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An Algorithm for Optimal Placement of Voltage Sag Monitors

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Abstract

Voltage sags are disturbances that deserve special attention in power quality (PQ) area, given its frequent occurrences. Their constant monitoring is, therefore, essential to diagnose its causes and mitigate economic losses of electric utility customers. However, the cost of a monitoring system may be excessive if not evaluated strategically. In this context, this work presents an algorithm for the installation of PQ monitors at strategic points of electric power distribution systems in order to diagnose voltage sags. Observability area concept and binary particle swarm optimization method were used to evaluate the problem. A sensitivity analysis was also performed, in which the influence of several parameters, such as fault resistance, system loading, detection threshold, fault type, and system expansion, was evaluated. The algorithm was validated in a Brazilian distribution system and in IEEE 34-bus system. The results indicated that the algorithm was able to detect voltage sags throughout the system using monitors at few buses, reducing the cost of the monitoring system.

Keywords Power quality · Voltage sags · Observability · Binary particle swarm optimization · Sensitivity analysis

1 Introduction

The continuous increase in demand for electricity and in exigency of consumers for a better quality product has required investments in electrical power system improvement and research, particularly in power quality (PQ) area disturbances. According to Dugan et al. (2004), a PQ problem is defined as any problem in voltage, current or frequency variation that results in failure or misoperation of customer equipment. Among the PQ disturbances found in power systems, voltage sags are one of the most noticeable by customers (Mali et al. 2015) and their occurrence can trigger the protection devices, leading to shutdown of processes and equipment life cycle reduction. Therefore, the study of monitoring this phenomenon is a current and important topic for the state of the art.

In the context of PQ, the ideal monitoring would be the installation of equipment at all buses, but this approach is not economically feasible. Therefore, the use of techniques that minimize the number of monitors is crucial, since they can reduce the cost of monitoring and the redundancy of measured data, still contributing to minimize the effects of voltage sags in the system (Eldery et al. 2004).

In general, the problem of monitor placement at strategic locations can be solved by four main methods: monitor reach area (MRA), covering and packing (CP), graph theory (GT) and multivariable regression (MRV). Among the limitations are (Kazemi et al. 2013): CP presents as a response, a greater number of monitors; GT cannot be applied to transmission systems; the number of monitors is limited by a preset minimum and maximum quantity in MRV. Due to the continuous studies and reduction in its limitations, MRA became more suitable method among those mentioned and was chosen for the development of the work.

Analysis of the state of the art indicated that some research has been conducted in this regard. In Olguin and Bollen

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Table 1 Literature review

Author	System		Parameters				
	T	D	R	L	D_t	F	E
Olguin and Bollen (2003)	✓	–	–	–	–	✓	–
Olguin et al. (2006)	✓	–	–	–	–	✓	–
Almeida (2007)	✓	–	✓	–	–	✓	–
Juarez et al. (2009)	✓	–	–	–	✓	✓	–
Ibrahim et al. (2012)	✓	✓	–	–	✓	✓	–
Solano et al. (2015)	–	✓	–	–	–	✓	–
Bertho et al. (2016)	–	✓	–	–	✓	✓	–
Martins et al. (2018)	–	✓	–	–	✓	✓	–
Proposed algorithm	–	✓	✓	✓	✓	✓	✓

(2003) and Olguin et al. (2006), MRA concept was used for monitors placement at strategic locations from the simulation of three-phase short-circuits at the buses of transmission systems. In Almeida (2007), the increase in the database with simulations of symmetrical and asymmetrical short-circuits in transmission systems, for different fault resistance values, resulted in a more reliable solution. In Juarez et al. (2009), it was shown that using the MRA concept for simulated faults at the system buses, the monitoring system would not guarantee the detection of voltage sags along the transmission lines. In the work, a new MRA was proposed from remaining voltage along the lines for all fault types and evaluating different detection thresholds.

In Ibrahim et al. (2012), topological monitor reach area (TMRA) concept was presented, where the system topology was considered during monitor placement, making it applicable to both transmission and distribution systems. However, only single-phase faults and different detection thresholds were taken into account to solve the problem. In Solano et al. (2015), TMRA was used, simulating all fault types, to evaluate the impact of the reconfiguration of a distributed generation plant. Bertho et al. (2016) consider different fault types and thresholds to evaluate the variations in observability area of the monitors in a distribution system. And Martins et al. (2018) simulated single-phase solid faults and different detection thresholds to solve the problem of monitor placement in a distribution system with maximum capacity to identify unique events.

In this regard, this work presents an algorithm for installation of PQ monitors at strategic points of distribution systems to detect voltage sags. A sensitivity analysis was also performed, in which the influence of several parameters in phenomenon was evaluated, such as fault resistance (R), system loading (L), detection threshold (D_t), fault type (F) and system expansion (E). A summary of the analysis of state of the art is presented in Table 1, where T and D represent the transmission and distribution system, respectively.

This paper is divided into 7 sections, including this introductory section. In Sect. 2, the voltage sags characteristics and the technique used for its detection are described; in Sect. 3, the construction of the optimization problem as well as binary particle swarm optimization (BPSO) method used are presented; in Sect. 4, the proposed algorithm for optimal placement of monitors is presented; in Sect. 5, the results are indicated; in Sect. 6, comments are made and, finally, in Sect. 7, the conclusions are presented.

2 Voltage Sags Detection

A voltage sag is defined as a decrease between 0.1 and 0.9 pu in root mean square (RMS) voltage value from half-cycle of the fundamental to 1-min period (IEEE 2014). Voltage sags are caused by faults, switching of heavy loads, switching of capacitors etc., and may be classified as:

- instantaneous: 0.5 to 30 cycles;
- momentary: 30 cycles to 3 s;
- temporary: 3 s to 1 min.

According to EPRI (2003), about 90% of voltage sags have a voltage remaining between 0.5 and 0.85 pu and last less than 2 s; therefore, a special analysis with these characteristics is important. In Fig. 1, the characteristics of a voltage sag are shown. During a fault, their main cause, the occurrence of transients in its initial (fault occurrence) and final (protection and fault elimination) instants added to the randomness of this phenomenon make their detection a non-trivial task (Costa et al. 2010).

Among the various mathematical tools available for this purpose, discrete wavelet transform (DWT) was selected for

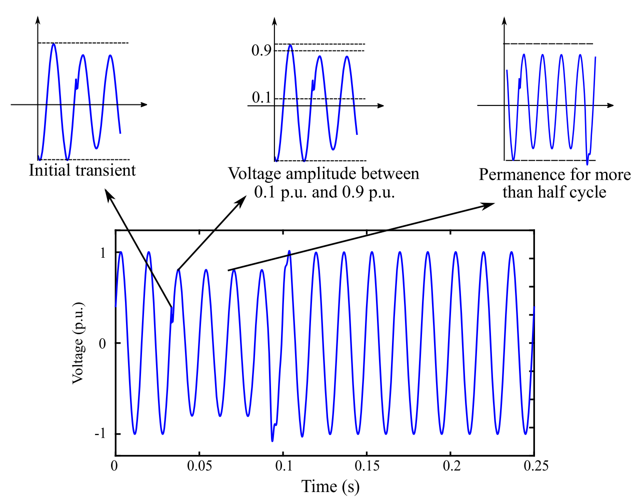

Fig. 1 Voltage sag characteristics

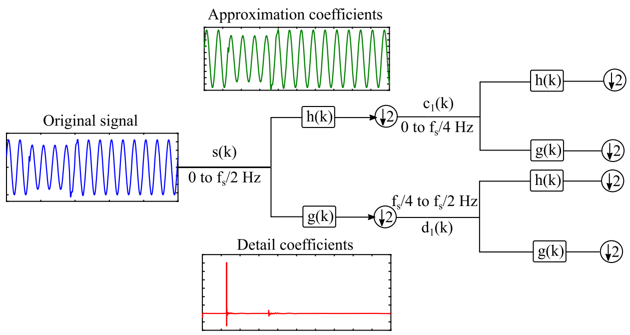

Fig. 2 Sub-sampling process of the DWT

development of this work, since it has been widely used in diagnostic of disturbances.

2.1 Discrete Wavelet Transform (DWT)

The mathematical basis of discrete wavelet transform (DWT) was presented in Daubechies (1992), which can be implemented rapidly and efficiently using the filter bank concept proposed by Mallat (1989). The filters are represented by approximation (c_j) and detail (d_j) coefficients, for each scale j, which are obtained by low-pass ($h(k)$) and high-pass ($g(k)$) filters, respectively. After a digital filtering process, with a sub-sampling by a factor of two ($\downarrow 2$), the number of samples of c_j and d_j becomes equal to half of the number of samples of the original signal. Sub-sampling process is present in Fig. 2.

Coefficients d_j are commonly used to detect transients in the signal (high frequency signals), but these coefficients can be influenced by noise, which is typically present in the system. To minimize the effect of noise, many authors (Costa et al. 2010; Santos 2017) make use of energy of detail coefficients (ξ_d) concept. In turn, the energy of the approximation coefficients (ξ_c) is directly related to the amplitude of the signal and can be used as an intensity detector for voltage sag (Costa et al. 2010). Mathematically, ξ_d and ξ_c are defined as :

$$\xi_\mathrm{d} = \sum_{k=1}^{k+\frac{\Delta k_{\mathrm{ciclo}}}{2j}} |d_j^2(k)|^2, \tag{1}$$

$$\xi_\mathrm{c} = \sum_{k=1}^{k+\frac{\Delta k_{\mathrm{ciclo}}}{2j}} |c_j^2(k)|^2, \tag{2}$$

being: k, the number of samples.

2.2 Voltage Sags' Detection Method

The detection method implemented in this work is based on the method proposed by Costa et al. (2010), which made use of the information from ξ_d and ξ_c. The following items are the steps adopted for detection of voltage sags:

1. The maximum value of ξ_d and ξ_c for each phase is calculated before the occurrence of the voltage sag;
2. The values of ξ_d and ξ_c, before the voltage sag, are normalized by their respective maximum values, so that initially they are equal to 1 pu;
3. A safety threshold of the maximum value of ξ_d is chosen (in this work, the empirical value chosen was 15%);
4. If the threshold is exceeded by at least one of the phases, a transient was detected, marking the beginning of a disturbance;
5. After that, if the ξ_c is below of 0.9 pu by at least half-cycle, a voltage sag was detected.

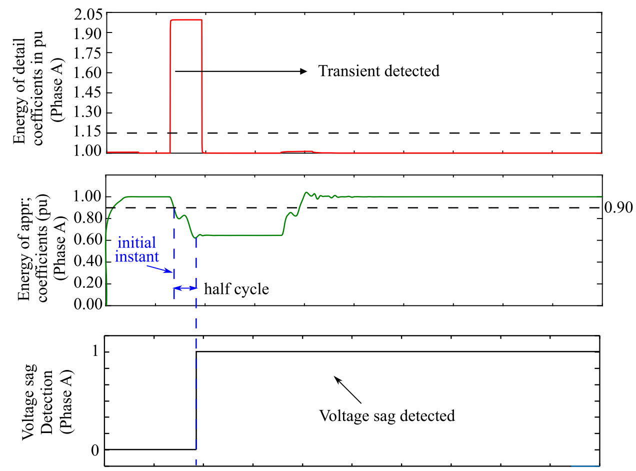

Fig. 3 Voltage sag detection

An application of the voltage sag detection method applied to the signal of Fig. 1 is shown in Fig. 3.

3 Optimal Placement of Voltage Sag Monitors

The proposed algorithm for solving the problem of placement of voltage sag monitors is based on work of Olguin and Bollen (2003), in which the following questions were discussed:

– How many monitors should be installed?
– Where do the monitors need to be installed?

The answer to these questions require some definitions.

3.1 Binary Placement Vector

This vector represents the answer to the optimal placement problem of voltage sag monitors and indicates the number

1	0	0	1

Fig. 4 Example of a binary placement vector

Remaining voltage (p.u.)

	bus 1	bus 2	bus 3	bus 4
Fault at bus 1	0.14	0.14	0.13	0.11
Fault at bus 2	0.91	0.13	0.12	0.11
Fault at bus 3	0.94	0.42	0.33	0.13
Fault at bus 4	0.98	0.91	0.91	0.11

→

Observability matrix

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

Fig. 5 Example of a observability matrix

of monitors and the buses at which the equipment will be installed. Binary placement vector is defined as:

$$V_{\text{BinPlac}}(i) = \begin{cases} 1, & \text{monitor installed at bus } i \\ 0, & \text{monitor not installed at bus } i. \end{cases} \quad (3)$$

Figure 4 shows an example of a binary placement vector with a suggestion of monitor installation at buses 1 and 4.

3.2 Observability Matrix

A matrix, based on MRA, containing information of voltage values at each bus, for simulated faults at all buses, is defined. Each roll represents the fault position (system bus) and each column, the remaining voltage at the bus. A threshold is adopted, in such a way that below its value a voltage sag must be detected. From this, a binary matrix called observability matrix (OM) is defined. Each element is defined as (Olguin and Bollen 2003):

$$om_{i,j} = \begin{cases} 1, & \text{when a fault at bus } i \text{ causes} \\ & \text{a voltage sag at bus } j \\ 0, & \text{when a fault at bus } i \text{ do not cause} \\ & \text{a voltage sag at bus } j. \end{cases} \quad (4)$$

The matrices for a hypothetical example considering a fixed threshold of 0.9 pu are shown in Fig. 5.

3.3 Topological Observability Matrix

One of the limitations of Olguin and Bollen (2003) is the fact that OM guarantees that voltage sags are only detected when faults occur at system buses (Juarez et al. 2009). To provide a greater reliability of the solution found, Ibrahim et al. (2012) proposed the use of a new matrix based on the system topology, which in this work is called topological observability matrix (TOM), defined as:

$$\text{TOM} = \text{OM} \& T, \quad (5)$$

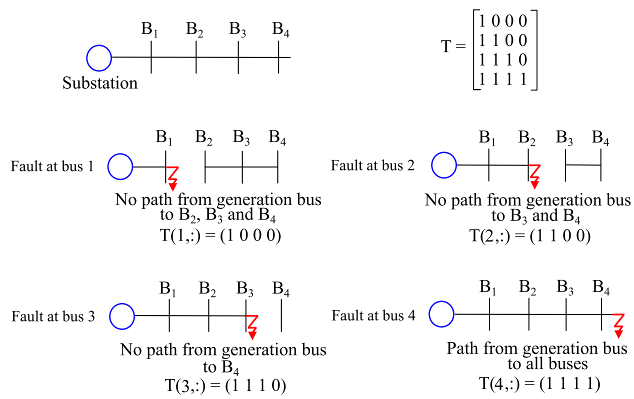

Fig. 6 Example of filling the matrix T

being, &, the logical operator 'AND'; T, the topological matrix with the same size of OM.

Matrix T is based on Graph's theory, that defines a path as a composition of vertices (buses) and a set of edges (lines). An initial vertex is connected with a final vertex by means of an edge. During a fault at a bus, the edge of the bus is separated from the others and the vertex is no longer connected by this edge (Ibrahim et al. 2012).

Matrix T contains information about system topology and can be used for other types of distribution systems (parallel, ring and meshed) as well as transmission systems. Each generation bus is considered an initial vertex and each bus that can be installed a monitor, a final vertex. According to this, matrix T is filled with 1 if there is a path from the generation bus to an installation bus, and 0 otherwise. Each line of the matrix represents the position of the simulated fault, whereas each column shows whether there is a path or not from generation bus to install bus. As a result, each monitor downstream of the fault location requires a monitor upstream of the fault location, increasing the measurement efficiency.

The filling of matrix T for a 4-bus radial hypothetical with a single power supply system (substation) is shown in Fig. 6.

3.4 Objective Function and Constraints

In a problem of optimal placement of PQ monitors, the objective is to determine the equipment position such that the number of monitors is minimal. In this sense, the objective function is defined as follows:

$$F_{\text{obj}} = \min \sum_{i=1}^{n} c_i \times V_{\text{BinPlac}}(i), \quad (6)$$

being: n, the number of buses in the system; c_i, the installation cost at bus i; $V_{\text{BinPlac}}(i)$: the binary placement vector in position i. In the case of solutions with the same number of monitors, the overlap index (O_{index}) was adopted. It represents the sum of $V_{\text{constraint}}$ divided by the number of system

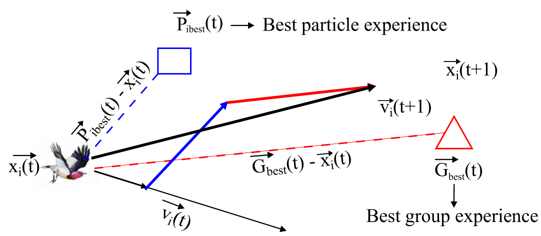

Fig. 7 Particle moving by PSO method

buses. The lower its value, the less data overload and memory usage for processing the monitor, leading to a better solution.

The constraint for choosing the monitor position is: no matter where voltage sag was found in the system, at least one monitor must be able to detect it. In this sense, a vector called constraint vector, also known as redundancy vector, is defined as (Ibrahim et al. 2012):

$$V_{\text{constraint}} = \text{TOM} * V^t_{\text{BinPlac}} \geq [1]_{n\times 1}. \tag{7}$$

This inequality shows the number of monitors that are, according to the binary placement vector, able to monitor the voltage sags at the buses that correspond to their position. To make possible to find a solution for this problem, it is necessary to use optimization methods.

3.5 Binary Particle Swarm Optimization

BPSO method is a particularity of particle swarm optimization (PSO) method, proposed in Kennedy and Eberhart (1995), which is an algorithm based on the behavior of a set of birds, bees or fish. Each individual is represented by a vector relative to its current position ($\vec{x_i}$(t)). The movement of this individual to the next position ($\vec{x_i}\,(t+1)$) will depend on its current speed ($\vec{v_i}$(t)), defined as the variation of its position, the best experience of that individual ($\overrightarrow{P_{i\text{best}}}$(t)) and the best experience of the group of individuals ($\overrightarrow{G_{\text{best}}}$(t)).

Mathematically, particle's velocity and position are respectively, as:

$$v_i(t+1) = wv_i(t) + c_1r_1(P_{i\text{best}}(t) - x_i(t)) + c_2r_2(G_{\text{best}}(t) - x_i(t)), \tag{8}$$

$$x_i(t+1) = x_i(t) + v_i(t+1), \tag{9}$$

being: c_1 and c_2, the acceleration coefficients; w, the weight coefficient; r_1 and r_2, uniformly distributed random variables in the range of 0–1. High c_1 values indicate that the algorithm will give more importance to the individual experience ($P_{i\text{best}}$) and high c_2 values indicate that the group experience (G_{best}) has more influence in the algorithm.

The process of moving a particle by PSO method is shown in Fig. 7.

Table 2 Analogy with the problem of optimal placement monitors

BPSO term	Meaning
Particles	System buses
Position	Binary placement vector
Optimal solution	Best location for the monitors
Fitness function	Minimize the cost of the monitoring system
P_{best}	Best monitors placement of a particle
G_{best}	Best monitors placement from all particles

BPSO method was selected because it is used when the solution space consists of vectors composed by either 1 (one) or 0 (zero). Since the optimization problem of this work consists of placement (bit 1) or non-placement (bit 0) of a monitor at a certain system bus, then BPSO method suits perfectly.

The differences between BPSO and PSO methods are in velocity calculation: BPSO method is computed via sigmoidal function and the new position by means of probability. The mathematical formulation for BPSO method is presented in the equations below.

$$v_{ij}(t+1) = wv_{ij}(t) + c_1r_1(P_{i\text{best}}(t) - x_i(t)) + c_2r_2(G_{\text{best}}(t) - x_i(t)), \tag{10}$$

$$v'_{ij}(t+1) = \text{sig}(v_{ij}(t+1)) = \frac{1}{1+e^{-v_{ij}(t)}}, \tag{11}$$

$$x_{ij}(t+1) = \begin{cases} 1, & \text{if } r < \frac{1}{1+e^{-v_{ij}(t)}} \\ 0, & \text{otherwise,} \end{cases} \tag{12}$$

being: i, a particle; j, the position in the particle vector i; r, uniformly distributed random variables in the range of 0–1.

According to Khanesar et al. (2007), BPSO method presents some difficulties regarding the selection of the weight coefficient (w) and depends on the problem:

- values of w greater than 1 (one) increase the probability of particle bits change to 1;
- values of w between -1 (negative one) and +1 (one) result in velocity equal to 0 (zero) over time;
- values of w less than -1 (negative 1) increase the probability of particle bits change to zero 0;

Table 2 presents the nomenclatures used in BPSO method and its respective meaning related to the problem of optimal placement of monitors.

The algorithm of BPSO method used in this work is described as follows:

1. Generate the population of i particles ($[V_{i\text{BinPlac}}]_{1\times n_{\text{buses}}}$), randomly;
2. Evaluate the objective function for each particle, according to Eq. (6);

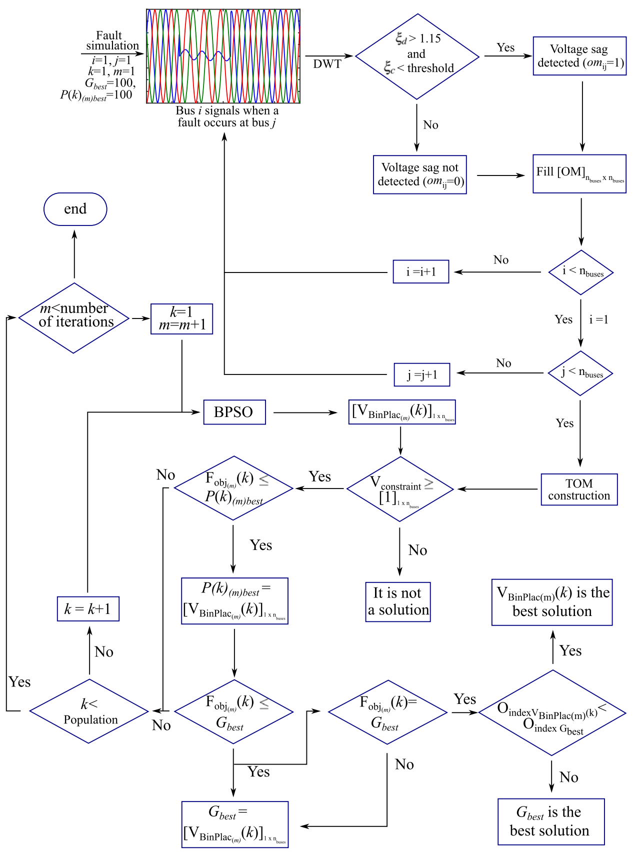

Fig. 8 Proposed algorithm flowchart

3. Initialize the first iteration:
   - Set $P_{i\text{best}}$ to the lowest value of the objective function of particle i up to the current iteration;
   - Set G_{best} to the lowest value of the objective function of the group of particles up to the current iteration;
4. Modify particles velocities according to Eqs. (10) and (11);
5. Update particles' position (new $[V_{i\text{BinPlac}}]_{1\times n_{\text{buses}}}$), according to Eq. (12);
6. Start the next iteration;
7. Repeat steps 2 through 6 until maximum iteration number is reached.

3.6 Proposed Algorithm

A flowchart for the algorithm to optimal placement of voltage sag monitors is shown in Fig. 8.

The algorithm starts with the measurement of the signal at bus 1 ($i = 1$) for a simulated fault at bus 1 ($j = 1$). DWT application in the measured signal informs if any of the phases had a voltage sag occurrence, filling the element $om_{1,1}$ with 1, if a voltage sag was detected, or 0 otherwise. The measurement is done for each of the system buses, filling the $om_{1,n_{\text{buses}}}$ element as described previously. Following that, fault location is varied and the measurement process returns to bus 1. After fault been simulated at all buses, the OM and, consequently, the TOM matrix are constructed, according to Eq. 5.

With TOM built, the optimization process initiates, with randomly generated V_{BinPlac} vectors. The constraint of the problem is evaluated (Eq. 7) and if not satisfied, that value of V_{BinPlac} is not configured as a solution to the problem. If it is met, the objective function (Eq. 6) is evaluated and in case the result found is less than that of the position in the previous iteration (initial value of 100 to P_{best} and G_{best}), the result will be the P_{best}. If the solution is best found in the solution population of k particles, it will be equal to G_{best}. With these two values (P_{best} and G_{best}), it is possible to move the vector V_{BinPlac} to a new position, using the BPSO method. The process repeats until the maximum number of iterations (m) is reached. At the end of the process, solutions that have the same minimum values of the objective function are differentiated by the overlap index (O_{index}).

4 Methodology

The methodology used for the development of this work is present in Fig. 9.

After selecting one resistance value, one fault type, one system loading and one detection threshold, the algorithm presented in Sect. 3.6 is used to obtain the number and position of monitors in the analyzed electrical systems. The process repeats until all parameters are tested and their result is obtained.

To develop and validate the methodology, a Brazilian distribution system was selected to analyze the sensibility to variations for a specific condition of fault resistance, system loading, detection threshold and fault type. The system single-phase diagram is shown in Fig. 10, and the characteristics are presented in Santos et al. (2010).

In order to analyze the placement of monitors taking into account their expansion, an IEEE 34-bus distribution system was used, which their characteristics are presented in IEEE (2010) and its single-line diagram is shown in Fig. 11. The red highlighted part represents the initial 24-bus system. The blue highlighted part represents the projection of its expansion with addition of 10 buses. Before the expansion, the algorithm is applied, obtaining a placement result of the monitors. After the expansion, the algorithm is applied again, taking into account the monitors found in the previous answer.

The implementation of distribution systems and all routines was done using a commercial software and the Alternative Transient Program (ATP). A database was created, and the specifications were based on works that present a similar

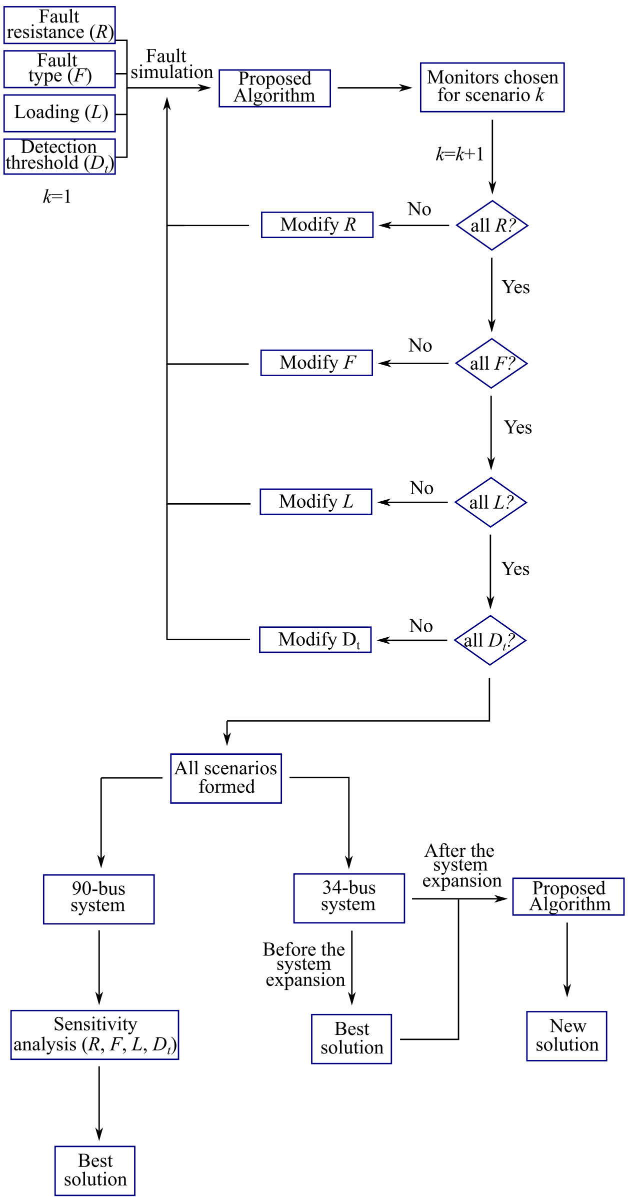

Fig. 9 Methodology to develop and validate the proposed algorithm

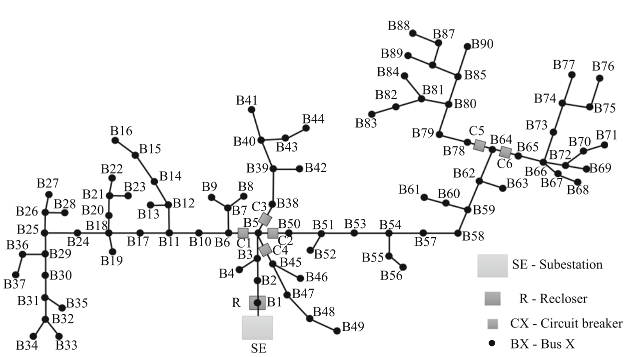

Fig. 10 90-Bus Brazilian distribution system

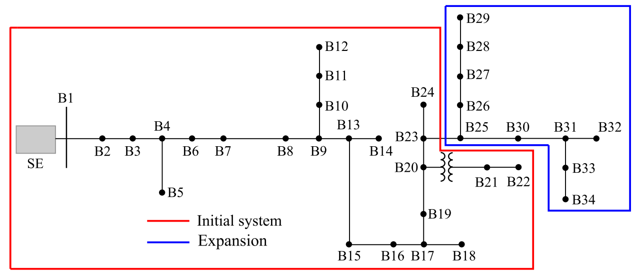

Fig. 11 IEEE 34-bus distribution system (Color figure online)

Table 3 Parameters for database generation

Variables	Specification
Fault resistance (Ω)	0.5, 1 and 5
Loading (%)	25, 50, 75 and 100
Fault type	LG, LL, LLG and LLL
Detection threshold (pu)	0.9, 0.8, 0.7 and 0.6

theme (Ibrahim et al. 2012; Santos et al. 2010), as shown in Table 3.

5 Results and Discussion

In order to perform an analysis of the proposed algorithm, the following considerations were made:

1. The parameters used in the BPSO method are present in Table 4.
2. The weight coefficient, w, was chosen to be negative; given that the algorithm must return the binary vector with the most number of zeros in it, as described in Sect. 3.5;
3. For the 90-bus system, the redundancy vector was adapted in such a way to consider the detection at each position being made by two monitors except for bus 1. This was done considering that in case of a monitor malfunctioning, there would be another equipment monitoring.

Sections 5.1–5.4 show the variations in the number and optimal positions of the monitors from a sensitivity analysis for the 90-bus system. Section 5.5 presents the variations in the number of monitors, considering the expanded 34-bus system.

Table 4 BPSO method parameters

Weight coefficient $(w) = -12$	
Acceleration coefficients (c_1 and c_2) $= 2$	
Population (individuals number) = 100	
Number of iterations = 100	

Table 5 Loading variation results

Scenario	Loading (%)	Number of solutions	Best solution (buses)	Overlap index
1	100	90	1, 2, 23 and 58	2.41
2	75	132	1, 2, 26 and 62	2.46
3	50	128	1, 2, 31 and 64	2.53
4	25	144	1, 2, 31 and 62	2.57

Table 6 Fault-type variation results

Scenario	Fault type	Number of solutions	Best solution (buses)	Overlap index
5	LG	80	1, 2, 15 and 56	2.25
6	LL	129	1, 2, 15 and 25	2.47
7	LLG	114	1, 2, 15 and 26	2.45
8	LLL	136	1, 2, 28 and 59	2.44

Table 7 Fault resistance variation results

Scenario	Fault resistance (Ω)	Number of solutions	Best solution (buses)	Overlap index
9	0.5	90	1, 2, 23 and 58	2.41
10	1	116	1, 2, 37 and 59	2.38
11	5	80	1, 2, 15 and 56	2.25

5.1 Loading Variation (90-Bus System)

For system loading variation, only single-phase faults were analyzed, with fault resistance of 0.5 Ω and a detection threshold of 0.9 pu. For each load, four factors were used to represent percentages of its original value (1, 0.75, 0.5 and 0.25). The results obtained are present in Table 5.

As shown in Table 5, the loading variation: (i) did not influence the number of monitors in the best solution; (ii) influenced the position of monitors; (iii) influenced the number of solutions obtained. There are no heavy loads throughout the 90-bus system; therefore, variations in loading do not result in significant changes in the observability area of the installed monitors that explains the same number of monitors in all scenarios obtained for all load variations.

5.2 Fault-Type Variation (90-Bus System)

For fault-type variation, it was used: 5 Ω resistance fault between phase and ground, 0.001 Ω resistance fault between phases, 100% loading and detection threshold of 0.9 pu. The results obtained are presented in Table 6.

As shown in Table 6, the fault-type variation: (i) did not influence the number of monitors; (ii) influenced the allocation of monitors. (iii) influenced the number of solutions obtained. Three-phase faults are the most intense faults, sensitizing monitors with greater ease than single-phase faults. Despite the same number of monitors found for all fault types, the number of solutions for three-phase faults was the largest because of this higher intensity.

5.3 Fault Resistance Variation (90-Bus System)

For fault resistance variation, loading of 100%, a single fault and a detection threshold of 0.9 pu were analyzed. The results obtained are presented in Table 7.

As shown in Table 7, the fault resistance variation: (i) did not influence the number of monitors; (ii) influenced the allocation of detectors; (iii) influenced the number of solutions obtained. No concrete difference was noticed due to the variations in fault resistances for these values.

Scenarios 5 and 11 from Tables 6 and 7, respectively, have the same characteristics and, therefore, have the same index of overlap. All solutions found are also solutions for all other scenarios. Therefore, for these first 3 parameters, the solution with the lowest overlap index (scenario 5 or 11) was chosen. The monitors' location as well as the monitoring area are shown in Fig. 12.

5.4 Detection Threshold Variation (90-Bus System)

Due to the frequent occurrences of voltage sags between 0.5 and 0.85 pu (Sect. 2), a sensitivity analysis of the installed monitors was performed for a detection threshold variation. A 100% loading, single-phase faults and 5 Ω fault resistance were considered. The results obtained are present in Table 8.

The results obtained from Table 8 show an increase in the number of monitors due to the decrease in the observability area. In addition, the overlap index increases when the detection threshold decreases.

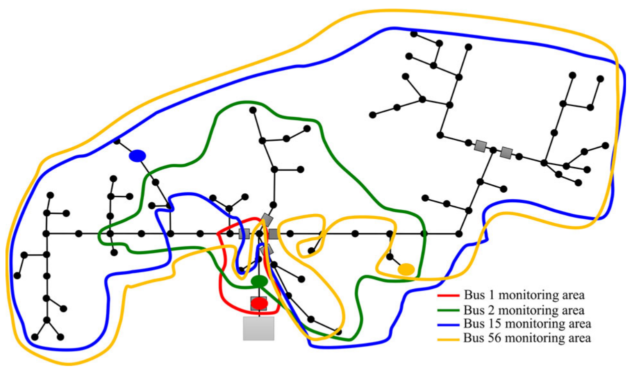

Fig. 12 Monitoring area of buses 1, 2, 15 and 26

Table 8 Detection threshold variation results

Scenario	Threshold (pu)	Number of detectors	Best solution (buses)	Overlap index
12	0.8	6	1, 2, 3, 35, 58 and 68	2.79
13	0.7	9	1, 2, 3, 4, 11 15, 47, 56 and 57	3.64
14	0.6	13	1, 2, 3, 5, 12 15, 32, 34, 45, 56, 57 68 and 71	4.94

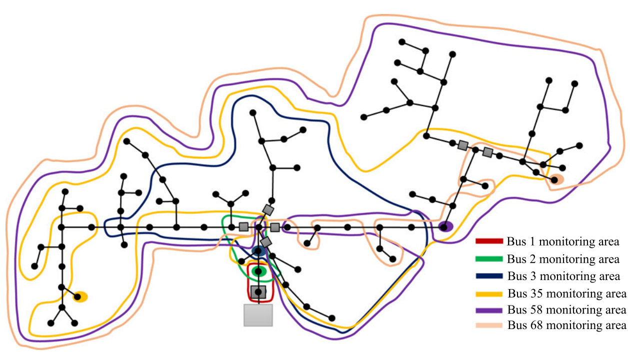

Fig. 13 Monitoring area of buses 1, 2, 3, 35, 58, 68

The monitors' location as well as the monitoring area of the solution found for the detection threshold of 0.8 pu are shown in Fig. 13.

From the results, it is noticed that for all solutions, buses 1 and 2 were chosen. This is due to the fact that with a fault occurrence at these buses, all the others would have an interruption of the supply and would be under voltage of 0.1 pu.

Some monitors were able to detect voltage sags at buses farther from their installation point, thereby avoiding a larger number of installed monitors and lowering the monitoring system cost.

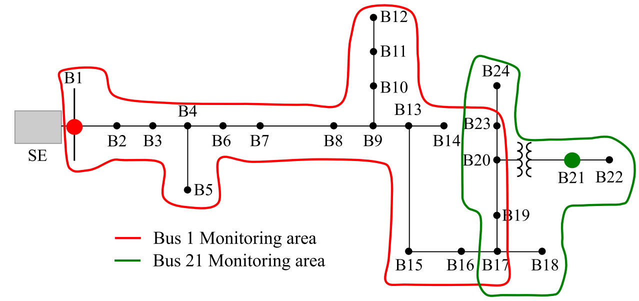

Fig. 14 Monitoring area of buses 1 and 21

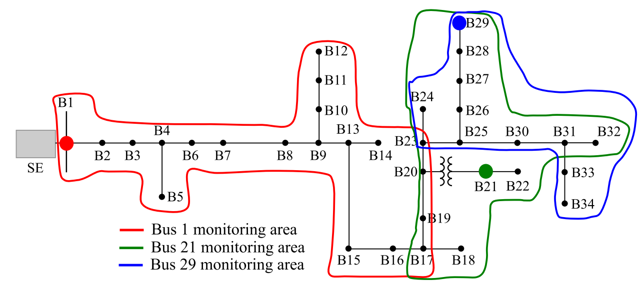

Fig. 15 Monitoring area of buses 1, 21 and 29

According to Figs. 12 and 13, it can be seen that voltage sags at each bus of the system were detected by at least one monitor, satisfying the restriction of the optimization problem.

5.5 System Expansion (34-Bus System)

For system expansion, two databases were constructed. First database took into account the simulation of faults at the 24 buses of the initial system, forming an $[\mathrm{OM}]_{24\times 24}$ and a $[T]_{24x24}$ for each of the eleven (3 fault resistance, 4 loading, 4 fault type) scenarios. As a result of the procedure described in Fig. 11, the best solution proposed by the algorithm is the installation of the monitors at buses 1 and 21. Figure 14 presents the monitoring area of the solution found.

After system expansion, a new database was made, forming an $[\mathrm{OM}]_{34\times 34}$ and a $[T]_{34\times 34}$ for each scenario and takes into account the already installed monitors, assigning the value 1 in the binary placement vector in their respective positions. From this, each particle will move to a new position containing values 1 and 21 as a part of the solution.

As a final result, the solution with the lowest number of monitors and overlap index is the one that includes buses 1, 21, 29. This means that for the initial system, only two monitors were needed; however, after expansion, these monitors were not able to detect certain voltage sags in the new system and a new monitor is required at bus 29. Figure 15 presents the monitoring area for each monitor choose.

6 Comments

The use of the DWT proved to be useful in detection of voltage sags caused by fault. In addition, this tool can be used in future works to calculate the event duration, by detecting the initial and final transients, fully characterizing the voltage sags.

BPSO method presented a fast convergence to the optimal placement using 100 iterations in the process. Although it did not guarantee global optimum, the method converged to a low number of monitors (4 in most scenarios).

The use of matrix T to the optimization problem brought greater reliability to the process of choosing the monitors, but a deeper analysis, considering faults along the line could be considered to increase robustness to the database.

From the sensitivity analysis, it was possible to evaluate parameters that directly influence the detection of voltage sags in the system. With the combined scenarios, a global solution could be provided, considering all the variations adopted.

Other types of systems and reconfigurations can be applied using this algorithm, simply adapting its information to the problem. The higher the number of simulations with different parameters, the greater the reliability of the presented algorithm.

To prevent monitors from detecting voltage sags caused by the same event, it is necessary to synchronize the devices. This can be done from monitor configuration and transmission via UTP cable or, more commonly, via GPS.

7 Conclusion

This work presents an algorithm for installation of power quality monitors at strategic points of electric power distribution systems for the diagnosis of voltage sags. A database was created to evaluate the influence of voltage sags, from the observability area that the fault situation generated for each simulated scenario. For this, a Brazilian 90-bus and an IEEE 34-bus distribution system were used. A sensitivity analysis was also performed, in which the influence of several parameters on the phenomenon, such as fault resistance, fault type, system loading, detection threshold and system expansion, was evaluated.

For voltage sags detection, the DWT was used, where the energy of the detail coefficients (high frequency) detected transients of the fault and the energy of approximation coefficients was used for detection of the signal amplitude.

Remaining voltages at buses were used to model the optimization problem, and BPSO method was chosen for its resolution. The optimization method presented fast convergence (maximum of 100 iterations) for a solution with a reduced number of monitors (four for most cases).

Due to the light loads throughout the 90-bus system, the number of monitors did not vary with the variation of system loading. Regarding the type of fault, the number of monitors was the same, but with a greater number of solutions for the three-phase faults, due to their higher intensity. For the variation of the resistance values chosen, a considerable influence on the number of monitors was not observed. For the variation in the detection threshold, an increase in the number of monitors was observed by decreasing the threshold and, consequently, from the observability area of the monitors. Finally, an increase in the number of monitors was shown when the 34-bus system indicated an expansion, confirming that the monitors of the initial system could not detect voltage sags at some locations in the expanded system.

The search for improvements and refinements in relation to previous works is important for research development and for the state of the art. The combination of concepts and techniques that allow being applied in subjects of public interest of a financial nature contributed essentially to the development of this work in the thematic approach. Although some work with the same theme has been presented in the state of the art, the proposed methodology has the following advantages: (i) the usage of a detection method that may be used to detect the duration of the voltage sag and its complete characterization; (ii) the construction of a more robust database with parameters variation; (iii) a global solution applicable to different scenarios was presented.

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