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Optimization of Surge Arrester Locations in Overhead Distribution Networks (Article)

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Abstract

Lightning is considered one of the main causes of faults in overhead distribution networks. Direct strokes usually lead to flashovers due to the insulation levels that are used. Induced overvoltages caused by indirect lightning are usually lower and can be efficiently reduced by metal-oxide surge arresters. Hence, its associated flashover rate can be reduced. In this paper, a heuristic method is proposed to optimize the number of surge arresters as well as their locations. The method presented is based on genetic algorithms and an economic approach is taken into account by means of evaluating the cost of insulation flashover. © 1986-2012 IEEE.

Author keywords

Flashover; lightning; optimization; overvoltage; surge arrester

Indexed keywords

Engineering controlled terms: Flammability testing; Flashover; Genetic algorithms; Heuristic methods; Lightning; Optimization; Surge protection

Economic approach; Flashover rate; Indirect lightning; Induced overvoltages; Insulation level; Metal oxide surge arresters; Over-voltages; Surge arresters

Engineering main heading: Electric surges

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Optimization of Surge Arresters Location in Overhead Distribution Networks

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***Abstract*—Lightning is considered one of the main causes of faults in overhead distribution networks. Direct strokes lead usually to flashovers due to the used insulation levels in those networks. Induced overvoltages caused by indirect lightning are usually lower and can be efficiently reduced by metal oxide surge arresters, hence its associated flashover rate can be reduced. In this paper an heuristic method is proposed to optimize the number of surge arrester as well as their location. The presented method is based on genetic algorithms (GA) and an economic approach is taken into account by means of evaluation the cost of insulation flashover.**

***Index Terms*—Lightning, Overvoltage, flashover, surge arrester, optimization.**

I. Introduction

Overhead lines of distribution grids are usually exposed to lightning which is one of the main source of faults. Most of these networks are not protected by overhead ground wire against direct strokes due to the low insulation level and the extremely high voltages reached by the strokes. However, induced voltages by indirect strokes are lower and can be effectively reduced by metal oxide surge arresters. As the occurrence of the indirect lightning is much higher than direct ones, the installation of surge arresters can be considered as effective protection measure. However, the installation of surge arrester in every pole is economically not feasible. This leads to the need to develop a method to establish the number of surge arresters and their location in a distribution network according to an economical criterion. Several related studies have been done [2] [3] [4] using an optimization procedure for number and location of surge arresters based on heuristic techniques. In [2], the optimization is done by fuzzy logic techniques while [3] and [4] have applied evolutionary strategies based on genetic algorithms (GA).

The aim of this work is to develop a methodology to determine the number and location of surge arresters in a distribution network according to an economical criterion to protect the distribution grid against indirect lightning strikes. As is determined that the efficiency of surge arresters in distribution grids is limited when direct strokes occurs [1], in this paper only indirect lightning is taken into account. The proposed methodology is analogue to [4] where the optimization based on GA is done for a fixed number of arresters. In the presented approach, the method is reaching the optimization without predefinition of the number of surge arrester and taking into account different insulation strength along the overhead line. The computer application presented in this paper has been developed in MATLAB environment and the simulation software to calculate the induced over voltages is EMTP-ATP.

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II. Lightning modelling and flashover rate calculation

Lightning can be considered as a current source which shape can be depicted by Heidler functions [5], [6], more simplified wave shapes like double ramp [7] [8] or just a step function as resulting in the well-known Rusck formula. In this paper, a double step ramp (Fig. 1) is considered and its statistical parameters, I_c, T_c and T_h are taken from [13] with the speed of propagation of the return stroke uniformly distributed between $0.29 \cdot 10^8\ m/s$ and $2.4 \cdot 10^8\ m/s$.

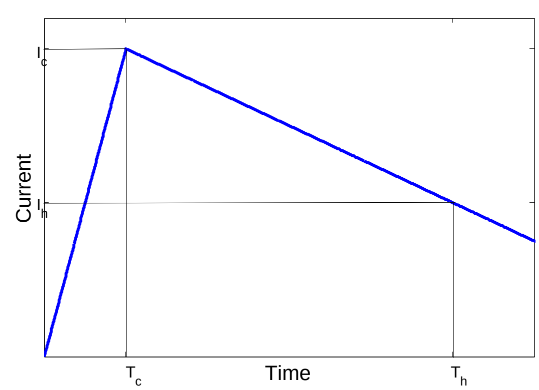


Fig. 1. Lightning current shape

Lightning location coordinates are considered statistical and uniformly distributed along the study area. After obtaining a random lightning waveform and its location, the electrogeometric model [1] is applied to distinguish direct from indirect lightning and only the latter are studied. According to [1] once the peak current and the lightning location is determined, two striking distances, r_s and r_g, may be calculated by

$$r_s = 10 \cdot I_c^{0.65} \quad (1)$$

$$r_g = 0.9 \cdot r_s \quad (2)$$

where r_s is the striking distance to the conductor (m) and r_g the striking distance to the ground (m).

Then, the minimum distance, y_{min}, which lightning will not strike to the conductor is determined by

$$y_{min} = \sqrt{r_s^2 - (r_g - h)^2} \tag{3}$$

where h is the conductor height.

The overvoltage calculations are done by software simulations in EMTP-ATP applying Agrawal coupling model implemented in [7], considering a Transmission Line (TL) model for the lightning channel.

The Agrawal coupling model is expressed by (4) and (5) which the equivalent electrical circuit and its geometry is shown in Fig. 2.

$$\frac{\partial u^s(x,t)}{\partial x} + L' \cdot \frac{\partial i(x,t)}{\partial t} = E_x^i(x,h,t) \tag{4}$$

$$\frac{\partial i(x,t)}{\partial x} + C' \cdot \frac{\partial u^s(x,t)}{\partial t} = 0 \tag{5}$$

where $E_x^i(x,h,t)$ is the horizontal component of the electric field along the x axis at the conductor's height, h is the conductor's height, L' and C' are the line inductance and capacitance per unit length, $i(x,t)$ is the current through the line, $u^s(x,t)$ is the so called scattered voltage expressed as $u^s(x,t) = -\int_0^h E_z^s(x,z,t)dz$ being $E_z^s(x,z,t)$ the vertical component of the scattered electric field.

The total line voltage then is expressed as

$$u(x,t) = u^s(x,t) + u^i(x,t) \tag{6}$$

being $u^i(x,t) = -\int_0^h E_z^i(x,z,t)dz \approx -h \cdot E_z^i(x,0,t)$.

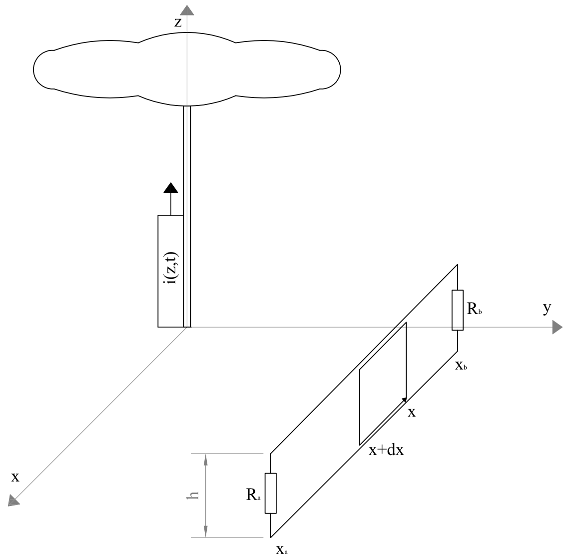
Finally, the boundary conditions for the scattered voltage are given by

$$u^s(x_b,t) = -R_b \cdot i(x_b,t) - u^i(x_b,t) \tag{7}$$

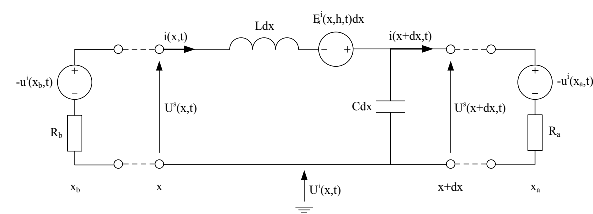
$$u^s(x_a,t) = R_a \cdot i(x_a,t) - u^i(x_a,t) \tag{8}$$

Once the random lightning generation and its simulation are automated, flashover rates on the grid can be obtained. Typically, this is achieved by applying the Monte Carlo method. In this method, flashover rate can be calculated by the following steps:

- Lightning parameters generation: all lightning parameters (peak current, rise time, tail time and speed of propagation) and its location are determined.
- Electrogeometric model: each lightning is classified by direct or indirect lightning.
- Maximum overvoltage calculation: by simplified methods [1] or complex simulations [7] [9] [10] [11] [12] the maximum overvoltage is stored.
- Flashover determination: generally is assumed that a flashover occurs when the maximum overvoltage V_{max} is greater than $1.5 \cdot CFO$ [1] [13], where CFO is the critical flashover voltage or the overvoltage that produces 50% of flashover probability.



(a) Line representation



(b) Equivalent electrical scheme

Fig. 2. Line representation and its equivalent electrical scheme according to the Agrawal coupling model

- Flashover rate calculation: flashover rate can be calculated by

$$FR = \frac{N}{N_l} \cdot N_g \cdot A \cdot \frac{100}{l} \tag{9}$$

where FR is the flashover rate expressed in $flashovers/100km/year$, N the number of lightning producing flashover, N_l the number of lightning simulated, N_g the so called ground flash density (in $flashes/km^2/year$), A is the study area in km^2 and l the grid length in km.
- Repeating the process: go back to the first point and repeat the process until the flashover rate calculation remains stable.

As Monte Carlo method requires a long computing time due to the high number of simulations needed (typically 1000, 10000, 40000, etc.) it is not reasonable to use this method in an optimization procedure where many scenarios must be evaluated.

Hence, to design an optimization method in a reasonable computing time, flashover predictions are obtained under the risk concept. If we obtain the maximum overvoltage probability density function and the flashover probability function is known, the risk can be calculated by

$$R = \int_0^{\infty} f(V) \cdot P(V) dV \tag{10}$$

and flashover prediction can be calculated as

$$N_f = R \cdot N_g \cdot A \tag{11}$$

where R is the flashover risk, $f(V)$ the maximum overvoltage probability density, $P(V)$ the flashover probability function and N_f is the number of flashovers per year prediction in the electrical grid.

III. Optimization procedure based on genetic algorithms

A. General overview

Genetic algorithm (GA) techniques were first introduced by Holland in 1975 [14] and are well described in [15] and [16]. GAs are searching and optimization process based on the biological evolution. According to Darwin's postulates individuals of a population evolve in nature with principles of natural selection and survival of the fittest. In the nature, individuals of a population compete with each other for searching resources and survival. The strongest are more likely to attract other individuals and reproduce. By this way, genes of strongest individuals have more probability to move to the following generations which will get better adapted to the surrounding environment.

GAs use the analogy of the biological evolution. A GA begins with a population of individuals where each individual represents one possible solution. Each individual is evaluated in the objective function and is given a score according to its fitness. Then, better scored individuals have a higher probability to be selected for reproduction where their characteristics (genes) will be transmitted to subsequent generations.

B. GA steps

The general sequence of GA can be described by the following steps as shown in Fig. 3:

- Codification: in the codification, all parameters must be identified in order to represent each individual by a chromosome (string of genes). Each characteristic (gene) must be able to be represented by a unique codification.
- Generating first population: the first population of the GA must be created. It can be generated completely randomly or forcing to get some good genes which are known to behave well against objective function.
- Evaluation: for each individual of the population, the objective function is evaluated.
- Selection: a probability of survival is associated to each individual according some criterion related to the objective function. The criterion adopted must give more probability to survival to best individuals than worsts. Then the individuals to the reproduction process are selected randomly.
- Reproduction: in reproduction process new individuals are created. These new individuals inherit its parents characteristics (genes).
- Mutation: Once all new individuals are created, their genes have a mutation probability (generally low). When one gene mutates, the value associated to this gene is changed.
- Termination: the GA ends when some condition criterion is completed.

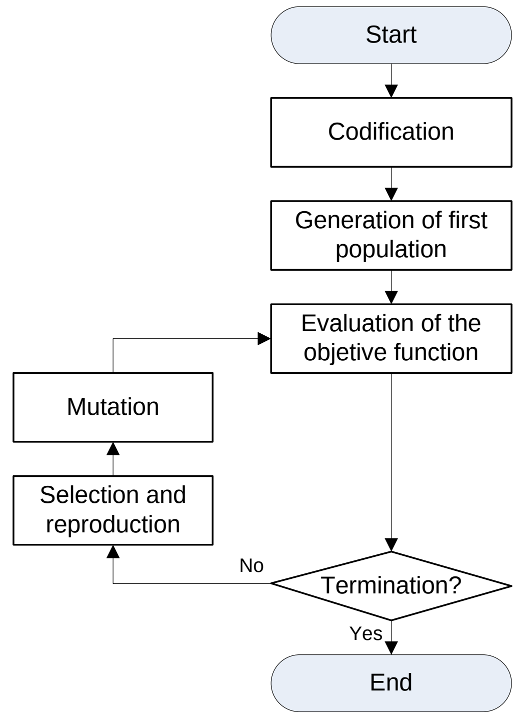


Fig. 3. Basic GA scheme

IV. Proposed algorithm to optimize the number of surge arresters and their location

Here is presented our optimization algorithm based on GA which is implemented with MATLAB calling external software (EMTP-ATP) to calculate the induced over voltages. Each GA step explained above is described.

A. Codification

Each individual is depicted by a chromosome which contains n genes, where n is the number of towers of our distribution network. Each gene g_i can get two values: when surge arrester is connected to tower i, gene $g_i = 1$ otherwise, gene $g_i = 0$. Fig. 4 shows an example of individual codification for a 12 nodes grid with surge arresters in towers 1, 5, 7 and 8.

1	0	0	0	1	0	1	1	0	0	0	0

Fig. 4. Example of individual codification. 12 towers grid with surge arresters in towers 1, 5, 7 and 8

B. Generation of first population

Each individual of our population is generated randomly. But as it is known that installing surge arresters in each tower or each 2 towers is not applicable due to economic reasons, the probability to assign the code 1 to a gene is 1/5.

Other aspect in this section is to define the number of individuals for each population. It is said that a good population size is between n and $2n$ individuals where n is the number of genes [17]. In this work, we use a population of 8 individuals due to the restriction of the computation time.

C. Evaluation

For each individual of a population the objective function is computed. In this section is described the objective function of our algorithm. As the objective function, an economical formulation have to represent the benefits and loses and must be evaluated in an acceptable computation time, flashover predictions are done under risk concept explained above.

After simulating k indirect lightning induced voltages in de base case (case without surge arresters) and in the case represented by an individual, the maximum overvoltage probability function is obtained, risk may be calculated as well as the reduction of flashover rate for a constant CFO.

In order to adapt the calculations for a network with a variable CFO, an overvoltage margin is obtained for each tower, defined as

$$m(i) = V_{max}(i) - 1.5 \cdot CFO(i) \tag{12}$$

where $V_{max}(i)$, $CFO(i)$, and $m(i)$ are the maximum overvoltage, the CFO and the so called margin of tower i.

For each indirect lightning simulated, the maximum overvoltage margin in the grid is stored. With k simulations and assuming that the flashover occurs when the voltage is greater than $1.5 \cdot CFO$ [1], the risk of flashover and flashover prediction can be calculated by

$$R = \int_0^{\infty} f(m) dm \tag{13}$$

$$N_f = R \cdot N_g \cdot A \tag{14}$$

where N_f is the number of flashovers per year, R is the risk of flashover, $f(m)$ is the margin density probability function, N_g is the ground flash density and A is the area considered.

In order to fit the maximum margin density probability function, 1000 random lightning are generated in the study case with and without arresters. Fig. 5 shows the results where can be observed a typical log-normal shape for the case without arresters.

Hence, the results are normalized in order to fit a log-normal probability by applying an offset to achieve all margins greater than zero. Then the margin density probability function is fitted as shown in Fig. 6. The p-value of the log-normal probability test has been greater than 0.5 which can be considered a good fitting.

Then, the risk calculation is modified by

$$R = \int_{offset}^{\infty} f(m) dm \tag{15}$$

where $offset$ is the offset applied to force all margins to be positive.

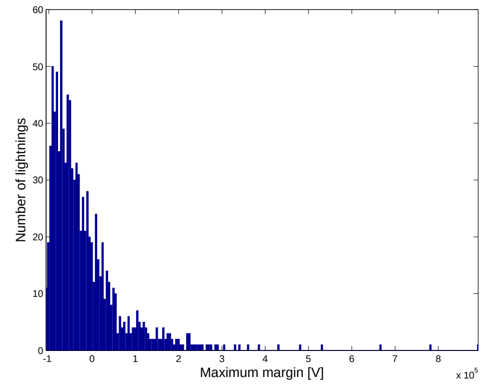


Fig. 5. Maximum margin histogram for 1000 lightning generated in the study case without surge arresters

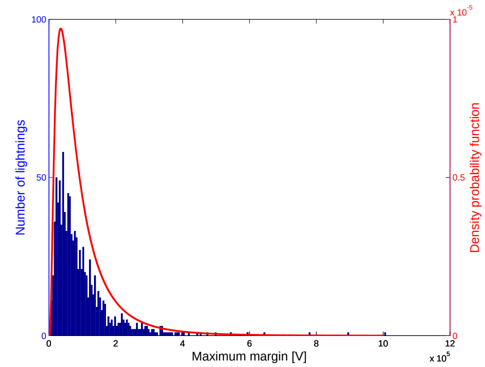


Fig. 6. Maximum margin histogram with offset and log-normal density probability function for 1000 lightning generated in the study case without surge arresters

By the same way, the margin density probability function is represented in Fig. 7 for the study case with surge arresters. It can be observed that in this case the log-normal probability function has not a good fitting, nevertheless the risk of flashover can be calculated assuming an error. Because of the error, after the optimization algorithm the flashover prediction is done by Monte Carlo method as suggested in [13].

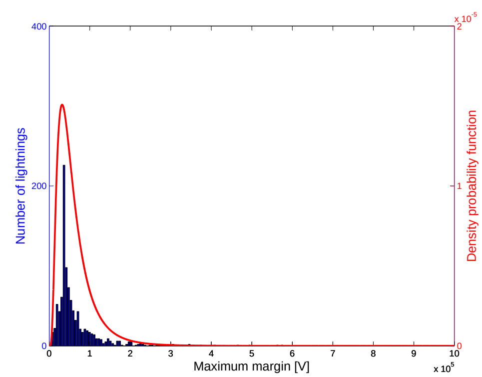


Fig. 7. Maximum margin histogram with offset and log-normal density probability function for 1000 lightning generated in the study case with surge arresters

Once risk is calculated for the base case and each case with surge arresters, the benefits in €are determined by

$$b = (R_b - R) \cdot N_g \cdot A \cdot T \cdot C_{fl} - C_{arr} \cdot N_{arr} \tag{16}$$

where b is the benefit, R and R_b are the risks of flashover for the case with arresters and the base case (without arresters), N_g is the ground flash density, A is the area considered, T is the lifetime for a surge arrester, C_{fl} is an approximate cost assigned to a flashover event, C_{arr} is the cost of surge arresters and N_{arr} is the number of surge arresters.

The objective function to maximize the benefit is defined by

$$F_{obj} = MAX\,[b] \tag{17}$$

D. Selection

The selection process has been done by assigning to each individual a probability to be selected and forcing the best individual is chosen. The probability of selection for an individual i is calculated by (18).

$$P_i = \frac{b(i) - min(b)}{\sum_{i=1}^{n} (b(i) - min(b))} \tag{18}$$

Note that the worst individual will never be selected. In total, 4 individuals are selected.

E. Reproduction

In the reproduction process, two pairs of the selected individuals are chosen in order to combine their characteristics. For each pair or individuals (parents) a random number rnd between 1 and $n-1$ is generated, where n is the number of towers of the study case. Then, the reproduction is performed as shown in Fig. 8.

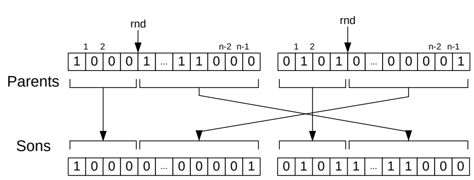


Fig. 8. Reproduction process

The new generation is composed by the four individuals selected and the new individuals resulting from the reproduction and the following mutation.

F. Mutation

For all new individuals and each gene, a mutation probability is applied. When one gene mutates, its value is permuted. The mutation probability is 10% at the beginning and is decreased with the algorithm iterations. As done in [4], when last 20 iterations have not improved the objective function, the probability is increased.

G. Termination

The GA ends when 200 iterations are reached or the last 50 iterations have not improved the objective function.

H. Implementing the methodology

The methodology explained above have been implemented as shown in Fig. 9 and programmed in MATLAB. After modeling the grid, EMPT-ATP generates a plain file containing the grid data which is imported into MATLAB. So, each characteristic like lightning parameters or surge arresters can be modified in MATLAB environment. Once ATP file is modified, a DOS command permits to execute EMTP-ATP generating the output file (.PL4 format) with the simulation results. This file is modified to MATLAB format via PL42MAT tool wich also can be executed with a DOS command. Before running a simulation, it is verified that the lightning generated is an indirect lightning applying the electrogeometric model from [1].

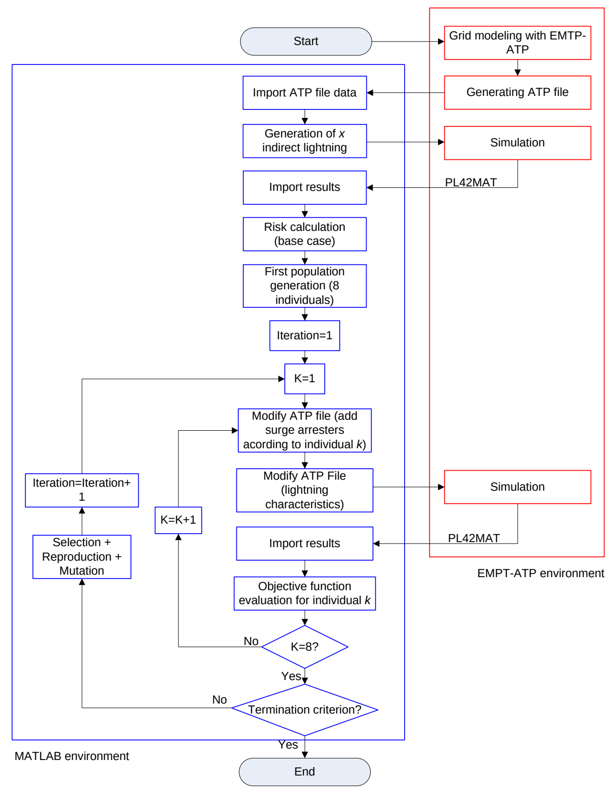


Fig. 9. GA implementation scheme

V. Study Case

In order to test the suggested procedure, the GA has been executed for the following case studies. The grid is represented in Fig. 10 where it was tried to emulate the same geometry used in [4]. In this case, a single conductor wire is considered and the height is equal to 10 m.

Lightning surge arrester model and characteristics are given in [18] and shown in Table I. The cost of a surge arrester is established with 600 € and flashover cost is estimated by 300 €.

The GA has ben excecuted for different conditions which are shown below:

- **Case 1**: opened grid at endings, CFO = 75 kV, N_g = 1 lightning/km^2/year, ground conductivity σ = 1 mS/m, surge arrester lifetime of 10 years.

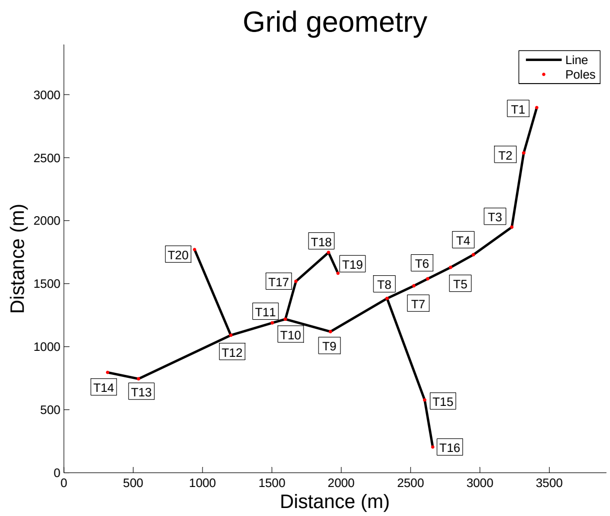


Fig. 10. Distribution grid

Rated voltage [kV]	Maximum continuous operating voltage [kV]	Residual voltage [kV] with current waveform of		Residual voltage [kV] with lightning impulse (8/20 μs)		
		10 kA 1/5 μs	20 kA 1/5 μs	5 kA	10 kA	20 kA
20	16	50.7	57.4	44.2	46.2	51.0

TABLE I
SURGE ARRESTER CHARACTERISTICS

- **Case 2**: same considerations as Case 1 but towers 17, 18 and 19 have a CFO = 200 kV.
- **Case 3**: Surge impedance at the endings, CFO = 75 kV, $N_g = 2$ lightning/km^2/year, ground conductivity $\sigma = 10$ mS/m, surge arrester lifetime of 40 years.

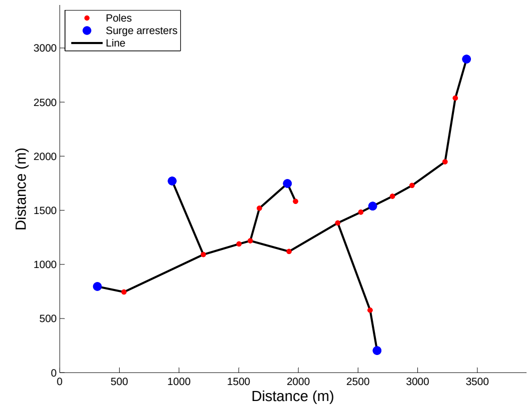
Case study 1 and 2 are for the purpose of testing the presented methodology. When terminals are open, due to the propagation and reflexion phenomena, over voltages tend to be increased. So surge arresters should be placed on the grid termination or near them. Surge arrester life time is reduced from its real value (around 40 years). With this condition, the GA puts only few surge arresters where we can see the appropriateness of their location.

The third case study represents a realistic grid situation due to the installation of surge impedances at the endings avoid the reflection phenomena. Hence, it may represent that the conductor continues and we only study a part of the rest of the MV grid. In this case, the lifetime is the typical of electrical devices (40 years).

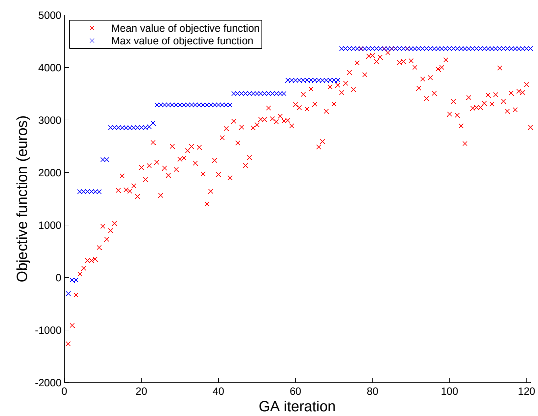
VI. RESULTS

Case study 1 and 2 are optimized two times in order to prove that the GA does not depend on the initial condition or the lightning sample.

Fig. 11 and 12 show the results for two executions of the GA for the first case study. Red dots in Fig. 11(a) and Fig. 12(a) represent the tower locations and blue dots the surge arrester location. Fig. 11(b) and 12(b) show the mean (red dots) and maximum (blue dots) of the objective function along the GA iterations.



(a) Surge arrester location (blue points)

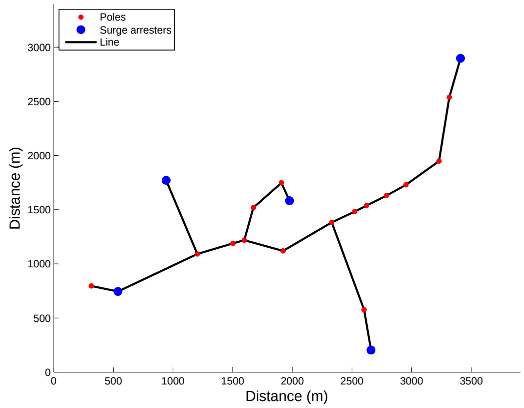


(b) Objective function among GA iterations. Blue = max of population, red = mean of population

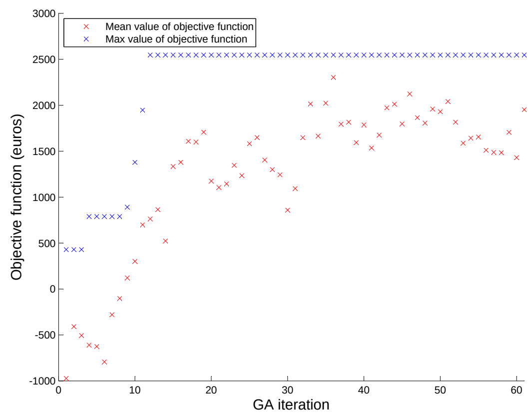
Fig. 11. Results for first execution and first case

Analysing these results it can be observed that effectively surge arresters have been located at the line terminations or close to them. Furthermore, in both cases, the result are remarkably similar and with convenient convergence. The objective function is depending on the random lightning values generated but it impacts in the same way the base case as well as in the case with surge arresters. Because of this, it could be explained that both cases reached practically the same solution despite of the initial condition dependence. As it is said previously, the objective function is finally calculated by Monte Carlo method which have result in 3173 € and 3693 € for the first and second result respectively. The results of this study case obtained are in a good accordance with [4] by means of surge arrester location.

Fig. 13 and 14 illustrate the results for two executions of the GA for the second case study. The respective sub-figures (a) and (b) correspond to the arrester location and the convergence of the algorithm. In this case, a branch with higher CFO is added to the cases in order to test the impact

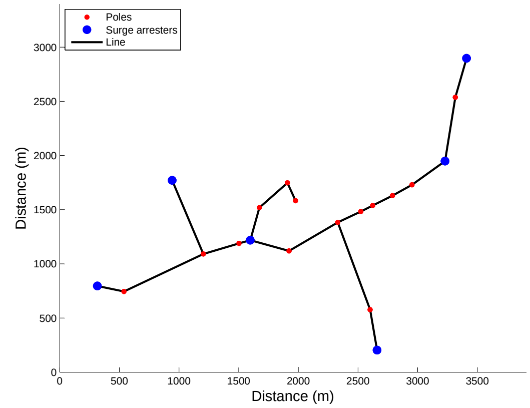


(a) Surge arrester location (blue points)

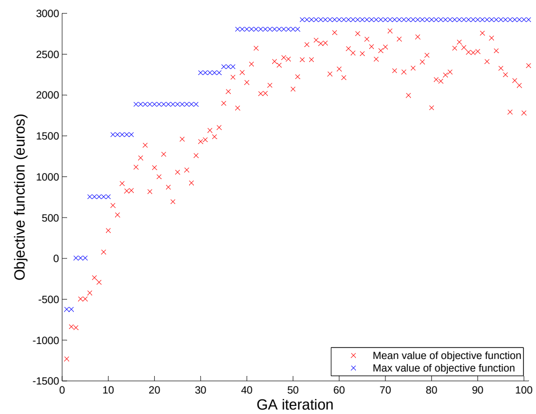


(b) Objective function among GA iterations. Blue = max of population, red = mean of population

Fig. 12. Results for second execution and first case



(a) Surge arrester location (blue points)



(b) Objective function among GA iterations. Blue = max of population, red = mean of population

Fig. 13. Results for first execution and second case

on the arrester location. These results show that in both cases the surge arrester in the high CFO branch have been moved and placed to the nearest pole with low CFO. The objective functions calculated via Monte Carlo method are 3890 €/ and 3571 €/ for the first and second execution respectively.

From the first and second case study, it can be seen that although the objective function of the GA depend on the lightning generated from the initial conditions, the number and location of surge arresters have not been dependency on it. Furthermore, when the Monte Carlo study is performed, it can be observed that despite the little differences between the surge arrester location for the two executions of the case study 1 and 2, the objective function is considerably similar. Once shown that the GA worked appropriately for the case study 1 and 2, a more realistic scenario is optimized in study case 3. Results from Fig. 15 (analogously as in the previous figures illustrating the location and convergence graph in the sub-figures) show that only 3 surge arresters are placed. In this case study this result was expected because the risk on the base case is lower due to the lower over voltages because the terminal endings are connected to a surge impedance. It can be observed that surge arresters have been placed in the less ramified part of the grid.

VII. Conclusion

The aim of this work is to develop a method to determine the number of surge arresters and their location in a MV network to protect against indirect lightning strokes, taking into account an economical criterion. Considering the random nature of lightning, statistics calculations have been done to estimate the flashover risk. At this process, it is considered the possibility of having different CFO along the grid by applying the margin concept explained above. The purposed GA is capable to find a satisfying solution with reasonable number of surge arresters as shown in the results of the study cases analysed. When insulators with different CFO voltages are installed along the grid, the methodology have obtained reasonable results as well as when a realistic case have been studied.

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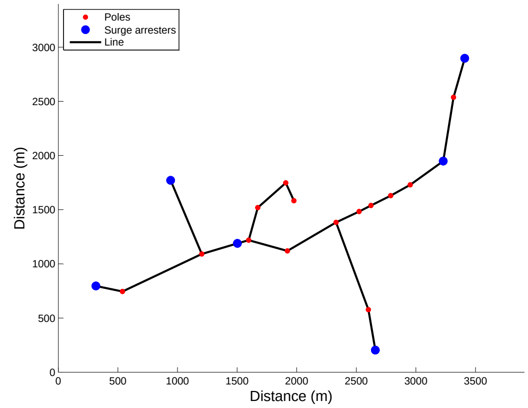
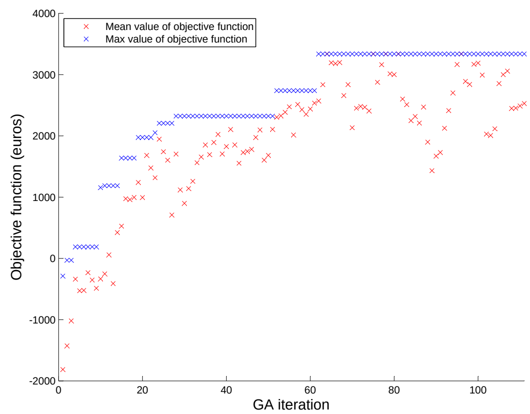
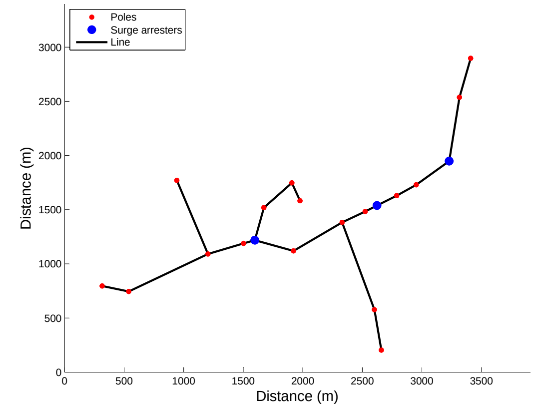


(a) Surge arrester location (blue points)



(b) Objective function among GA iterations. Blue = max of population, red = mean of population

Fig. 14. Results for second execution and second case



(a) Surge arrester location (blue points)

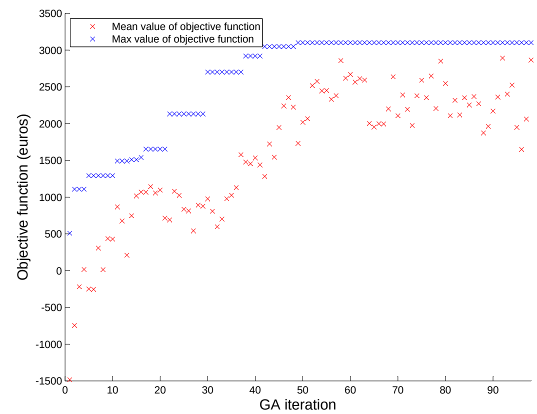


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Fig. 15. Results for third case

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