to improve the minimization process of global failure risk in the network considering failure risks related to the insulations and the surge arresters.

The purpose of the proposed method is to optimize the surge arresters location and select the best appropriate protection scheme in power network against lightning surges.

The simulation results prove that the proposed method is better in comparison to GA method which confirms the effectiveness of this BPSO based algorithm for determining desirable locations for the surge arresters.

## REFERENCES


[1] A. L. Orille-Fernández, S. B. Rodríguez and M. A. G. Gotes. “Optimization of surge arrester's location”, Power Delivery, IEEE Transactions on 19, no. 1, pp. 145-150, 2004.

[2] E. Perez, A. Delgadillo, D. Urrutia and H. Torres, “Optimizing the surge arresters location for improving lightning induced voltage performance of distribution network”, In Power Engineering Society General Meeting, 2007. IEEE, pp. 1-6. IEEE, 2007.

[3] R. Shariatinasab, B. Vahidi, S. H. Hosseinian and A. Ametani, “Probabilistic Evaluation of Optimal Location of Surge Arrester on EHV and UHV Networks Due to Switching and Lightning Surges”, IEEE Trans. PWRD, vol. 24, no. 4, pp.1903-1911, 2009.

[4] E. Bullich-Massague, A. Sumper, R. Villafafila-Robles and J. Rull-Duran. “Optimization of surge arrester locations in overhead distribution networks”, IEEE Trans. on Power Delivery, vol. 30, no. 2, pp. 674-683, 2015.

[5] K. E. Lonngren and E. W. Bai, “Simulink simulation of transmission lines”, Circuits and Devices magazine IEEE, vol. 12 ,no. 3, pp. 10-12, 1996.

[6] P. Chowdhuri, Electromagnetic Transients in Power Systems. Taunton, U.K.: Research Studies, 1996.

[7] A. R. Hileman, “Insulation coordination for power systems”, Marcel Dekker Inc., New York, 1999.

[8] R. B. Anderson and A. J. Eriksson, “Lightning parameters for engineering applications”, Electra, no. 69, pp. 65–102, 1980.

[9] J. A. Martinez and F. C. Aranda, “Lightning performance analysis of overhead transmission lines using the EMTP”, IEEE Trans. Power Del., vol. 20, no. 3, pp. 2200–2210, 2005.

[10] A. Dubi, “Monte Carlo Applications in Systems Engineering”, John Wiley, 1999.

[11] J. C. Das, “Transients in Electrical Systems: Analysis, Recognition and Mitigation” ,The McGraw-Hill Companies, Inc., New York, 2010.

[12] V. Hinrichsen, Metal-oxide surge arresters, Fundamentals, Siemens, 1st Ed., 2001.

[13] IEC 60099-4, Surge arresters – Part 4: Metal-oxide surge arresters without gaps for a.c. systems, 2nd Ed., 2004-05.

[14] A. L. Fernández, N. Khalil and S. B. Rodríguez, “Failure risk prediction using artificial neural networks for lightning surge protection of underground MV cables”, IEEE Trans. Power DeL., vol. 21, no. 3, pp. 1278–1282, 2006.

[15] Insulation Coordination: Application Guide, IEC Std. 71-2, 1996.