Genetic Algorithms applied for the Optimal Allocation of Power Quality Monitors in Distribution Networks

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Abstract – **This paper presents a methodology which determines the optimal allocation of power quality monitors, in order to monitor the occurrence of voltage sags and swells in distribution networks. Initially, the methodology characterizes the system under analysis regarding the occurrence of voltage sag and swells. This characterization is performed through the simulation of several short-circuits at different points of the system being studied and taking in to consideration several conditions (fault impedance, fault type, etc.). For this purpose, a new method that defines the most relevant short-circuit conditions is proposed. After the system´s characterization, the methodology makes use of Genetic Algorithms (GA) to define the minimum number of monitors required to monitor the whole system, and also the places where these monitors should be installed in the power network.**

Keywords – **Distribution Networks, Genetic Algorithms, Power Quality, Voltage Sags/Swells.**

I. INTRODUCTION

Voltage sags and swells are normally due to the switching of large blocks of load (motor starting, transformer energizing, etc.); or due to short-circuits. Usually, the most severe voltage variations are caused by short-circuits with no fault impedance, which may cause variations that can propagate through large distances in transmission and sub-transmission networks. Nowadays, these phenomena can be considered as the main sources of complains by the customers of the utility companies, since they may cause the malfunction of voltage sensitive equipment, affecting their regular operations and even resulting in considerable financial loss in some cases.

Voltage Sags and Swells are also among the most difficult phenomena to be monitored because they are caused by random and unpredictable factors, namely, fault impedance, fault type, fault location, etc. Therefore, the difficulty is not on measuring the magnitude and duration that characterize these phenomena, but on determining the frequency of occurrence and factors responsible for causing them.

Initially, the literature suggested that, in order to determine the frequency of occurrence of such phenomena in power networks, dedicated metering equipment should be installed at the buses of the system [1]-[2]. The disadvantage of this approach was the number of monitors needed to perform the assessment of the whole power network in a reasonable amount of time.

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Nevertheless, the need for determining the frequency of occurrence of such voltage variations increased in the new environment originated with the restructuring of the electric sector. On one hand, the establishment of new regulatory limits forced utility companies to invest in new permanent monitoring systems, in order to assess the performance of their networks and guide their remedial actions. On the other hand, competitiveness increased and forced companies to be more cautious with their investment decisions. As power started to be seen as a commercial product (which should not be seen only through its continuity, but also through its quality), companies able to supply energy at a better quality and at a lower cost, would have a higher chance to highlight in the market, especially among the consumers that require energy supplyfree of disturbances. In this context, a methodology to determine the minimum number of power quality monitors needed to monitor a whole distribution network would become an attractive alternative.

The determination of the minimum number of monitors needed to monitor a power network is achieved through the optimal allocation of the monitors. According to the optimal allocation criteria [3], [4] and [5], monitors should be installed in strategic positions of the power network in a way that minimizes the measurement redundancy (each bus of the system should be monitored by the smallest possible number of monitors, but each of them should be monitored by at least one monitor). So, the optimal allocation of monitors determines the positions in which certain numbers of monitors must be installed in order to maximize the reach of the monitoring area on a power distribution network. Therefore, the minimum number of monitors becomes a consequence of determining the optimal position of each monitor, because by maximizing the reach of each monitor (the *Observability* of the measuring equipment), the minimum number of monitors is achieved automatically. The term *Observability* can be seen through two different approaches. In the first approach, it regards the reach of a specific monitor installed in a power network. In the second approach, it regards the reach of a whole monitoring system over a power network.

The problem of allocating power quality monitors for voltage sags and swells monitoring has already been approached in some previous works. In [3], [5] and [6], the authors have solved the problem for transmission networks using linear programming techniques. Genetic algorithms and fuzzy logic have also been applied in [4], in order to solve the problem of allocating power quality monitors in transmission networks.

Similar problems have also been solved for distribution networks using different optimization techniques. In [7], the authors use a Modified Simulated Annealing (MSA) technique, considering also Tabu Search and Heuristic Methods, in order to define the optimal allocation of PMU units. In [8] the authors have used applied Tabu Search to allocate PMU units too. GAs [9] and Fuzzy Logic [10] have also been used to define the placement of monitoring equipment in power networks.

In the present paper, the proposed methodology executes a stochastic method in order to define short-circuit simulations that will be considered to characterize the behavior of the network being studied, regarding voltage sags and swells. This new method tries to go through all the possible combinations of the variables present in the occurrence of short-circuits, namely fault location, fault type and fault impedance. In order to do so, the values for some variables are defined according to probability distributions that reflect the real behavior of power network, while the values for the other variables are randomly defined. The use of this stochastic approach has originated the *Hybrid Method (HM)* that is presented in this paper. The advantage of using the *HM* to define the allocation of power quality monitors is that only the most likely short-circuit conditions would be considered. So, the number of monitor allocation will probably be more effective than the one defined by previous works.

Due to the combinatorial nature of the power quality monitor allocation problem, the authors of the present paper have also decided to use GAs based on a decimal codification, in order to define the optimal allocation of power quality monitors in distribution networks. The fitness function considered in the present work takes into consideration aspects as the *Observability* and the relevance of the measurement, simultaneously. Some special features, namely dynamic diversity, dynamic mutation rates and dynamic recombination, have also been implemented in the GA in order to improve its performance.

The methodology was applied in a real distribution system. The results are presented and discussed in the following sections.

II. Observability Matrix

The response of the distribution system regarding voltage sags and swells is obtained through a matrix composed by the voltage values at the system buses for each short-circuit condition as it is shown in (1). The short-circuit conditions to be considered are defined by the *HM*, to be presented in section III.

This matrix is then transformed into a binary matrix, known as *Observability* Matrix *(OM)*, according to the voltage values at the buses of the system under analysis. The binary value in the *OM* would indicate if the voltage at a specific bus is not within the pre-established limits.

The size of the *OM* would be $N_{Tot\text{-}Sh}$ x N_{bar}. $\mathrm{N_{bar}}$ corresponds to the total number of considered buses, and $N_{Tot\text{-}Sh}$ is the number of short-circuit conditions. N_{bar} is a fixed value, while $N_{Tot\text{-}Sh}$ is defined by the *HM* and may change from one assessment to the other. So, the size of the *OM* may be changed by the number of short-circuit conditions. A large *OM* indicates that a large number of short-circuit conditions will have to be detected by the monitoring system.

Equations (1)-(4) illustrate the process of obtaining the *OM.*

$$\mathrm{OM}\begin{bmatrix} \mathrm{B}_{1,1} & \mathrm{B}_{1,2} & \cdots & \mathrm{B}_{1,\mathrm{N_{bar}}} \\ \mathrm{B}_{2,1} & \mathrm{B}_{2,2} & \cdots & \mathrm{B}_{2,\mathrm{N_{bar}}} \\ \vdots & \vdots & \ddots & \vdots \\ \mathrm{B}_{\mathrm{N_{Tot\text{-}Sh}},1} & \mathrm{B}_{\mathrm{N_{Tot\text{-}Sh}},2} & \cdots & \mathrm{B}_{\mathrm{N_{Tot\text{-}Sh}},\mathrm{N_{bar}}} \end{bmatrix} \quad (1)$$

$$B_{i,j}=\begin{cases} 1 & \begin{matrix} V_{PUmin(i,j)} < V_{PUmin} \\ or \\ V_{PUmax(i,j)} > V_{PUmax} \end{matrix} \\ & \\ 0 & \text{Otherwise} \end{cases} \quad (2)$$

$$V_{PUmin(i,j)} \;\; \min(V_{PUa,b,c(i,j)}) \quad (3)$$

$$V_{PUmax(i,j)} \;\; \max(V_{PUa,b,c(i,j)}) \quad (4)$$

Where:

- *OM*: Observability matrix;
- $B_{i,j}$: Binary value at bus *j* due to short-circuit condition *i*;
- $N_{Tot\text{-}Sh}$: Total number of short-circuit conditions;
- N_{bar}: Total number of buses in the system;
- $V_{PUmin(i,j)}$: Minimum PU value for the voltage at bus *j* for short-circuit condition *i*;
- $V_{PUmax(i,j)}$: Maximum PU value for the voltage at bus *j* for short-circuit condition *i*;
- V_{PUmin}: Minimum limit value for the voltage in PU;
- V_{PUmax}: Maximum limit value for the voltage in PU;
- $\min(V_{PUa,b,c(i,j)})$: Minimum value in PU for the voltage among phases a, b and c at bus *j* for short-circuit condition *i*;
- $\max(V_{PUa,b,c(i,j)})$: Maximum value in PU for the voltage among phases a, b and c at bus *j* for short-circuit condition *i*.

As the *OM* stores all the short-circuit conditions needed to characterize the power network regarding voltage sags and swells, there might be some cases where the voltage does not varies beyond the pre-established limits. Thus, the *OM* can be reduced by eliminating the rows containing only null values, in order to store only the relevant short-circuit conditions. This procedure originates a *Reduced Observability Matrix (ROM).*

III. Hybrid Method: Obtaining Short Circuit Conditions

The concept of a hybrid method bases upon the setting up of a predefined number of short-circuit conditions adequately distributed according to the probabilistic variables involved, by respecting their corresponding probability distributions. Random variables related to short-circuit are as follows: fault location, fault type and impedance fault.

The *HM* comprises two types of methods, namely:

- Monte Carlo method, in which random numbers are generated to form possible network states [5];
- State enumeration, in which all possible combinations of random variables with corresponding probabilities are previously defined. Continuous random variables must be converted into discrete variables, by dividing their possible

range into intervals [11].

The *HM* follows the Monte Carlo method, though utilizing some State Enumeration for some specific variables.

In assessing the indices regarding voltage sags and swells, one has to establish the distribution of short-circuit conditions. This paper shows various criteria, which are shown herein over the following items so that the overall computation time tends to be decidedly diminished [12].

A. Network Reduction

Network reduction is a procedure to group various network branches into a single representative one. In such manner, the network decreases in size, i.e. number of buses and branches decreases without affecting final simulation results. This reduction is particularly useful in distribution networks.

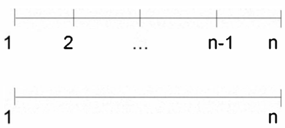


Fig. 1 - Criterion for network reduction

Fig. 1 shows the criterion for network reduction, which is particularly convenient for distribution networks that have a fairly geographical representation of buses and branches. In this figure, one notices that the set of branches 1:2, 2:3,...,n-1:n is reduced to a single branch 1:n. The equivalent values corresponding to the branch length, impedance and fault rate are achieved through Equations (5)-(7).

$$L_{1-n} = L_{1-2} + \ldots + L_{n-1,n} \tag{5}$$

$$Z_{1-n} = Z_{1-2} + Z_{2-3} \ldots + Z_{n-1,n} \tag{6}$$

$$\lambda_{1-n} = \frac{\left(\lambda_{1-2} \times L_{1-2} + \lambda_{2-3} \times L_{2-3} + \ldots + \lambda_{n-1,n} \times L_{n-1,n}\right)}{L_{1-n}} \tag{7}$$

Where:

- L_{1-n}: Length of equivalent branch between buses 1-*n*;
- L_{i-j}: Length of branch between buses *i* and *j*;
- Z_{1-n}: Impedance of equivalent branch between buses 1-*n*;
- Z_{i-j}: Impedance of branch between buses *i* and *j*;
- λ_{1-n}: Equivalent fault rate between buses 1-n;
- λ_{i-j}: Fault rate of branch between buses *i* and *j*.

The network reduction also takes into account that:

- The transformers and their corresponding buses should not be eliminated;
- The derivation buses should not be eliminated;
- The supply buses and the charge buses should not be eliminated.

B. Grouping based on length: More and Less Prevailing Groups

Following network reduction, a grouping procedure of network branches is carried out, regarding the lengths of each branch along the new reduced network. This criterion groups reduced branches within a length range. Each group will be added to a list called *LGr*.

Aiming at reducing the computational effort, the *LGr* are reallocated to two different lists called LGr_{Pre} and LGr_{NonPre}. Such reallocation allows for characterizing the length of the groups. Groups at very low length values in comparison to the total network length represent lower impact when compared to a higher length values.

$$L_{Gr(i)} = \sum_{j=1}^{N_{Gr(i)}} L_{(j)} \tag{8}$$

Where:

- $L_{Gr(i)}$: Total group length *i*;
- $L_{(j)}$: Length of each element *j* in group *i*;
- $N_{Gr(i)}$: Number of elements in group *i*.

In order to carry out the reallocation pursuant to the 'Prevailing' criterion for the groups' length value, the ratio between each group value and the network total length value is analyzed, following the equation:

$$L_{GrMin} = P_{min}\% \,.\, L_{GrTot} \tag{9}$$

$$L_{GrTot} = \sum_{i=1}^{N} L_{Gr(i)} \tag{10}$$

Where:

- N: Total number of groups;
- L_{GrMin}: Minimum length for the Group to be considered Prevailing;
- L_{GrTot}: Sum of all lengths for the groups on hand;
- $P_{min}\%$: Minimum percentage of total sum of the groups on hand.

Those *LGr*, which length is shorter than L_{GrMin}, will be reallocated to LGr_{NonPre}. Those *LGr*, which length is longer than or equal to L_{GrMin}, will be reallocated to LGr_{NonPre} will be reallocated to LGr_{Pre}.

C. Elaborating a set of short-circuits conditions

After getting acquainted with LGr_{Pre} and LGr_{NonPre}, the total number of simulations (conditions for short-circuits) for each element in each group must be distributed. In order to do that and bearing the length value and the fault type in mind, the following steps are to be followed:

Step1: *Number of conditions for short-circuits for each Group*

The process of distribution is carried out after fixing the total number of conditions for short-circuits $N_{Tot\text{-}Sh}$ one wishes to simulate. The number of conditions for short-circuits for each group, be it Prevailing or Non-Prevailing, depends on the ratio between each group's length value and the total length value of *LGr*, that is:

$$N_{Sh-Gr(i)} = N_{Tot-Sh} \times \frac{L_{Gr(i)}}{L_{GrTot}} \tag{11}$$

Where:

- $N_{Sh\text{-}Gr(i)}$: Number of short-circuits corresponding to Group i;
- $N_{Tot\text{-}Sh}$: Total Number of short-circuits for a simulation;
- $L_{Gr(i)}$: Length value for group i;
- L_{GrTot}: Total length value for *LGr*.

Step 2: *Number of conditions for short-circuits in each Group by fault type*

Once the number of conditions for short-circuits (N_{Sh-Gr}) for each Group is known, the following step is to distribute this number by each fault type. Such procedure is both applied for Prevailing and Non-Prevailing Groups. In this case, the distribution of probability is considered for each fault type.

$$N_{Sh-TF(f)(i)} = N_{Sh-Gr(i)} \times \mathrm{Prob}_{(\mathrm{f})} \tag{12}$$

Where:

- f: Index for fault type (three-phase, phase-to-ground, double phase-to-ground and double phase);
- $N_{Sh-TF(f)(i)}$: Number of short-circuits for fault type f corresponding to Group i;
- $Prob_{(j)}$: Probability associated to fault type f.

After taking Step 2, the number of conditions for short-circuits corresponding to each group by fault type (N_{Sh-TF}) is made known.

The number of conditions for short-circuits for the impedance variables of fault and fault point may be achieved by following the criteria herein:

a) Achieving the fault impedance:

The criterion followed for the number of short-circuits for fault impedance will be set apart based on the Group under analysis, whether prevailing or not. The number of fault impedance values will be the same N_{Sh-TF} as the one achieved before.

Prevailing Groups

For these groups, the criterion utilized converts the fault impedance variable into a discrete variable in ranges from zero up to a maximum value, stipulated to the fault type.

$$Z_{TF(f)} = \frac{(k-1)}{N_{Sh-TF(f)(i)}} \times Z_{TF-Max(f)} \tag{13}$$

Where:

- i: Group index;
- k: Fault type index, k=1,..., $N_{Sh-TF(f)(i)}+1$
- $Z_{TF-Max(f)}$: Maximum fault impedance value for fault type f(Ω);
- $Z_{TF(f)}$: Fault impedance value for fault type f (Ω);

For the double phase to ground faults case, in which there are fault impedances among phases and between phase to ground, the fault impedance value among phases will follow the same criterion previously explained. For the impedances between phase to ground, the value will be randomly achieved (deriving a random number) between zero and the maximum value.

Non-Prevailing Groups

As for non-prevailing groups, the fault impedance, ranging from 0 to a maximum value according to the fault type, will be determined by random generation.

b) Achieving the position of the Fault Point

Based on the number of short-circuits for each Group by fault type, be it Prevailing or Non-Prevailing, $N_{Sh-TF,}$ the branches must be determined (on the reduced network) where the fault takes place. The choice for the branch in the Group under analysis will be randomly carried out.

As long as the reduced branches include sets of original branches, the choice for the original branch is also randomly carried out. Following that, the choice for the fault point within this branch is also randomly carried out.

For illustration Fig. 2 sake, the shows a Group k of branches from the reduced network, from which the branch Lin_{R1-5} was randomly selected. Randomly chosen from branch Lin_{R1-5} are the original branch Lin_{2-3} and the fault point on this branch.

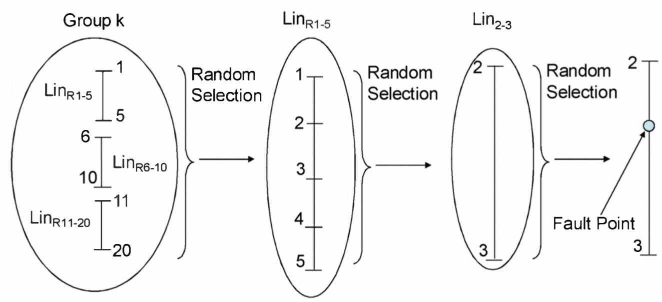


Fig. 2 - Achieving the fault point by using the hybrid method

D. Stipulating the number of conditions for short-circuits

‘ In order to achieve the number of conditions for short-circuits (N_{Tot-Sh}), one stipulates a value that allows for carrying out the minimum required distribution for each considered variable:

$$L_{Tot-Gr} = \sum_{i=1}^{N} L_{Gr(i)} \tag{14}$$

$$L_{\min-GrPre} = \underset{j=1}{\overset{Npre}{Min}} \left(L_{GrPre(j)}\right) \tag{15}$$

$$K_{L-Min} = \frac{L_{\min-GrPre}}{L_{Tot-Gr}} \tag{16}$$

$$K_{\mathrm{Prob}-Min} = \underset{k=1}{\overset{4}{Min}}(\mathrm{Prob}_{(\mathrm{k})}) \tag{17}$$

$$N_{Sh-Net} = \frac{N_{\mathrm{Fx-Min}}}{K_{L-\min} \times K_{\mathrm{Prob-Min}}} \tag{18}$$

Where:

- N: Number of LGr;
- N_{pre}: Number of LGr_{Pre};
- $L_{Gr(i)}$: Total length for Group i;
- $L_{GrPre(j)}$: Total length for Prevailing Group j;
- $L_{min-GrPre}$: Minimum length of LGr_{Pre};
- L_{Tot-Gr}: Total length resulting from the sumo f all groups;
- K_{L-Min}: Coefficient for minimum length;
- $Prob_{(k)}$: Distribution of probability for fault type k;

- $K_{Prob\text{-}Min}$: Coefficient for minimum probability by fault type;
- $N_{Fx\text{-}Min}$: Minimum number of ranges for the fractioning of fault impedance;
- $N_{Sh\text{-}Net}$: Number of simulations or conditions for short-circuits utilized in the Hybrid Method.

Once branch length values and the probability for fault types are pre-stipulated, the number of simulations required for the Hybrid Method is directly related to the minimum number of ranges chosen for turning discrete some possible values for fault impedance. The higher the minimum number of ranges, the higher the number of simulations will be.

IV. Evolutionary Algorithm Applied To The Problem Of Power Quality Monitor Allocation

The optimum power quality monitor allocation determines the positions where these devices should be installed, in order to maximize the monitored area over the power system that is being studied. Another way to put it would be through considering a given monitor; this should be installed in a bus that would allow it to "observe" the largest possible number of disturbances that may occur in the power network. This "observation" characteristic for a monitor installed in a certain bus in a power network defines the *Observability* concept that is used in this paper. The aim of this concept is to make possible the quantification of the monitoring reach for a given power quality meter installed in a certain bus of the power network, given the possible disturbances that may occur.

On the other hand, the determination of the minimum number of power quality meters aims to establish how many of them are required to monitor a whole power network with the lowest possible *Redundancy*. It means that, on the limit case (where each bus would be monitored by at least one meter), each possible disturbance that may occur in the power network should be "observed" by at least one of the installed monitors.

The determination of the minimum number of monitors and the optimal allocation of them are then linked together, since the minimum number of monitors is reached through the optimal allocation of them, i.e., by installing the monitors in strategic network buses (buses with the highest *Observability* capacities), the number of monitors required is reduced.

The use of GAs to formulate the solution for this problem characterizes an interesting alternative, given that the problem consists on determining the most suitable configuration of the monitoring system among the many possibilities for it. GAs provides a convenient framework to evaluate the possible configurations for the monitoring system alternatives. It allows the representation of different objectives (maximization of the *Observability*, minimizing the number of monitors required, minimizing installation costs, etc.), subject to specific constraints (buses where monitors may not be installed, customers that require monitoring, etc.). Such multi-objective optimization problem applied to real power networks cannot be simply solved by using conventional approaches, such as standard linear programming techniques.

GA is a sub-class of algorithms that is included in the Evolutionary Algorithms (EAs). EA is considered a metaheuristic optimization algorithm, which uses natural selection, mutation and recombination processes they are based on analogies with genetics, to introduce variations among the possible solutions of a specific optimization problem. The main differences between EAs and GAs rely on the size of the population, crossover and mutation operators, and on the codifications adopted [13].

During the GA execution, populations of individuals are generated at different stages, and each population corresponds to a set of possible solutions to the problem being studied. Basically, at a specific stage, each possible solution is evaluated, in order to verify which one is the fittest solution.

A GA´s individual is "chromosome" that carries information defining its own characteristics ("genes"). In GAs, the chromosome is represented by a *string*. So, the main function of the GA is to adapt the *strings* of each individual through the manipulation of the data stored in its genes, in a way that does not disrespect the problem´s constraints.

A. Chromosome

In order to represent a possible configuration of the monitoring system, the chromosome´s structure will use an integer codification. Each gene stores a value corresponding to the index of a network bus where the installation of a power quality monitor is possible. The structure of the genetic chain used is illustrated in Fig. 3.

Bus_1	Bus_2	…	$Bus_{N_M\text{-}1}$	Bus_{N_M}

Fig. 3 - Chromosome Structure

The number of genes (which corresponds to the number of monitors N_M) is fixed at the beginning of the evolutionary process.

B. Generation of the Initial Population

In order to obtain feasible configurations for the monitoring system, the values for the genes that compose the individuals´ chromosome of the initial population are randomly chosen. The value to be assigned to each gene is chosen among the indices of the buses where the installation of the power quality monitor is possible to be executed.

C. Fitness Function

In order to estimate the quality of each individual during the evolutionary process, each configuration for the monitoring system is evaluated according to two relevant aspects. Firstly, the individual is evaluated according to its *Observability*, i.e., according to the number of short-circuit conditions in the *ROM* that are detected by the configuration suggested by the individual. The higher is the number of short-circuit conditions detected by the monitoring system; the better is the evaluation of its corresponding individual.

Secondly, each individual is evaluated according to the redundancy of the monitoring system. Due to the structure of the chosen chromosome, one specific individual may have the same bus in some of its genes. Physically, this situation would suggest the installation of more than one monitor in the same bus of the system. Such condition is not needed in reality because there is no need to have more than one monitor installed in the same bus of the system. These redundant monitors were not considered for defining the total number of monitors needed for the monitoring system. Thus, the higher is the redundancy, the higher is the number of monitors not considered, and the lower is the number of monitors needed to monitor an entire power network with the same *Observability*.

Observability Index

This index correlates the number of simulated short-circuits detected by an individual with the total number of simulated short-circuits considered to characterize the entire power network regarding voltage sags and swells. In order to calculate this index, one has to evaluate every row in the *ROM*. For each row (short-circuit condition), one checks if there is at least one element equal to 1 in the same position of the column given by the individual´s chromosome. In case the element of the corresponding column is 1, the number of detected short-circuits should be incremented by 1. Equation (19) illustrates the index.

$$I_{Obs}(k) \quad \frac{N_{Sh\text{-}k}}{N_{Tot\text{-}Sh}} \tag{19}$$

Where:
- $I_{Obs}(k)$: Obvervability index for individual k;
- $N_{Sh\text{-}k}$: Number of short-circuits detected by individual k;
- $N_{Tot\text{-}Sh}$: Number of rows in the *ROM* (total number of simulated short-circuits).

Redundancy Index

This index corresponds to the relation between the genes that present different values and the total number of genes of each individual. Equation (20) illustrates the index.

$$I_{Red}(k) \quad \frac{N_{M\text{-}k}}{N_{M\text{-}Tot}} \tag{20}$$

Where:
- $I_{Red}(k)$: Redundancy index for individual k;
- $N_{M\text{-}k}$: Number of genes or different monitors inside the chromosome of individual k;
- $N_{M\text{-}Tot}$: Total number of genes or monitors of individual k.

Finally, the fitness function which should be minimized is given by Equation (21):

$$min(FA(k)) = [1 - I_{Obs}(k)] \times F_{Obs} + I_{Red}(k) \times F_{Red} \tag{21}$$

Where:
- $FA(k)$: Fitness function for individual k;
- F_{Obs}: Importance factor for *Observability*;
- F_{Red}: Importance factor for *Redundancy*.

D. Selecting the Best Configurations

When applying the GA to such an optimization problem, the lower is the fitness function assigned to a chromosome, the better the allocation is fitted or adjusted to the problem. This implies that such chromosome has a greater chance to survive for future generations. And in the following generation(s), it will have the skill to produce even better descendants. The selection process makes use of tournament and elitism:

Tournament

The configurations are selected by means of tournaments. The number of applied tournaments is equal to the size of the population, what makes this procedure significantly different from the proportional selection, normally used for the Canonical GA. At each tournament, a set of T_k configurations is randomly chosen and the winning configuration is that one with better fitness function. A total of n tournaments generate a population of n individuals. The value of T_k is generally small, typically $T_k \in \{2, 3, 4\}$.

Elitism

The elitism procedure is carried out before the recombination procedure. In each generation, a percentage of the best determined solutions, E_{tk}, is considered as the local elite. During the iterative process of the algorithm, those better quality configurations are preserved to form the set of global elite E_{TG}. The global elite set receives configurations from good quality configurations in each local elite set.

D. Recombination

The recombination procedure is executed after the evaluation of the individuals of an entire population, at a specific iteration of the GA. Basically, it selects two individuals from the population, where one is randomly chosen from the subset E_{tk}, and the other one is randomly chosen from the rest of the population (disregarding the subset E_{tk}).

In this paper, the adopted recombination procedure assures the preservation of the genetic information of their antecessors. In order to do so, two aspects were followed during the execution of the recombination procedure:

i – Individuals generated through the recombination procedure must have genes similar to their parents;

ii – Genes that differ from the ones of the parents have 50% probability of being switched, depending on their positions. So, considering N_{gd} as the number of different genes, the number of possible switchings becomes (N_{gd} -1), in order to avoid returning to the initial configuration of the parents. A random number is evaluated ($y_{Tro} \in [0,1]$) for each possible gene switching. If $y_{Tro} \leq 50\%$, the switching is executed between the parents. Fig. 4 illustrates the recombination procedure.

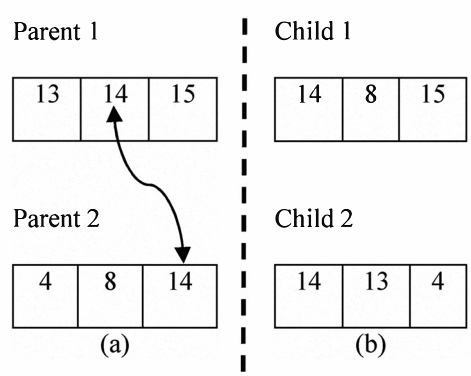


Fig. 4 - Recombination process: (a) Before and (b) After recombination

E. Mutation

After the recombination, the mutation is carried out among the individuals of a population. The mutation procedure has a special influence for the GA because it helps the GA to avoid local minima (premature convergence). The gene that suffers mutation is randomly selected. The value to be stored in the selected gene is also randomly selected among the values corresponding to the indices of the buses where power quality monitors may be installed. Through this criterion the value of a bus already present in the chromosome could also be selected. This particular situation would contribute towards the increase of the redundancy for the monitoring system.

E. Control Parameters in GA

The recombination and mutation rates are dynamically varied during the generations. The dynamic variation of these parameters in the GA depends on the presence of the fittest solution through the generations. In other words, in the beginning, if the process finds a new value of the fittest solution, the recombination rate assumes its highest value and the mutation rate assumes its lowest value. During the final generations, when the fittest solution does not alter after a pre-established number of generations, the value of the recombination rate assumes its lowest value, whereas the value of the mutation rate assumes its highest value.

The following equations show how the described criteria are applied:

$$\rho_R = \rho_R^{max} - \frac{N_c}{N_c^{max}} \times \left(\rho_R^{max} - \rho_R^{min}\right) \tag{22}$$

$$\rho_M = \rho_M^{max} + \frac{N_c}{N_c^{max}} \times \left(\rho_M^{max} - \rho_M^{min}\right) \tag{23}$$

Where:

- ρ_R : Recombination rate;
- ρ_R^{min}: Minimum recombination rate;
- ρ_R^{max}: Maximum recombination rate;
- ρ_M : Mutation rate;
- ρ_M^{min}: Minimum mutation rate;
- ρ_M^{max}: Maximum mutation rate.

F. Criterion for diversification

An unfavorable characteristic of EAs is its strong attraction for local optima, provoked by a population submitted to the selection mechanisms. The lack of diversity is one of the principal factors for this event. Observing this problem, a mechanism was adopted to preserve a minimum degree of diversity in the population for each generation.

The diversification of a population can be determined by the following equation:

$$D_{iv}(\%) = (1 - \frac{\#C_{Mig}}{Pop})x100 \tag{24}$$

Where:

- *Div*: Diversification (%);
- $\#C_{Mig}$: Maximum number of equal configurations;
- *Pop*: Total number of configurations in the population.

Diversification during the Recombination

In order to maintain this diversity before carrying out the proposed recombination, half of the local elite set, E_{tk}, is exchanged by another subset of the global elite set, E_{TG}, every time saturation is achieved, i.e. when configurations in the local elite set present the same fitness function values.

Diversification during the Mutation

Another mechanism that favors an efficient way out from saturation is applied before mutation. Similarly to the process used in the recombination, the recombined configurations are analyzed. If the number of equal configurations surpasses half the total number of configurations, i.e. D_{iv} is greater than a pre-established percentage (*x%*), then the mutation rate is assigned a high value, so as to improve the diversity of the configurations. This conversely tends to increase the average fitness function of the population. The mutation rate returns to its original value, after saturation is no longer present in the population.

G. Stop Criterion

The stop criterion is based on the average value of the fitness function for the elite set E_{TG}. If its value does not improve after a given maximum number of generations (N_{Cmax}), the process is assumed as converged.

V. Results

In order to illustrate the methodology herein proposed, a real distribution network was utilized, as presented in Fig. 5. This is a 25.4 km distribution network, comprising 426 buses and 104 consumers.

Fig. 5 presents 9 different areas where power quality monitors may be installed for that specific power distribution network.

The following parameters were utilized in the simulation:

a) Fault rate for each branch: 0.0533 fault/km/year.
b) Probability distribution per fault type: 5% Three-phase faults, 10% Double phase faults, 10% Double phase-to-ground faults and 75% Phase-to-ground faults.
c) For the fault impedance, the following maximum values based on the short-circuit type were considered: 10 Ω Three phase faults (impedance/phase), 30 Ω Phase to ground faults, 20 Ω Phase to phase fault (impedance among phases) and 10 Ω Double phase to ground faults (impedance among phases) and 30 Ω (impedance to ground).
d) Short-circuit power at the substation: Three phase = 300.2 $\underline{|88.09^{\circ}}$ MVA, Single phase = 250.2 $\underline{|87.7^{\circ}}$ MVA.

The control parameters for the GA, considering dynamic recombination and mutation rates as well as diversity control are shown in the Table I.

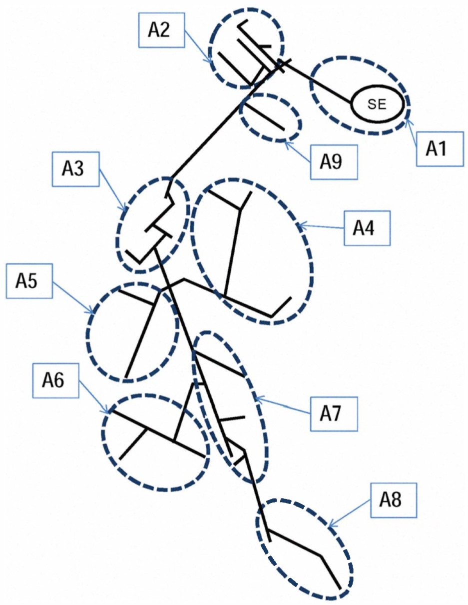


Fig. 5 - One-line diagram of a real power distribution feeder containing 9 different areas to be considered for the installation of monitoring equipment

The computational system used in all the tests was a 2.2 GHz Core 2 Duo CPU with 4 GB RAM.

Table I: Control parameter for the evolutionary algorithm

F_{Obs}	F_{Red}	ρ_R^{min}	ρ_R^{max}	ρ_M^{min}	ρ_M^{max}	T_k	E_{Tx} (%)	E_{TG} (%)
10000	1	0.1	0.9	0.01	0.5	2	30	40

The initial configurations for the individuals were randomly generated (400 poputation). In all the tests, voltage limits used to build the OM were 0.95pu for V_{PUmin} and 1.05pu V_{PUmax}. The diversity limit $D_{iv}x$ was set to 30%. The stop criterion uses $N_c^{max} = 50$.

Test Case #1

Test Case #1 was executed first considering a configuration for the monitoring system in which monitors could be installed only on areas A1, A2, A7 and A8.

In order to assess the impact of the random variable $N_{Fx\text{-}Min}$ was varied to {1, 5, 10 and 100} (minimum number of ranges for discretizing the fault impedance) for the short-circuit simulations by the *HM* in order to obtain I_{Obs} and I_{Red}. Results are shown in Table II.

Table II: Impact of the fault impedance in a possible configuration for the monitoring system

$N_{Fx\text{-}Min}$	$N_{Tot\text{-}Sh}$	$N_{Tot\text{-}ShR}$	$N_{ShC\text{-}k}$	I_{Obs}	I_{Red}	*Time (s)*
1	1934	449	442	0.984	1	2
5	9675	2187	2140	0.979	1	10
10	19349	4335	4253	0.981	1	21
100	19349	43149	42250	0.979	1	210

From Table II, one can notice that the values for I_{Obs} are very close when $N_{Fx\text{-}Min}$ is 10 or 100. However, for $N_{Fx\text{-}Min}$ equal to 10, the processing time is lower (21 s). Due to this advantage, this value was used when defining the *ROM* for the following test cases.

Fig. 6(a) presents the configuration achieved considering only 4 monitors to be installed in the system. Fig. 6(b) shows the areas containing the buses that will be affected by voltage sags and that will not be detected by any of the 4 monitors. The total number of non-monitored buses is 80, which corresponds to 18.8% of the total number of buses in the power distribution network being studied.

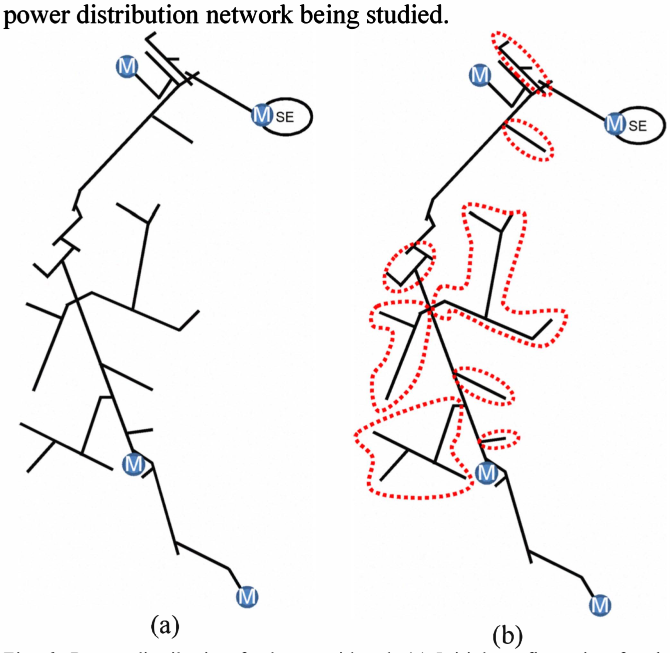


Fig. 6- Power distribution feeder considered: (a) Initial configuration for the monitoring system (b) Areas where some short-circuit conditions are not detected by the monitoring system.

Test Case #2

For this test case, $N_{Fx\text{-}Min}$ is set to 10, 1 monitor is installed at the substation bus, and 3 monitors can be installed at any other buses of the system. Table III shows the best two configurations achieved by the GA.

Table III: Results from the best two monitoring configurations achieved, for Test Case # 2

Configurations	*Installation Areas*	*FA(k)*	I_{Obs}	I_{Red}	*Time (min)*
1	A1, A4, A6, A8	75	0.9926	1	4.0
2	A1, A4, A6, A7	80	0.9921	1	

Observing Table III one can notice that changing the buses where the monitor is installed can improve the value for I_{Obs} and reduce the size of the areas (number of buses) which will be detected by that monitoring system. Fig. 7 illustrates the improvement achieved in Test Case #2.

In Fig. 7, the total number of non-monitored buses is 62, which corresponds to 14.6% of the total number of buses. This corresponds to an improvement of 4.2%, when compared with Test Case #1. So, by re-allocating the same number of monitors, the *Observability* indices can be improved in the same distribution network.

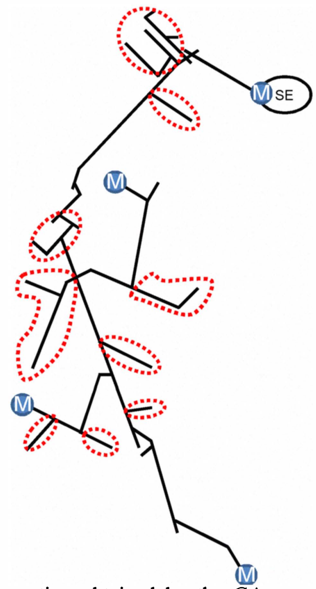


Fig. 7 – Final configuration obtained by the GA , considering 1 monitor installed at the substation bus and 3 monitors to be installed at any other bus.

Test Case #3

For this test case, two different simulations were carried out. Firstly, a Monte Carlo approach was used. Thus, instead of using the *HM* for defining the *OM*, a State Enumeration Method (*SEM*) was used, similarly to the one used by the authors of [14]. On the second simulation, the *HM* was used for defining the *OM*. All short-circuit conditions should be detected in both simulations.

Basically, for the first simulation, all types of faults being considered were independently simulated at every power network bus and at every 10% of each branch (after the network reduction), and twenty different values for the fault impedance were considered for each types of fault; for example, {1.5, 3.0, 4.5, …., 30} to phase to ground faults. So, a total of 111,000 short-circuits were simulated, from which only 25,514 originated voltage sags/swells in at least one bus of the power network. These 25,514 short-circuit cases were then used to define the *ROM*, which was used by the GA to define the best configuration for the monitoring system. The GA achieved a configuration for the monitoring system that is composed by 15 monitors, which should be installed accordingly to the configuration illustrated in Fig. 8 – (a).

For the simulation using the *HM*, 1 monitor is installed at the substation bus, and an unlimited number of monitors can be installed at any other buses of the system. The same number of short-circuit conditions were considered (111,000), but for this case only 31,141 originated voltage sags/swells in at least one bus of the power network. The GA achieved a configuration for the monitoring system that is composed by 20 monitors, which should be installed accordingly to the configuration illustrated in Fig. 8 – (b).

The number of monitors increased because the *HM* executed the simulation of more relevant short-circuits, which were not considered through the *SEM*. As the *HM* takes into consideration the probabilistic aspect of the fault impedance, more values for the fault impedance are considered. For example, while the *SEM* takes into consideration only 1.5Ω, 3.0Ω, 4.5Ω,…, 30Ω for phase to ground faults, for each combination of fault position; the *HM* may also consider 0.5Ω and 0Ω. Due to these different fault impedance values, the number of buses that suffer voltage sags/swells might be higher, affecting buses that are not affected for the same combination of fault type and fault position, but with 1.5Ω as fault impedance. As a result, when the *GA* uses the *OM* defined by the *HM*, the number of monitors tend to increase, in order to guarantee that all buses affected by voltage sag/swell be monitored.

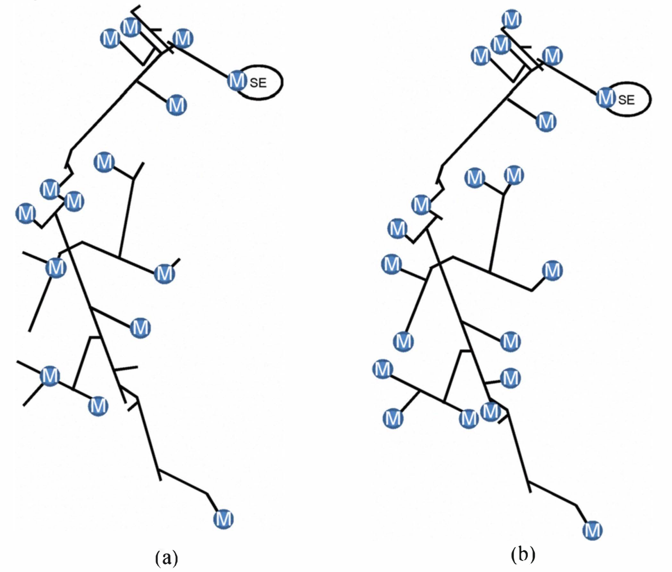


Fig. 8 – Best configurations for the monitoring system. (a) Configuration achieved by using the Enumeration method to define the *OM*. (b) Configuration achieved by using the *HM* to define the *OM*.

In Fig. 9, illustrates Fault positions that originated voltage sags/swells which were not monitored by any of the 15 monitors suggested by the SEM and the Buses where voltage sags/swells may occur without being monitored by any of the 15 monitors suggested by the SEM.

Table IV shows the best three configurations achieved by the GA considering the *HM* to define the *OM*.

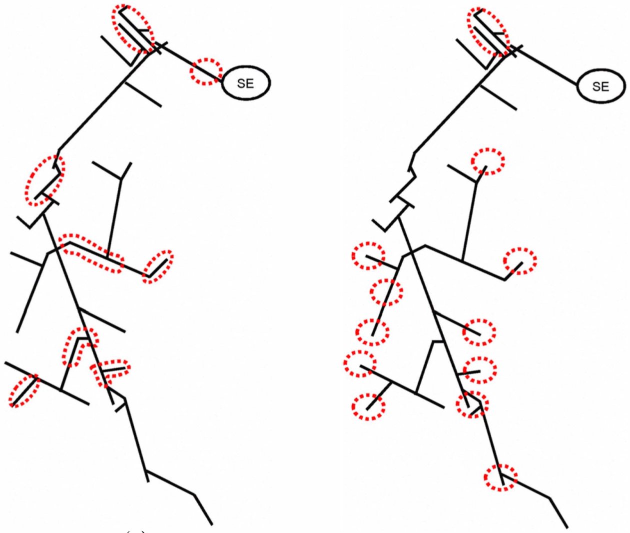
VI. Conclusions

This paper presents a methodology which provides the minimum number of monitors needed to detect voltage sags and swells due to short-circuits in distribution networks. The methodology defines the optimal location of each monitor, in order to maximize a detection capability index.

The *HM* was used for defining an *OM* with the most likely short-circuit conditions than may happen on a power distribution network, avoiding the simulation of non-relevant short-circuits.

Then, after the definition of the *OM*, a GA was used to search for the best monitoring configuration. Different number of monitors and installation positions are simultaneously considered in order to determine which would be the best configuration, according to the problem restrictions.

This methodology may also be used when only acquiring part of the ideal number of monitors needed to monitor the whole network. For such condition, the methodology would suggest the installation of the limited number of monitors in strategic points of the system, maximizing the *Observability* index.



(a) (b)

Fig. 9 – (a) Fault positions that originated voltage sags/swells which were not monitored by any of the 15 monitors suggested by the *SEM*. (b) Buses where voltage sags/swells may occur without being monitored by any of the 15 monitors suggested by the *SEM*.

Table IV: Three best monitoring configurations achieved by the GA considering the HM to define the OM.for in Test Case #3

	NUMBER OF MONITORS PER AREA		
	#1	**#2**	**#3**
A1	1	1	1
A2	4	4	4
A3	2	2	2
A4	3	3	4
A5	2	2	2
A6	3	4	3
A7	3	3	3
A8	1	1	2
A9	1	1	1
Total # of Monitors	20	21	22

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