# OPTIMAL VOLTAGE SAG AND SWELL MONITORING THROUGH GENETIC ALGORITHMS, FUZZY MATHEMATICAL PROGRAMMING AND STOCHASTIC SIMULATION OF SHORT-CIRCUITS

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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 power 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.*

*The methodology considered the IEEE 30-bus network in order to evaluate its performance.*


## INTRODUCTION

As voltage sags and swells are caused by unpredictable factors, the literature suggests the installation of a power quality monitor in each bus of a power system where measuring voltage sags and swells is relevant [1]. The inconvenient of this technique is the number of devices required, and the high capability of the equipment to analyze the large amount of data to be captured. Thus, the evaluation of power quality becomes an expensive activity. In this context, a methodology that determines the minimal number of power quality meters to monitor a power network, and that defines the buses where these meters should be installed becomes an interesting alternative.

The determination of the minimum number of meters and their optimal allocation are linked together. In other words, the minimum number of meters is reached through their optimal allocation, i.e. by installing the meters in strategic buses (buses with the highest The main idea of this work is to find out a configuration of meters (with lowest possible number of meters), from which any of the short-circuit conditions used to characterize the network may the determined. In order words, the meters should be installed at some specific buses from which, considering only the voltage values, one could determine the short-circuit condition most probable of having occurred. Through this approach, it is possible to estimate the voltage values at non-monitored buses.

## METHODOLOGY

### Observability Matrix

The response of the 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 the next section.

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 $N_{bar}$. $N_{bar}$ 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.

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

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

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

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

Where:

- $B_{i,j}$: Binary value at bus j due to short-circuit condition i;
- $V_{PUmin(i,j)}$: 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).

## Hybrid Method: Short-Circuit Conditions

The concept of a HM 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. Further information about the HM can be found in [2].

**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. Fig. 1 shows the criterion for network reduction. 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).

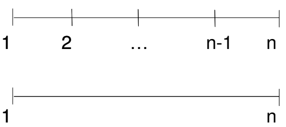


Fig. 1 - Criterion for network reduction

$$L_{1-n} = L_{1-2} + ... + L_{n-1,n} \quad (5)$$

$$Z_{1-n} = Z_{1-2} + Z_{2-3} ... + Z_{n-1,n} \quad (6)$$

$$\lambda_{1-n} = \frac{(\lambda_{1-2} \times L_{1-2} + \lambda_{2-3} \times L_{2-3} + ... + \lambda_{n-1,n} \times L_{n-1,n})}{L_{1-n}} \quad (7)$$

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*;
- $\lambda_{1-n}$: Equivalent fault rate between buses 1-n;
- $\lambda_{i-j}$: Fault rate of branch between buses *i* and *j*.

**Elaborating a set of short-circuits conditions**

The number of conditions for short-circuits for each group depends on the ratio between each group's length value and the total length value of $L_{Gr}$, that is:

$$N_{Sh-Gr(i)} = N_{Tot-Sh} \times \frac{L_{Gr(i)}}{L_{GrTot}} \quad (8)$$

Where:
- $N_{Sh-Gr(i)}$: Number of short-circuits corresponding to Group i;
- $L_{Gr(i)}$: Length value for group i;

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.

$$N_{Sh-TF(f)(i)} = N_{Sh-Gr(i)} \times \text{Prob}_{(f)} \quad (9)$$

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*.

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

**Achieving the fault impedance criterion**

The criterion converts the fault impedance variable into a discrete variable in ranges from zero up to a maximum value.

$$Z_{TF(f)} = \frac{(k-1)}{N_{Sh-TF(f)(i)}} \times Z_{TF-Max(f)} \quad (10)$$

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);

**The Position of the Fault**

Based on the number of short-circuits for each Group by fault type $N_{Sh-TF}$, 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.

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

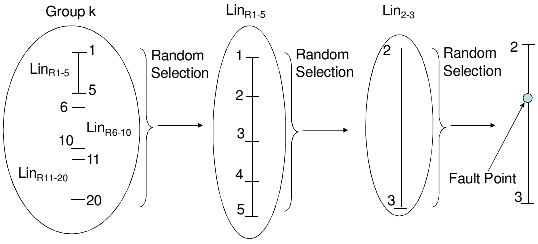


Fig. 2 - Achieving the fault point by using the hybrid method

**Number of Short-circuit Conditions**

In order to achieve the number of conditions for short-circuits ($N_{Tot\text{-}Sh}$), equations (11)-(15) stipulate a value that defines the minimum distribution required for each variable.

$$L_{Tot-Gr} = \sum_{i=1}^{N} L_{Gr(i)} \quad (11)$$

$$L_{\min-Gr} = \underset{i=1}{\overset{N}{Min}}(L_{Gr(i)}) \quad (12)$$

$$K_{L-Min} = \frac{L_{\min-Gr}}{L_{Tot-Gr}} \quad (13)$$

$$K_{\text{Prob}-Min} = \underset{k=1}{\overset{4}{Min}}(\text{Prob}_{(k)}) \quad (14)$$

$$N_{Sh-Net} = \frac{N_{\text{Fx}-\text{Min}}}{K_{L-\min} \times K_{\text{Prob}-\text{Min}}} \quad (15)$$

Where:

- $N$: Number of $LGr$;
- $L_{Gr(i)}$: Total length for Group $i$;
- $L_{min\text{-}Gr}$: Minimum length of $LGr$;
- $L_{Tot\text{-}Gr}$: Total length resulting from the sumo f all groups;
- $K_{L\text{-}Min}$: 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 HM.

Once branch length values and the probability for fault types are pre-stipulated, the number of simulations required for the HM 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.

## GA Applied to the Problem of Power Quality Monitor Allocation

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. Further information about GAs applied to this specific problem can be found in [4].

**Chromosome**

In order to represent a possible configuration of the monitoring system, the chromosome´s structure uses 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 number of genes (which corresponds to the number of monitors $N_M$) is fixed at the beginning of the evolutionary process.

**Fitness Function**

The Fuzzy Set Theory was applied to model the objectives related to the problem. Through this approach, the convergence of the GA was not be affected by the values of the objective functions related to the problem constraints.

The Fuzzy Set Theory can be used in decision problems [3], as it is the case of the allocation problem considered in this paper. Thus, the aim is to determine a solution that satisfies the objectives and the constraints in a symmetrical way. This is done through the application of membership-functions in the description of the problem's objectives and constraints.

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. Such aspect is quantified through an Observability Index.

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 present the same bus index in more than ones gene. These redundant monitors were not considered for defining the total number of monitors needed for the monitoring system. Such aspect is quantified through a Redundancy Index. Equations (16) and (17) illustrate how these indices can be obtained.

$$I_{Obs}(k) = \frac{N_{Sh\text{-}k}}{N_{Tot\text{-}Sh}} \quad (16) \qquad I_{Red}(k) = \frac{N_{M\text{-}k}}{N_{M\text{-}Tot}} \quad (17)$$

Where:

- $N_{Sh\text{-}k}$: Number of short-circuits detected by individual k;
- $N_{Tot\text{-}Sh}$: Number of rows in the ROM.
- $N_{M\text{-}k}$: 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.

The fitness function to be minimized is given becomes:

$$min(FA(k))=[1 - I_{Obs}(k)] \times F_{Obs} + I_{Red}(k) \times F_{Red} \quad (18)$$

Where:

- $F_{Obs}$: Importance factor for Observability;
- $F_{Red}$: Importance factor for Redundancy.

## RESULTS

In order to illustrate the methodology herein proposed, it was applied for the IEEE-30 Bus network [5].

The following parameters were considered for the simulations:

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) The fault impedance value used was 40 Ω for all short-circuit types.

d) Short-circuit power at the generators and synchronous condensers:
- Three phase = $2{,}000\angle 90^{o}$ MVA;
- Single phase = $2{,}000\angle 90^{o}$ MVA.

The initial configurations for the individuals were randomly generated. Each population was composed by 300 individuals. For all simulations, the voltage limits used to build the OM were 0.9pu for $V_{PUmin}$ and 1.1pu for $V_{PUmax}$. $N_{Fx\text{-}Min}$ was set to 200 (20,000 short-circuit conditions).

Two different simulations were executed. Table I show the best configurations for the monitoring system achieved by the GA considering the HM to define the OM. Configuration #1 is illustrated in Fig. 3. Thus, as the reader can notice, there is more than one solution for the allocation problem.

## CONCLUSIONS

The methodology proposed clearly shows the feasibility to completely observe power networks regarding voltage sags and swells without installing power quality monitors at every system bus, i.e., depending on the system´s topological characteristics, some few monitors can suffice to characterize the system performance related to short duration voltage variations.

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

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 at strategic points of the system, maximizing the Observability Index.

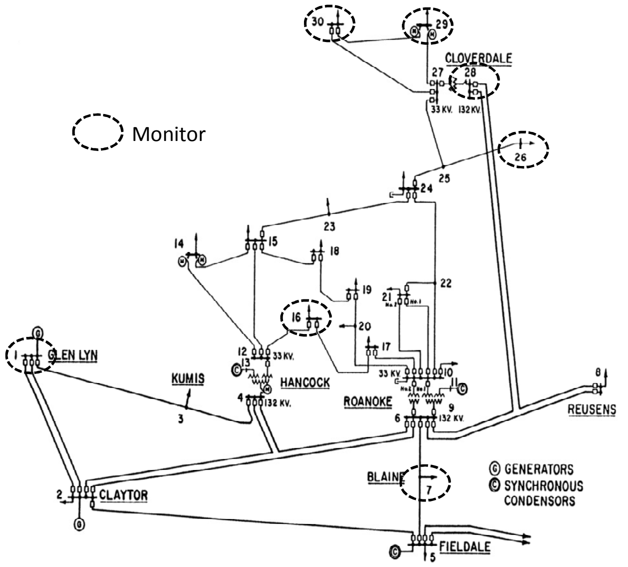


Fig. 3 - Best configuration for the monitoring system.

Table I: Best Configurations

| | Bus Number | | | | | | |
|---|---|---|---|---|---|---|---|
| ***Configuration #1*** | 1 | 7 | 16 | 26 | 28 | 29 | 30 |
| ***Configuration #2*** | 1 | 7 | 20 | 26 | 28 | 29 | 30 |

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