


Article

Optimized Surge Arrester Allocation Based on Genetic Algorithm and ATP Simulation in Electric Distribution Systems

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Abstract: Lightning discharges in electric power networks generate voltage and current surges that are propagated through the electrical network causing damage and shutdowns in the electrical system. To protect the system against these phenomena, surge arresters are very effective and widely used by electrical utilities in their electric grids. This paper presents a methodology for optimized surge arrester allocation based on genetic algorithm (GA), creating a simulation environment in the software ATP (Alternative Transients Program) to implement the proposed methodology. The optimized allocation procedure is based on a fitness function that minimizes the cost of surge arresters and maximizes the number of protected equipment. To carry out this optimized arrester allocation procedure using ATP may demand too much processing time when running large distribution grids. To overcome this difficulty a procedure is proposed to obtain an overvoltage severity description of the grid and select the most critical electric nodes for the incidence of lightning discharges, in the GA allocation procedure. The case study is applied to the IEEE 123-bus electrical feeder to demonstrate the effectiveness of the proposed methodology.

Keywords: Transient Analysis; Surge Arrester Allocation; Genetic Algorithm; ATP

1. Introduction

Lightning discharges and operational maneuvers, like switching of capacitor banks (CB), can generate overvoltage that propagates in the electrical network. The increased levels of voltage in distribution networks cause concern to electric power utilities, because the presence of overvoltage can cause, among others, malfunctioning and reduction of lifespan of equipment and devices, and in some cases might even cause permanent failures that may result in partial or complete shutdown of the electrical network. In addition to the losses due to equipment damage, if the electric power utility remains too long with no power supply, it shall be subjected to penalties which may reach significant values as the shutdown time period increases.

So, using mitigating measures is essential in order to avoid these costs, and as important as mitigation, it is to conduct preventive measures in order to protect the equipment and the electrical

26 grid against overvoltage. One way to achieve equipment protection against high levels of overvoltage
27 is through the installation of surge arresters along the power grid. A surge arrester, as long as it is
28 properly grounded, is able to damp overvoltage, sending part of the electrical current to ground.

29 A recurring problem among electric utilities is how to define an efficient methodology to perform
30 surge arresters allocation along the electric network. To perform this allocation in an efficient manner,
31 it is recommended to take into consideration the optimal placement of surge arresters along the power
32 grid. In addition to maintaining the quality of power delivered to consumers by keeping the voltage
33 levels below the system insulation limit, it is of great importance to ensure the equipment protection
34 and secure operation, as well as allow better planning on future equipment installation.

35 This article presents a methodology for surge arresters optimal allocation in electric networks
36 based on genetic algorithm (GA). For each individual of the GA population the electric grid is
37 automatically configured with a combination of surge arresters, which performances are evaluated
38 through electromagnetic transient simulation using ATP.

39 Two main aspects differentiate this work with respect to others found in the literature. The first
40 one is the use of a fitness function that takes into account weight factors to distinguish the desired
41 protection level for electrical nodes and equipment individually, and also considering restrictions on
42 the number of surge arresters to be allocated. This aims at maximizing the protection level and at the
43 same time minimizing the number of surge arresters needed, which allows the user to configure the
44 problem focus through the definition of the fitness function. The second aspect to be highlighted is the
45 proposed procedure to select the most critical points in the electric network concerning the incidence
46 of lightning discharges. This procedure makes possible to apply the optimal surge arrester allocation
47 even in large electrical networks using ATP. Many works can be found in literature whose focus is the
48 optimized allocation of surge arresters using metaheuristics and among them one can mention the
49 following papers.

50 In [1] and [2] it was developed a computer application to determine the surge arresters optimal
51 allocation in power systems minimizing the risk of failure, thus permitting the selection of appropriate
52 protection schemes for each electrical network. As a consequence, protection costs are reduced in
53 accordance to the costs of the elements actually protected, ensuring the continuity of service. It was
54 used the software Matlab and its toolboxes Simulink and Powersys to simulate the electric networks.

55 In [1] the proposed procedure is based on statistical analysis of voltage surges and fuzzy logic
56 techniques with the objective of establishing arresters locations that provide risks of failure at network
57 nodes that are lower than the admissible limits. In [2] the proposed method is also based on statistical
58 analysis of voltage surges but using Monte Carlo method and mathematical techniques to find the
59 minimum risk of failure based on the gradient method. However, it can be only applied to single-phase
60 electrical networks. In [2] the surge arresters allocation optimization is made by using a formulation
61 based on genetic algorithms. The Monte Carlo method is used for estimating the electric distribution
62 network lightning performance. The methodology is implemented in a software which links the
63 YALUK-ATP and the genetic algorithm. The initial population is randomly generated, and the fitness
64 function is set to minimize the percentile 60 or 90 of the probability distribution curve of the distribution
65 network voltages.

66 In [3] the surge arresters allocation optimization is made by using a formulation based on genetic
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69 genetic algorithm. The initial population is randomly generated, and the fitness function is set to
70 minimize the percentile 60 or 90 of the probability distribution curve of the distribution network
71 voltages.

72 In [4] the surge arrester allocation optimization is made based on genetic algorithm and network
73 simulations with a developed electromagnetic transients program software. The fitness function is set
74 to minimize overvoltage in a specific number of towers. Induced lightning discharges are used in the
75 simulation studies.

76 The method presented in [5] is based on genetic algorithms and an economic approach is taken
 77 into account by means of evaluating the cost of flashover insulation. Only indirect lightning is taken
 78 into account. The computer application was developed in MATLAB environment, and the simulation
 79 software to calculate the induced overvoltage is the ATP. After modeling the grid, ATP generates a
 80 plain file containing the grid data which are imported into MATLAB. So, each characteristic such as
 81 lightning and surge arresters parameters can be modified in the MATLAB environment. It is assumed
 82 that a flashover occurs when the maximum overvoltage is greater than $1.5 V_{CFO}$ (Critical Flashover
 83 Voltage). The initial population is randomly generated.

84 2. Proposed Metodology

85 To perform the surge arrester allocation using the proposed GA procedure, firstly it is necessary
 86 to model the electrical network via ATP input cards, which serve as template for the genetic algorithm.
 87 This template can be constructed manually by using ATPDraw module or automatically by using the
 88 procedure as presented in [6].

89 Once the template is built, it is necessary to choose in the electrical network under study, the
 90 critical electric nodes to apply lightning discharges, which will propagate voltage and current surges
 91 along the power grid [7]. It is important that all genetic individuals created in all populations of the
 92 GA evolution be tested in the same scenario, with the same lightning incidence points, otherwise
 93 it is considered that the GA individuals represent distinct scenarios. Before presenting the genetic
 94 algorithm configuration it is necessary to introduce some concepts that were used in the proposed
 95 methodology for surge arresters allocation.

96 2.1. Cross Mean Table

97 Firstly, it is highlighted that for every surge arrester allocation suggested by the GA solution, a
 98 simulation of ATP electromagnetic transient analysis is performed. With respect to this point, it is
 99 worth mentioning that the use of the GA in conjunction with ATP for the optimal solution is a process
 100 that consumes too much processing time, which makes it impracticable in terms of the solution time
 101 duration, the application of this optimization process to a great diversity of lightning discharges in
 102 large electric distribution grids.

103 Because of that, it was created the concept of Cross Mean Table (CMT) which represents an
 104 organized summary of ATP simulation results obtained by simulating the incidence of lightning
 105 discharge in each electrical node of the grid, one by a time. In this case, when applying the GA
 106 optimization procedure, instead of considering lightning discharges in all nodes of the electric network,
 107 only the electrical nodes with the most critical over voltages values obtained in the ATP simulation are
 108 considered for incidence of lightning discharges and participate in all GA generations.

109 To construct the CMT it is necessary to create a $(m + 1) \times n$ array, as depicted in Figure 1, where m
 110 is the total number of nodes in the electric network and n is the number of nodes at which it is desired
 111 to evaluate the impacts of lightning discharges, such that $m \leq n$. For each node n in the column array
 112 it is simulated, by using ATP, the incidence of a lightning discharge with same parameters for each
 113 node. The highest overvoltage resulting in phases A-B-C of nodes m due to lightning discharges in
 114 nodes n are stored in the column array forming the elements $CMT(i, j)$, for $i = 1, 2, \dots, m$.

	<i>Node 1</i>	<i>Node 2</i>	<i>Node 3</i>	...	<i>Node n</i>
<i>Node 1</i>	V_{11}	V_{12}	V_{13}	...	V_{1n}
<i>Node 2</i>	V_{21}	V_{22}	V_{23}	...	V_{2n}
<i>Node 3</i>	V_{31}	V_{32}	V_{33}	...	V_{3n}
...
<i>Node m</i>	V_{m1}	V_{m2}	V_{m3}	...	V_{mn}
V_{avg}	$V_{avg(1)}$	$V_{avg(2)}$	$V_{avg(3)}$...	$V_{avg(n)}$

Figure 1. Cross Mean Table.

115 A sensitivity analysis is performed in order to evaluate for which node j , the overvoltage caused
 116 in the electric network is more critical. The average of overvoltage per column is calculated and stored
 117 in the array V_{avg} . Once this array is sorted, it is possible to identify the most critical nodes for lightning
 118 discharge. So, it is reasonable that any study done to mitigate the impacts caused in the network due
 119 to lightning discharges should first consider the most critical nodes, assuming that by minimizing
 120 damages caused in this scenario, shall consequently reduce impacts due to lightning discharges in
 121 other nodes.

122 2.2. Genetic Algorithm

123 Genetic algorithm is a technique of local search that uses evolution-based procedures to make
 124 small changes in a population of chromosomes in searching for an optimal solution [8]. In the following
 125 it is presented a discussion on the main elements that compose the genetic algorithm fundamentals
 126 applying to the problem of surge arrester optimal allocation.

127 2.2.1. Chromosome

128 The chromosome represents a solution to be tested as a possible candidate to the optimal solution
 129 for the problem. In Figure 2 it is represented the chromosome definition to be used in the problem of
 130 surge arresters optimal allocation as proposed in this paper, where each gene represents a network
 131 electric node that is candidate to receive a set of surge arrester.

<i>Node 1</i>	<i>Node 2</i>	<i>Node 3</i>	<i>Node 4</i>	...	<i>Node n</i>
0.2345	0.5001	0.8903	0.4590	...	0.5000

Figure 2. Example of chromosome.

132 The number of chromosome genes is equal to the number of electrical nodes that a study is desired
 133 and do not have any surge arrester installed. Each gene uses real coding with values in the range of [0,
 134 1].

135 2.2.2. Individual

136 The population individuals, as presented in Figure 3, refer to solutions found from decoding a
 137 chromosome. Each gene is decoded considering the value 0.5 as cutoff point, that is, if $gene \leq 0.5$
 138 then it is assigned a value 0, otherwise it is assigned a value 1. A gene with value 0 indicates that the
 139 corresponding electric node has no surge arresters allocated; value 1 indicates that surge arresters are
 140 allocated in all phases of the corresponding node, being one, two or three-phase nodes.

<i>Node 1</i>	<i>Node 2</i>	<i>Node 3</i>	<i>Node 4</i>	...	<i>Node n</i>
0	1	1	0	...	0

Figure 3. Example of individual.

141 2.2.3. Population

142 Population is a set of chromosomes that will undergo changes over the genetic algorithm
 143 generations. Two population settings have been defined that can be chosen by user. The first
 144 configuration is set to carry out a search for a solution that performs optimal allocation with the
 145 least amount of surge arresters possible. For this, the minimum population size is defined as being
 146 twice the sum of the number of candidate electric nodes plus 1 as in (1).

$$size = 2 \times (n + 1) \quad (1)$$

147 Half of this population is stochastically generated using a uniform distribution to generate the
 148 genes, and the other half in a deterministic way, where one of the chromosomes created does not
 149 contain surge arresters allocated, that is, all genes are equal to zero. The other chromosomes have only
 150 one surge arrester set allocated. In other words, for each candidate electrical node, a chromosome with
 151 only one surge arrester set is placed in the corresponding gene, and no surge arresters in the other
 152 genes, according to Figure 4.

<i>Node 1</i>	<i>Node 2</i>	<i>Node 3</i>	<i>Node 4</i>	...	<i>Node n</i>
0	0	0	0	...	0
0	0	0	0	...	1
0	0	0	0	...	0
0	0	0	1	...	0
0	0	1	0	...	0
0	1	0	0	...	0
1	0	0	0	...	0

Figure 4. Population configuration 1.

153 If the electrical network has many electrical nodes and equipment, the combined execution time
 154 of GA and ATP may take several hours, depending on the number of generations and the number of
 155 distinct chromosomes that are created over the generations. As a result, the second configuration aims
 156 to reduce the number of chromosomes to be generated in order to reduce execution time. This way it
 157 is suggested to focus the search around the electric nodes whose lightning discharges have caused the
 158 most critical over voltages, according to the results obtained from the *Cross Mean Table* analysis.

159 Like the in the first configuration, in the second one, half of the population is also generated
 160 stochastically using a uniform distribution to generate the genes, and another half deterministically.
 161 The difference is in the size of the population and how individuals are created. The population size
 162 is defined as in (2), where n is the number of lightning discharges to be analyzed.

$$size = 2^{n+1} \quad (2)$$

163 The deterministic half consists of generating the truth table of surge arresters combinations in
 164 the electric nodes where there was incidence of lightning discharges. Figure 5 presents an example of
 165 the deterministic construction, where each individual represents one of the 2^n possible combinations,
 166 considering the number of discharges $n = 3$, for illustrative purpose. In these individuals, surge
 167 arresters will be allocated in the n electric nodes with value 1, and in the others it is assigned value
 168 zero, that is, no surge arrester allocated.

	Node Discharge 1		Node Discharge 2		Node Discharge 3	
...	0	...	0	...	0	...
...	0	...	0	...	1	...
...	0	...	1	...	0	...
...	0	...	1	...	1	...
...	1	...	0	...	0	...
...	1	...	0	...	1	...
...	1	...	1	...	0	...
...	1	...	1	...	1	...

Figure 5. Population configuration 2.

169 2.2.4. Selection

170 The tournament selection operator is used, where a set of chromosomes is randomly chosen to
 171 participate in a *ring*. The two best evaluated chromosomes are chosen as parents to generate a new
 172 pair of chromosomes. The size of the *ring* is defined by the user.

173 2.2.5. Crossover

174 The crossover operator used is the arithmetic crossover. With each generation a new empty
 175 population is created and filled with new individuals until it reaches the configured size. For
 176 that, repeatedly two chromosomes are selected and a random number is generated using a uniform
 177 distribution. If it is verified that this number satisfies the stipulated crossover rate, a random number
 178 α is generated which will serve to create weights by performing the weighted average of the parent
 179 chromosomes genes, generating new genes for each child chromosome, as in (3) and (4). Otherwise,
 180 two new chromosomes with the same parent genes are generated.

$$child1[i] = \alpha \times parent1[i] + (1 - \alpha) \times parent2[i] \quad (3)$$

$$child2[i] = (1 - \alpha) \times parent1[i] + \alpha \times parent2[i] \quad (4)$$

181 2.2.6. Mutation

182 The mutation operator used is the reflexive gaussian mutation. For each chromosome gene a
 183 random number is generated using a uniform distribution and checked if it satisfies the configured
 184 mutation rate. If false, the gene remains unchanged; otherwise a number is generated from a gaussian
 185 distribution with mean $\mu = 0$ and standard deviation σ in the range of $[0, 1]$ as defined in the settings.

186 The standard deviation represents the maximum change that the gene will suffer. The number
 187 generated in the range $[-\sigma, \sigma]$ is added to the gene, if the result exceeds the range limits of $[0, 1]$, the
 188 surplus is reflected in the opposite direction, so the gene will never overcome this range.

189 2.2.7. Fitness

190 The fitness function aims to evaluate how good the solution represented by a chromosome is. To
 191 perform this evaluation it is necessary to execute the ATP input cards using the *template* created and
 192 modified based on the individuals, allocating a surge arrester set at the electric nodes where there is a
 193 gene with value 1. For each individual, n lightning discharge scenarios are simulated. At the end of
 194 each simulation the maximum phase voltage peaks of each electrical node is extracted from the output
 195 file.

196 The defined fitness function is composed of the sum of 3 terms. The first term B aims to maximize
 197 the number of electrical nodes that are within the V_{CFO} voltage limit, which varies according to the
 198 feeder nominal voltage ($V_{nominal}$) and represents the voltage level above which the flashover occurs
 199 and, consequently, shutdown. For that, the percentage of electrical nodes whose electrical voltages are
 200 less than V_{CFO} is calculated according to (5).

$$B = \frac{B_{total} - B_{over}}{B_{total}} \times 100 \quad (5)$$

201 Where,

202 B_{total} is the total number of electrical nodes in the electrical network.

203 B_{over} is the total number of electrical nodes that has exceeded the electric voltage limit of V_{CFO} ,
204 considering V_{CFO} equal to the NIL (Basic Isolation Level).

205 An electrical node violates the V_{CFO} limit when at least one of its phases presents a voltage level
206 greater than V_{CFO} , defined as in Table 1, adapted from NBR 6939 [9]. When a nominal voltage occurs
207 at the ends of each range, a more conservative profile is adopted using the lowest value of V_{CFO} among
208 the possible ones.

Table 1. Insulation voltage levels: V_{CFO} limits

$V_{nominal}(kV)$		$V_{CFO}(kV)$	
	$x \leq$	3.6	20
3.6	$\leq x \leq$	7.2	40
7.2	$\leq x \leq$	12	60
12	$\leq x \leq$	15	95
15	$\leq x \leq$	24	125
24	$\leq x \leq$	36	145
36	$\leq x \leq$	72.5	325
72.5	$\leq x \leq$	92.4	380
92.4	$\leq x \leq$	145	450
145	$\leq x \leq$	245	650

209 The second term E consists of evaluating the percentage of equipment that has been protected
210 according to (6). A protected equipment is one whose electrical node has electric voltage level within
211 the V_{CFO} limit in all its phases. Capacitor banks (BCs) and transformers are considered as equipment.

$$E = \frac{E_{total} - E_{over}}{E_{total}} \times 100 \quad (6)$$

212 Where,

213 E_{total} is the total number of equipment in the electrical network.

214 E_{over} is the total number of equipment that is connected at electric nodes that have exceeded the
215 V_{CFO} limit.

216 The third term A evaluates the number of surge arresters that were required to perform the
217 optimal allocation, as in (7), considering that each electrical node receives a surge arrester in each
218 phase. This term acts as a bonus if $A_{allocated} \leq A_{desired}$; otherwise, it acts as a penalty to the individuals
219 that have exceeded the established *desired* number of surge arrester.

$$A = \frac{A_{desired} - A_{allocated}}{A_{max} - A_{desired}} \times 100 \quad (7)$$

220 Where,

221 A_{max} is the maximum number of surge arresters that can be allocated in the electrical network,
222 that is, a surge arrester in each phase of each electric node.

223 $A_{desired}$ is the user-defined desired number of arresters to be allocated.

224 $A_{Allocated}$ is the amount of allocated surge arresters by the GA procedure.

225 The final fitness function is defined by (8), as the weighted sum of terms B , E and A , where F_{ep} is
226 the equipment protection factor and F_a is the surge arrester factor, both of which can assume values in
227 the interval $[0, 1]$. It is possible that the weighted sum in (8) generates a negative value, and in this
228 case the fitness value will be set to zero, through the *max* function that returns the largest between two
229 numbers.

$$fitness = \max(0, (1 - F_{ep}) \times B + F_{ep} \times E + F_a \times A) \quad (8)$$

230 However, the user must define a *limit* number of surge arresters (A_{limit}) that can be tested on each
 231 solution. Individuals who exceed A_{limit} will not be simulated by the ATP and their fitness will be
 232 zero. In summary, individuals will receive in their fitness, a bonus if $A_{allocated} \leq A_{desired}$ or a penalty if
 233 $A_{desired} < A_{allocated} \leq A_{limit}$, and in the case $A_{allocated} > A_{limit}$ they will not be simulated in ATP.

234 2.3. Memory Map

235 A simulation run in ATP may take a few minutes depending on the size of the electrical network
 236 and the simulation parameters. It is necessary to perform an ATP simulation for each individual that
 237 was generated by the GA evolution, but it is possible that the same individual be generated more than
 238 one time during the GA execution.

239 Regardless of how many times the same simulation is performed the result obtained is the same.
 240 Therefore, these extra ATP calls spend unnecessary processing time, and to avoid them a memory map
 241 is used to store the calculated fitness.

242 A memory map is a data structure that indexes a value to a unique key, which is used as the
 243 search parameter. In Python a memory map is implemented in dictionary form. For this application
 244 the key consists of a tuple of the individual genes and the value is the calculated fitness and the
 245 tiebreaker criteria, as in Figure 6. The main advantage of using this feature is the reduced processing
 246 time, however there is also an increase in memory consumption.

<i>key</i>	:	<i>value</i>
(0,0,0,0)	:	[fitness ₀ , E ₀ , A ₀ , B ₀]
(0,0,0,1)	:	[fitness ₁ , E ₁ , A ₁ , B ₁]
(0,0,0,1,0)	:	[fitness ₂ , E ₂ , A ₂ , B ₂]
(0,0,0,1,1)	:	[fitness ₃ , E ₃ , A ₃ , B ₃]
...	:	...
(1,1,1,1)	:	[fitness ₃₁ , E ₃₁ , A ₃₁ , B ₃₁]

Figure 6. Example of memory map.

247 2.4. Parallelization

248 Running the genetic algorithm sequentially can be very costly due to the time spent with each
 249 ATP simulation. Therefore, it is essential to perform parallelization to perform multiple simulations
 250 of ATP simultaneously. Parallelization was performed in processing the fitness function and in the
 251 methodology of constructing the CMT because both routines use exhaustive ATP executions.

252 3. Results Discussions

253 To test the proposed methodology, the IEEE-123 Node Test Feeder [10] is used, whose single-line
 254 diagram can be seen in Figure 7. To guarantee the electrical network has no islands and is radial, all
 255 switches were considered closed except switches 18-135 and 54-94.

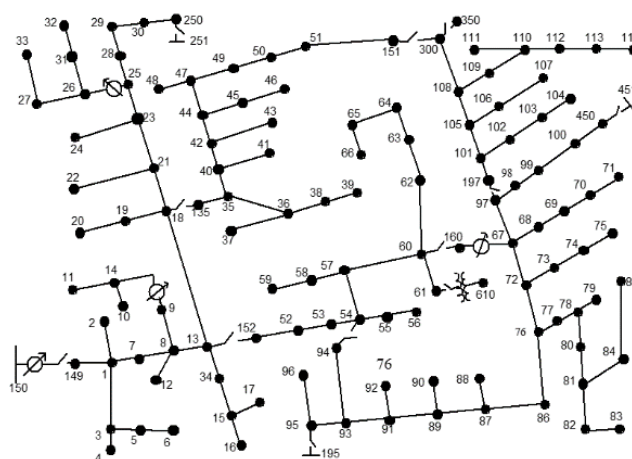


Figure 7. IEEE 123 node electric test feeder single-line diagram.

256 Figure 8 represents the sorted array V_{avg} obtained from the CMT, considering a lightning discharge
 257 of 10 kA. The runtime spent to get this curve was 6.12 minutes. As can be observed the three most
 258 critical nodes analyzed are B_{135} , B_{35} and B_{40} presenting overvoltage above 2 MV. From the definition
 259 of these nodes, the GA execution will be done considering the incidence of lightning discharges only
 260 in the three most critical nodes, firstly the most critical (B_{135}), then the two more critical (B_{135} and B_{35})
 261 and finally the three more critical (B_{135} , B_{35} and B_{40}).

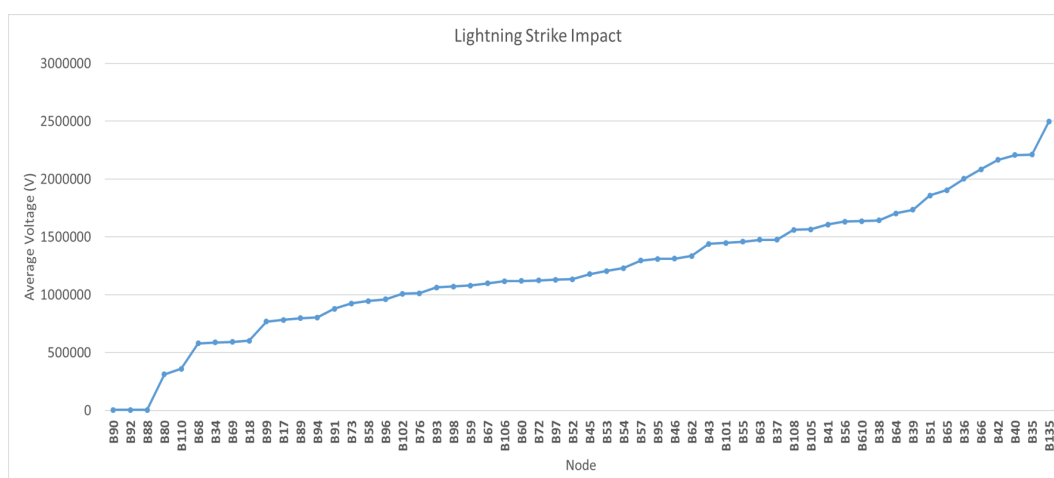


Figure 8. Graphical representation of CMT results for lightning discharges of 10 kA in each electric node of IEEE-123 node test system.

262 The GA parameters setting is described in Table 2. The minimum population size used was
 263 defined by (2).

Table 2. Genetic algorithm configuration.

Generations	Population Size	Ring Size	Crossover Rate (%)	Mutation Rate (%)	σ
30	16	3	80	50	0.5

264 The GA was executed considering six different configurations of fitness settings, as presented in
 265 Table 3. Each configuration has a specific focus that can vary between the high priority protection of
 266 electrical nodes with already installed equipment, namely transformers and capacitor banks, or an
 267 equal priority protection scheme of all electrical nodes, considering or not a restriction on the maximum

number of surge arresters to be allocated. For the current case study, the tests were performed with $A_{desired} = 29$ and $A_{limit} = 58$.

Table 3. Fitness configuration.

Configuration	F_{ep}	F_a	Description
1	0	0	Equal priority protection of all nodes, without limitation of surge arresters.
2	0	1	Equal priority protection of all nodes, with limitation of surge arresters.
3	1	0	Priority protection for transformers and CBs, without limitation of surge arresters.
4	1	1	Priority protection for transformers and CBs, with limitation of surge arresters.
5	0.5	0	Equal priority protection of all nodes, transformers and CBs, without limitation of surge arresters.
6	0.5	1	Equal priority protection of all nodes, transformers and CBs, with limitation of surge arresters.

As can be seen by inspection of Tables 4, 5, and 6, all configurations have presented a good percentage of equipment protection in all cases. For a lightning discharge at the most critical electric node B_{135} , the best surge arrester allocation solution was obtained by configuration 6, which resulted in 100% protection of equipment and 98.89% protection of electric nodes in general, allocating the smallest number of surge arresters. In the case of lightning discharges at nodes B_{135} and B_{35} , configurations 5 and 6 presented similar results for equipment protection reaching 89.23%, and allocating 56 and 55 surge arresters respectively. For lightning discharges at nodes B_{135} , B_{35} , and B_{40} the best solution corresponds to configuration 3, which reached 92.31% of equipment protection, allocating 58 surge arresters, that is the allowed limit.

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Table 4. Results obtained when simulating a 10 kA lightning discharge at bus B_{35} .

Configuration	Fitness (%)	B (%)	E (%)	$A_{allocated}$	AG runtime (min)
1	94.44	94.44	95.38	50	17.15
2	76.05	91.11	90.77	54	13.71
3	98.46	97.78	98.46	55	16.06
4	80.93	94.44	95.38	53	8.01
5	99.44	98.89	100.00	54	16.93
6	87.40	98.89	100.00	49	21.44

Table 5. Results obtained when simulating a 10 kA lightning discharge at buses B_{35} and B_{42} .

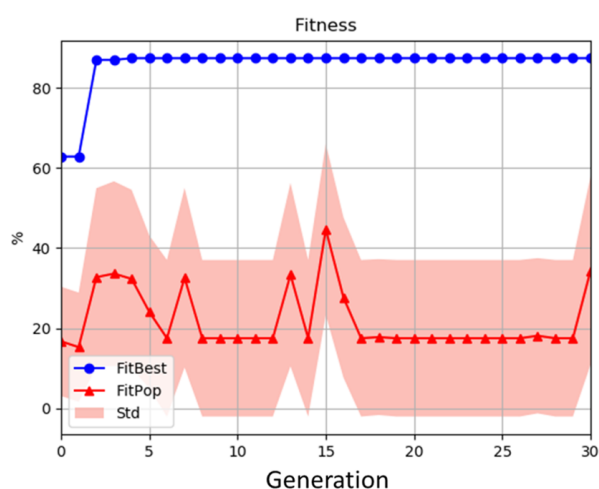
Configuration	Fitness (%)	B (%)	E (%)	$A_{allocated}$	AG runtime (min)
1	86.67	86.67	86.15	56	22.70
2	70.96	80.00	78.46	44	46.93
3	76.92	75.56	76.92	53	26.16
4	77.72	86.67	86.15	43	64.38
5	89.06	88.89	89.23	56	23.21
6	73.40	88.89	89.23	55	34.54

Table 6. Results obtained when simulating a 10 kA lightning discharge at buses B_{35} , B_{42} and B_{36} .

Configuration	Fitness (%)	B (%)	E (%)	$A_{allocated}$	AG runtime (min)
1	81.11	81.11	80.00	57	47.13
2	77.95	90.00	90.77	49	95.88
3	92.31	91.11	92.31	58	83.26
4	72.63	87.78	87.69	54	102.24
5	83.21	83.33	83.08	58	63.29
6	68.12	80.00	81.54	50	83.87

288 The GA average runtime for Tables 4, 5 and 4 were 15.55 min, 36.32 min and 79.28 min respectively.
 289 The larger the number of critical nodes to be analyzed the higher the runtime due to the increased
 290 ATP executions. A linear approximation, for example, considering that all IEEE-123-grid electric
 291 nodes are to be analyzed it would spend approximately 54 hours of continuous computing processing.
 292 Typical electric distribution grids may have thousands of electric nodes, so the direct application of
 293 GA optimization procedures using ATP may become not viable with respect to processing time, and
 294 using a procedure like the one proposed in this article may become it viable.

295 The GA convergence performance for configurations 1-6 has exhibited similar profiles.
 296 Configuration 1 was selected to illustrate this performance, whose results can be seen in Figures 9, 10
 297 and 11 respectively. For each GA execution Figure 9 presents the fitness function convergence profile,
 298 being the best individual convergence presented in dotted blue line and the population convergence
 299 in dotted red line, with the respective standard deviation confidence interval.

**Figure 9.** Fitness convergence.

300 The percentage of protected equipment and allocated surge arresters are updated with each
 301 generation, trying to keep the amount of protected equipment as bigger as possible, and the number of
 302 arresters as smaller as possible, as depicted in Figures 10 and 11.

303 In Figure 10 it is highlighted in dotted blue line the percentage of equipment protection for the
 304 best individual presented in Figure 9. It is also presented in dotted red line the population curve
 305 representing the average of all individuals in the generation, which variation profile is constrained by
 306 the standard deviation confidence interval.

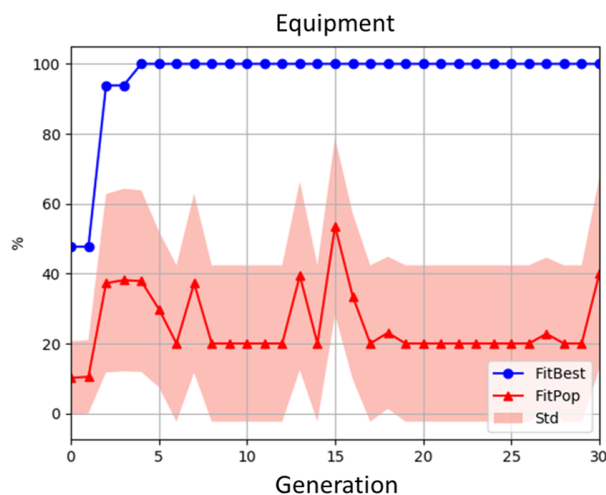


Figure 10. Protected equipment.

307 Figure 11 presents in dotted blue line the amount of allocated surge arresters for the best individual
 308 for each GA generation and the corresponding allocation profile for the average population individuals
 309 in dotted red line.

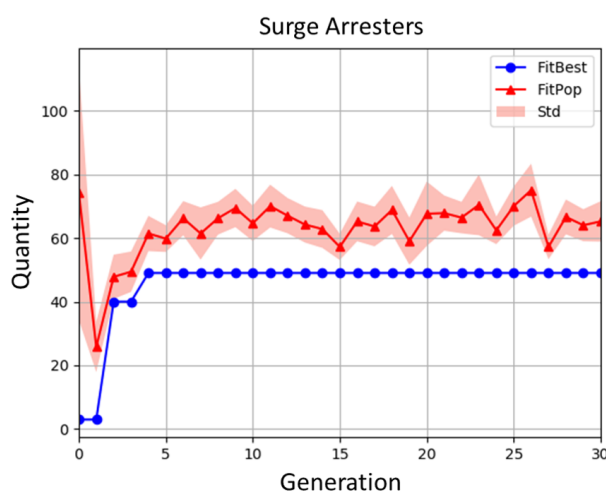


Figure 11. Allocated surge arresters.

310 To evaluate the GA optimal solutions performances in terms of the resulting system overvoltages,
 311 the Cross Mean Table methodology is again applied, considering 10 kA lightning discharges in all
 312 electric nodes, but now considering the optimal allocation of surge arresters as obtained by the GA
 313 optimal solutions. In order to exemplify this performance, configuration 6 as presented in Tables 4, 5
 314 and 4 will be used. Figure 12 shows the CMT results obtained after the optimal allocation of surge
 315 arresters, when considered the most critical node (dotted orange curve), the two most critical nodes
 316 (gray dotted curve) and, finally, the three most critical nodes (yellow dotted curve). These results are
 317 compared with results obtained for the original system without surge arrester allocation (dotted blue
 318 curve), as presented in Figure 8.

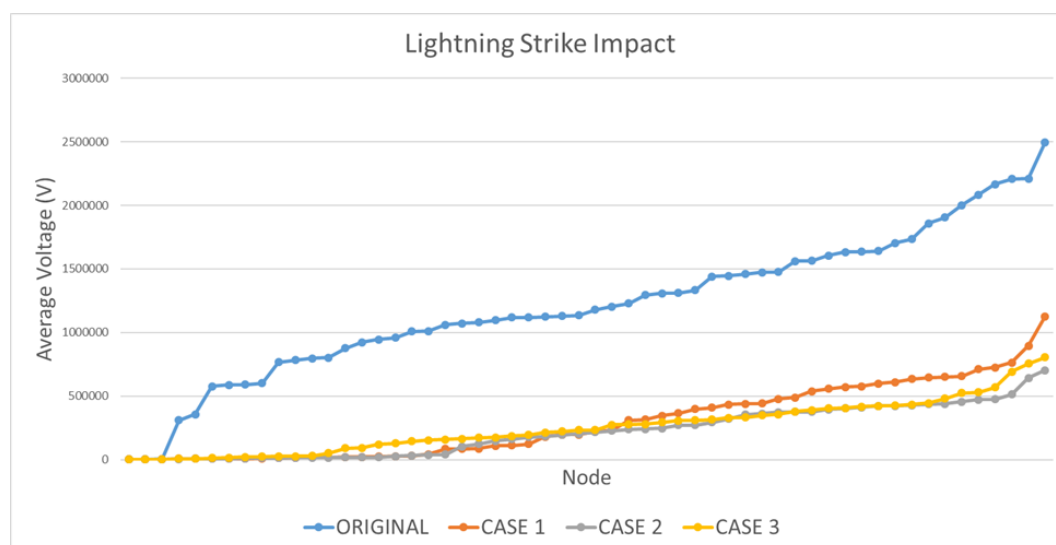


Figure 12. Graphical representation of CMT results before and after surge arresters allocation.

319 It is observed in Figure 12 that in all cases considered, that is, only the most critical node, the two
 320 most critical nodes, and the three most critical nodes, the proposed methodology presented a significant
 321 reduction of overvoltage with respect to the condition without surge arresters allocation (original
 322 electric network). The comparison among the three cases of optimal allocation, either observing
 323 Figure 8, or the previous results presented in Tables 4, 5 and 4, demonstrates that they are very
 324 similar, with slight variations between the solutions presented. In this way one has a varied set of
 325 feasible solutions to be adopted. It is worth to emphasize that by using the proposed methodology,
 326 these solutions are obtained with a reduced computational effort, when compared with standard
 327 optimization procedures using GA.

328 4. Conclusions

329 It is well known by researchers and engineers of electrical systems that using ATP as a calculation
 330 tool in optimization procedures, such as those using genetic algorithms, demands a lot of processing
 331 time, which can even make the combined use of AG and ATP unfeasible for the solution of optimization
 332 problems in large electric networks. This was one of the main aspects covered in this article, being
 333 proposed an optimization procedure to overcome this difficulty which is based on the analysis of the
 334 electric network regarding the critical over voltages caused by atmospheric discharges. The proposed
 335 solution using the CMT description of the electric network demonstrated to be very effective as a
 336 starting condition of the GA optimization procedure.

337 Surge arresters optimal allocation based on the most critical over voltages analysis proved to be
 338 quite effective, obtaining very good results regarding the over voltages reduction at all electric nodes,
 339 ensuring high percentages of electric nodes below the flashover voltage limit.

340 It is worth mentioning, too, that the proposed fitness function allows important features of
 341 electrical systems operation to be met in planning surge arresters allocation in electrical networks,
 342 namely, to protect a maximum possible number of electric nodes and equipment, with the least
 343 possible financial investments in surge arresters acquisition. The results demonstrated the proposed
 344 methodology has a great potential for application in real problems of electric distribution utilities,
 345 which typically involve large electric networks, serving as a guide in decision making concerning
 346 surge arresters allocation planning.

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360 Abbreviations

361 The following abbreviations are used in this manuscript:

362	ATP	Alternative Transients Program
	BIL	Basic Isolation Level
	CB	Capacitor Bank
363	CMT	Cross Mean Table
	GA	Genetic Algorithm
	V_{CFO}	Critical Flashover Voltage

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