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ORIGINAL RESEARCH

Optimal placement of STATCOM using a reduced computational burden by minimum number of monitoring units based on area of vulnerability

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Abstract
Various Flexible Alternating Current Transmission System (FACTS) devices are used to improve the power quality and reliability of power system. In addition to the technical constraints, the installation and maintenance costs limit the exploitation of such devices. To maximize the efficiency of FACTS, the least possible number of devices must be placed optimally in the network. In this vein, many types of research have been conducted to offer optimal placement solutions. Although these methods lead to optimal placement, they usually suffer from a huge amount of computational burden. Therefore, here, an intelligent optimal placement approach is presented, focusing on reducing computational volume. For this aim in the suggested method, the monitoring buses are limited, while monitoring other buses is carried out using an estimation approach. To avoid increasing calculations for this selection, applying the worst fault condition instead of all fault types, the least number of monitoring buses are selected. Moreover, high-risk zones are indicated for each monitoring bus so that by applying different fault conditions in only these areas, the study is conducted, which results in an additional decrement in computational burden. Finally, the optimal placement problem is solved by employing the genetic algorithm.

1 | INTRODUCTION

voltage sag is one of the most important power quality issues that occur frequently in power systems. According to the definition, voltage sag is a sudden reduction of supply voltage on one or more phases, with an RMS voltage threshold and a time duration of no more than 1 min [1]. This phenomenon can be considered as one of the most crucial sources of financial losses and malfunction of equipment in industries [2, 3]. In this regard, various researches have been conducted on different FACTS devices on their optimal capacity, location, type, and so forth [2–5]. These researches follow various objectives including reducing the number of voltage sags and power loss, or increasing power transmission capacity [1–3]. To improve the aforementioned items, equipment such as static compensator (STATCOM) [2–5], static VAR compensator (SVC) [6], and dynamic voltage restorer (DVR) [7] can be used.

To study voltage sag, various indicators can be used. System average RMS variation frequency index (SARFI) is one of the best indexes for measuring the number of voltage sags in the network. To calculate SARFI, the voltage of every single bus must be monitored, but it is not cost-efficient since a huge number of measurement instruments are required. Today, much research is done on the optimal placement of measuring and monitoring equipment [8–11]. An alternative cost-effective approach is approximating the voltage of buses based on a limited number of monitored buses. Thus, few buses must be chosen to provide voltage information of all buses. Therefore, the number and location of these buses are important and affect the accuracy of estimating the information of other buses. The location and number of monitoring buses must be selected in a way that ensures recording the occurrence of every type of fault (SLG-LL-LLG-3L) wherever in the network.

Recently, several studies have been conducted to determine the number and location of monitoring buses. The authors in [10] have employed a system impedance matrix to obtain efficient monitor placement. Although this article provides a simple approach to achieve the goals; the proposed method does not differentiate between various types of faults and the same result will be given for different faults. In [11], The author determines the monitoring buses by determining the vulnerable areas of network buses in different faults. In this work, although the speed of determining the monitor buses is high, but it is not very accurate. Authors in [12] have used the p-median algorithm to find the optimal placement, but this approach is merely applicable in the distribution system.

In [7], the fault position method is used to apply the fault, but only for the three-phase fault. In [10], while all fault types can be applied, the accuracy has been slightly reduced. Critical distance and fault position methods (FPM) have been used to determine the vulnerable area in [11–15], but they have some deficiencies in ring networks. Moreover, while the FPM has a good performance in both ring and radial networks, but since large networks require a large number of points to use this method, to determine the exact area of vulnerability (AOV), it is not a proper approach. Therefore, these methods are not suitable and impose a remarkable computational burden. To obtain less computational burden, the hybrid method introduced in [16, 17] can be used. In these papers two equations of the voltage-sag magnitudes and phase-angle jumps due to faults along a line are derived by using the impedance matrix building algorithm. By using the derived equation of voltage-sag magnitude, the area of vulnerability can be determined without performing short-circuit analysis. The quadratic interpolation and the secant are used to find critical points on the network lines. This method, despite its advantages in large networks, is not very popular due to its time-consuming nature. also, AOV can be achieved by using open and bracket methods to solve voltage equations, which are not appropriate due to convergence problems [18, 19], and to estimate the information of other unmonitored buses. In [20, 21], a method is suggested to solve an undetermined analytical set of equations by integer linear programming or singular value decomposition, but in these methods, each fault on the network must stimulate at least one monitored bus, which requires more monitored buses. In [22], to estimate the voltage information of unmonitored buses, the most probable fault location is used using the set of potential fault locations, which is based on the fault type. In [23], the Bayesian-theory-based method has been used with the Monte Carlo method.

For optimal STATCOM placement in the network, various methods such as genetic algorithm (GA), simulated annealing, and TABU have been adopted in [24]. Table 1 briefly shows the strengths and weaknesses of the mentioned papers. In [13], a method for enhancing the SARFI of a distribution system has been proposed based on only one D-STATCOM and its current limits. Here, GA is used for optimal placement of STATCOMs to reduce the number of voltage sags and enhance the SARFI index. However, in this article, we have tried to

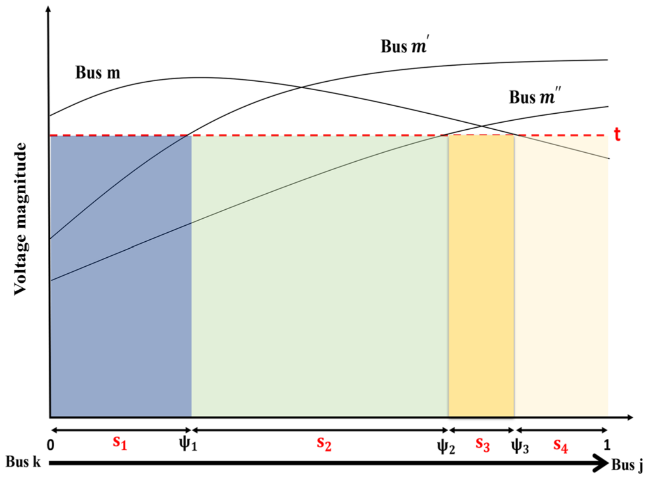

FIGURE 1 Residual voltage at buses m, $\mathbf{m'}$, $\mathbf{m''}$ due to fault in line l and comparison with threshold voltage.

obtain the required information only from monitoring buses. In this regard, different fault types are applied in the vulnerable areas of these buses and the information about the other buses are attained based on the information about these buses. This approach remarkably increases the computation speed and reduces the computational burden.

The rest of the paper is organized as follows: In Section 2, the optimal location of voltage sag monitors is calculated. In Section 3, AOV for monitored buses is determined, and in Sections 4 and 5, estimation of voltage sags from monitored buses and GA are defined, respectively. Finally, in Section 6, the proposed method is executed on the IEEE 14-bus system to show the proficiency of this approach. To validate the approach on a larger network, the simulation is carried out on a 57-bus network, too.

2 | OPTIMAL PLACEMENT OF MEASUREMENT INSTRUMENT

Due to financial issues, it is not possible to record all buses' data; instead, the data of some buses are recorded to estimate other buses' data. To indicate the monitored buses, the approach introduced in [25] is used.

2.1 | Indicating monitoring buses

This method applies to all fault types. First, the voltages of the buses are obtained by applying symmetrical or asymmetric faults on buses and lines. Then, by comparing the voltage magnitude of buses (resulting from the fault applied to the target line) with the threshold voltage (V_{th}), the line is divided into several parts. Figure 1 shows the voltage across the buses m, m', m'', for faults in all points in the line between kth and jth buses. By comparing the amplitude of the bus voltage with the threshold voltage, the line is divided into four parts. For example, the fault

TABLE 1 Comparing methods.

Item Reference no.	Indicating monitoring buses		Determining AOV			Estimation	
	Works for all fault types	High accuracy	Applicable for radial networks	Usable for meshed networks	Computational burden	No. of required monitoring buses	Accuracy
6	✗	✓					
7	✗	✗					
10	✓	✗					
11	✓	✗					
12-14			✓	✓	✗		
16-17			✗	✓	✗		
18-19			✗	✓	✗		
20-21						✗	✓
23						✓	✗
Proposed method	✓	✓	✓	✓	✓	✓	✓

in section s_2 of the line can only trigger bus $m''$and is a part of the monitor reach area (MRA) of the bus m''. The number of pieces of the line l is equal to s^l. The dimensions of the reach binary matrix (M_l) are equal to ($N * s^l$), and if $m_l\,(m, s)$is the input of this matrix, the value of this input will be equal to 1 if the fault occurred in the relevant part causes the voltage to drop below the threshold voltage, otherwise, it is zero.

$$M_l = m_l \;\; (m, s) \tag{1}$$

$$\begin{cases} 1, \; if \;\, V_m \left(\psi_a \le \psi \le \psi_b\right) \le t \\ 0, \; if \;\, V_m \left(\psi_a \le \psi \le \psi_b\right) > t \quad \forall m, s \end{cases} \tag{2}$$

$v_m = \;\; (\psi_a \le \psi \le \psi_b)$ shows the amplitude of voltage in the bus m when the fault is in the sth piece that is between the two values ψ_a and ψ_b, which are a fraction of the line l. This process must be performed for the entire L lines of the desired network, to form the following comprehensive matrix.

$$\mathrm{M} = (M_1 + M_2 + \cdots + M_L) \tag{3}$$

The number of rows is equal to the number of network buses and the number of columns is equal to the network lines. Monitor reach matrix can be set up for all fault types ($M_{3p}, M_{2p-g}, M_{2p}, M_{1p}$).

2.2 | Minimum monitoring buses

The purpose of this section is to determine the minimum number of measurement instruments to cover the entire network. For this purpose, monitoring buses must be selected in a way that any kind of fault, at which occurs in the network and causes a voltage sag, must be observed by at least one of the measurement instruments.

The vector X, which shows the location of the monitored buses in the N-bus network, is defined as follows:

$$X \;\; (i) = \begin{cases} 1 \; ; if \;\; monitoring \; bus \; exists \; at \;\; bus \; i \\ \qquad\quad 0 \; ; otherwise \end{cases} \tag{4}$$

The objective function to minimize the number of monitoring buses is:

$$f \;\; (x) = \; \min \sum_{i\,=\,1}^{N} x\,(i) \tag{5}$$

Since the voltage sag must be observed at least by one of the monitoring buses, the following constraints must be considered for the above equation.

$$\begin{gathered} \sum_{i\,=\,1}^{N} m_{3p}\,(i, s)\, x\,(i) \ge 1, \; \forall s \; = \; 1, 2, \ldots, s_{3p} \\ \sum_{i\,=\,1}^{N} m_{1p}\,(i, s)\, x\,(i) \ge 1, \; \forall s \; = \; 1, 2, \ldots, s_{1p} \\ \sum_{i\,=\,1}^{N} m_{2p}\,(i, s)\, x\,(i) \ge 1, \; \forall s \; = \; 1, 2, \ldots, s_{2p} \\ \sum_{i\,=\,1}^{N} m_{2p-g}\,(i, s)\, x\,(i) \ge 1, \; \forall s \; = \; 1, 2, \ldots, s_{2p-g} \end{gathered} \tag{6}$$

$s_{3p}, s_{1p}, s_{2p}, s_{2p-g}$ are the total number of columns of matrices, and $M_{3p(i,s)}, M_{1p(i,s)}, M_{2p(i,s)}, M_{2p-g(i,s)}$ are generic elements (i,s) of the reach matrices $M_{3p}, M_{1p}, M_{2p}, M_{2p-g}$, respectively. The outline of the method used to determine the monitoring buses is shown in Figure 2.

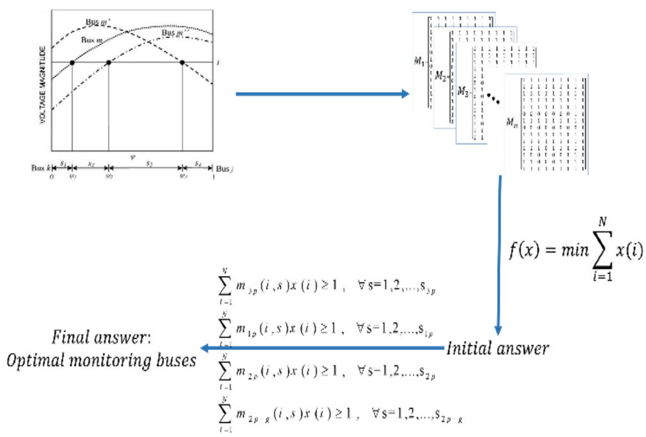

FIGURE 2 Outline of the method used to determine the monitoring buses.

2.3 | Area of vulnerability

The most important factor in determining AOV is to identify the critical points of this area. To determine this area, the method presented in [26] is used, which is based on the second-degree interpolation and the secant method. For this aim, first, the magnitude of the voltage of all buses, under the fault condition, must be recorded to find the AOV.

$$V_{mag} = \begin{bmatrix} \left|V_s^{fault\_1}\right| \\ \vdots \\ \left|V_s^{fault\_n}\right| \end{bmatrix} \tag{7}$$

where $|v_s^{fault\_i}|$ is the depth of voltage sag in bus s due to a fault in the ith bus. Moreover, n is the total number of network buses, so using the V_{mag} matrix, the vulnerability index vector (BVI) for the bus s can be formed. The inputs of this matrix are obtained by subtracting the V_{mag} matrix from the threshold voltage value.

$$\Delta V_{mag} = \begin{bmatrix} \Delta V_{mag\_1} \\ \vdots \\ \Delta V_{mag\_n} \end{bmatrix} = \begin{bmatrix} \left|V_s^{fault\_1}\right| \\ \vdots \\ \left|V_s^{fault\_n}\right| \end{bmatrix} - [V_{th}] \tag{8}$$

$$BVI = \begin{bmatrix} BVI_1 \\ \vdots \\ BVI_n \end{bmatrix} = \begin{cases} 1\,, & \Delta V_{mag\_i} \leq 0 \\ 0, & \Delta V_{mag\_i} > 0 \end{cases} \tag{9}$$

According to the above equations, if ΔV_{mag} is zero or negative, BVI will be equal to 1, which means that a fault in the bus i will cause a voltage drop across bus s. and consequently, bus i is within AOV, and vice versa.

If BVI_i is the vulnerability index of the bus i, LVI_j can be defined as below. Note that the line J is between F_j and T_j buses.

$$LVI_j = BVI_{Fj} + BVI_{Tj} \tag{10}$$

where $j = 1, 2, \ldots, m$ are the total number of lines. If the value of BVI for the F_j and T_j buses is 0, then the value of LVI_j is equal to 0, which means that the whole line j is not in the AOV of bus s; and if only one of BVI_{Tj} and BVI_{Fj} is equal to 1, LVI_j becomes 1, which means that one part of the line is in AOV, and that line has just one critical point. In this case, using the amount of voltage sag caused by the fault in the beginning, end, and middle points of the line, that is, $|v_s^{fault\_Fj}|, |v_s^{fault\_Tj}|$ and $|f(0.5)|$, the second-degree interpolation is performed. Then, the critical point is determined by applying the secant method [15], where the starting point is close to the interpolation root; and if both BVI_{Tj} and BVI_{Fj} are equal to 1, LVI_j will be equal to 2. In this case, first, the maximum amount of voltage of the sth bus caused by the fault is determined using the golden section search method [27]. If the value of $|f_{(P_{max})}|$ is less than the threshold voltage, the whole line j is in AOV of sth bus, otherwise two parts of this line are in AOV and two critical points must be defined. To find the critical points, using the $|v_s^{fault\_Fj}|, |v_s^{fault\_Tj}|$ and $|f\ (P_{max})|$, the second-degree interpolation is carried out, and by solving the equation $V_{th} = ap_i^2 + bp_i + c$, the two roots of the equation are determined. These roots are close to the starting points of the secant method for determining the two critical points. Figure 3 summarizes the process of determining the vulnerable areas for the target bus.

3 | SARFI ESTIMATION

The general steps for estimating the voltage of an unmonitored bus is shown in Figure 4. The details are explained in the following subsections.

3.1 | Creating a comprehensive database of SARFI based on the Monte Carlo method

In this method, while having the probability distribution function (pdf) of the influential factors (fault location, type of fault, fault impedance etc.) in each test using random numbers, the possible events that will affect the voltage sag are selected. Also, the voltage sags in reaction to these faults are examined. Each test is independent of the other tests.

To apply the Monte Carlo method to database formation, the algorithm introduced in [15], which determines the number of voltage sags of one bus per year, is exploited. More simulated years in the Monte Carlo method result in more accurate results. In this paper, the simulation time is 4000 years. And the factors affecting the voltage sag used as input parameters of this method are selected according to [15, 23].

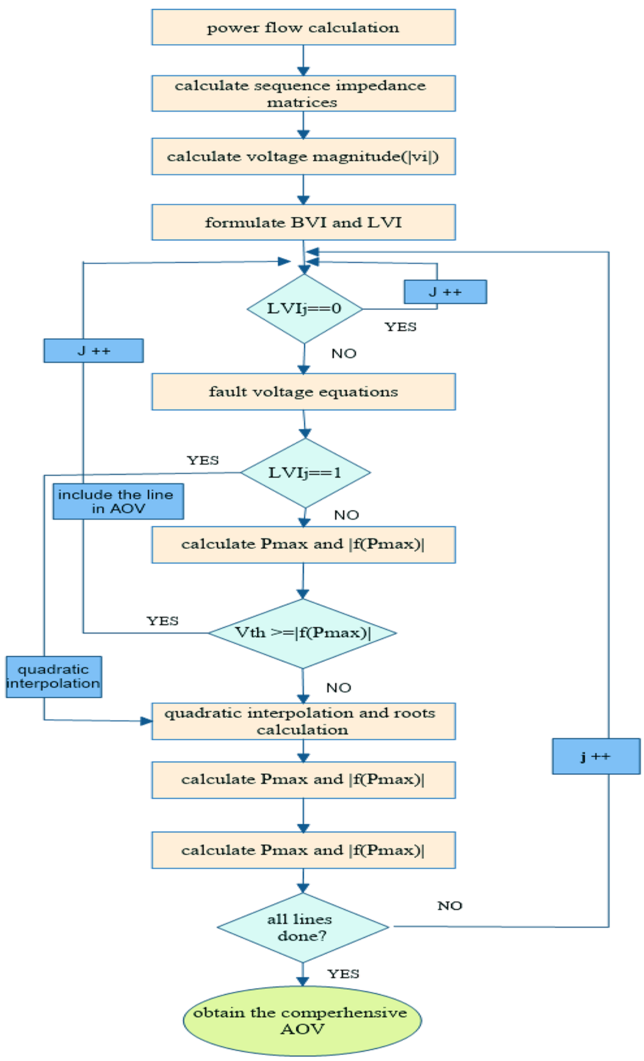

FIGURE 3 Method of determining the AOV.

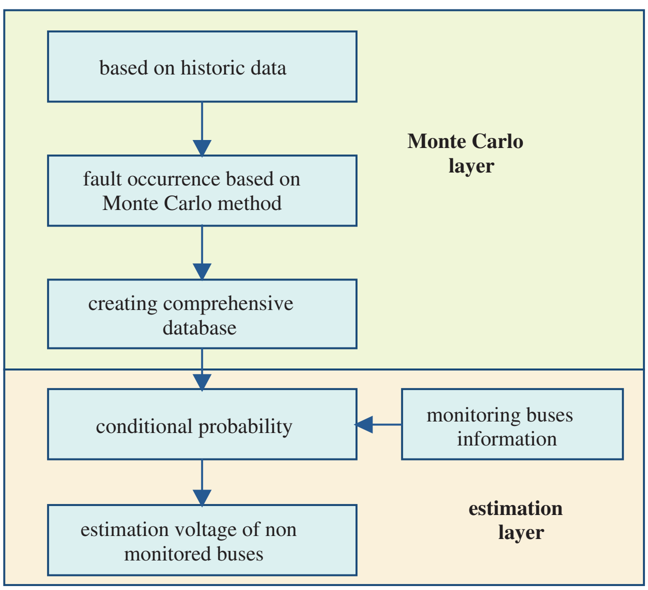

FIGURE 4 The general overview of the proposed method.

TABLE 2 Interpretation of correlation coefficient.

Correlation coefficient	Interpretation
$0 \le \lvert r_{ij} \rvert < 0.2$	Very weak
$0.2 \le \lvert r_{ij} \rvert < 0.4$	Weak
$0.4 \le \lvert r_{ij} \rvert < 0.6$	Moderate
$0.6 \le \lvert r_{ij} \rvert < 0.8$	Strong
$0.8 \le \lvert r_{ij} \rvert < 1$	Very strong

3.2 | Determining the relationship between the number of voltage sags in network buses and the Pearson coefficient

The correlation coefficient shows the correlation between the two variables. Here, Pearson coefficient, which is defined below, is used to determine the relationship between the number of network voltage sags.

$$r_{ij} = \frac{conv\,(i, j)}{\sigma_i \,.\, \sigma_j} \tag{11}$$

r_{ij} shows the degree of correlation between the voltage sag index (SARFI) obtained in i and j buses during the study period. σ_i and σ_j show the standard deviation of the voltage sag index in i and j buses during the study period (4000 years). The obtained information by Monte Carlo is used in the calculation of r_{ij}.

Table 2 shows the interpretation of the correlation coefficient obtained for the SARFI bus index.

3.3 | Bayesian theorem approach

Using the Bayes theorem, the likelihood of occurrence of an event given another even possibility can be determined [18, 19].

In other words, exploiting this theory, the most probable number of voltage drops in the buses can be obtained from the number of voltage sags in monitored buses. Thus, the Bayesian method can be rewritten as follows:

$$\mathrm{P}(H_i = \mathrm{h} \mid D_j = \mathrm{d}) = \frac{\mathrm{P}\,(H_i = \mathrm{h})\,.\,\mathrm{P}(D_j = \mathrm{d} \mid H_i = \mathrm{h})}{\mathrm{P}\left(D_j = \mathrm{d}\right)} \tag{12}$$

where

H_i: the number of voltage sags in ith unmonitored bus
h: the number of specified voltage drops in the monitorless bus i in the specified year
D_j: the number of voltage drops measured on monitor bus j
d: the number of voltage drops on the monitored bus j in a given year

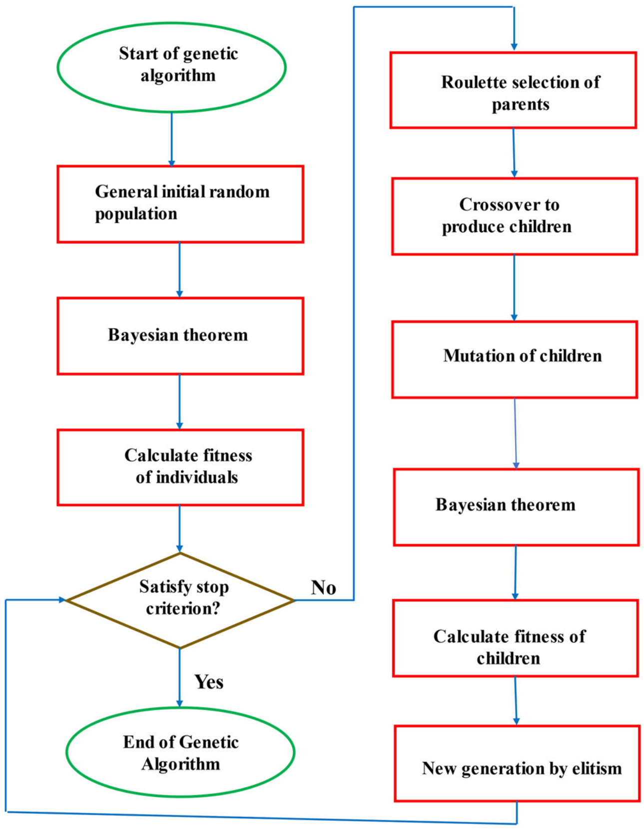

FIGURE 5 Proposed steps for implementing a GA.

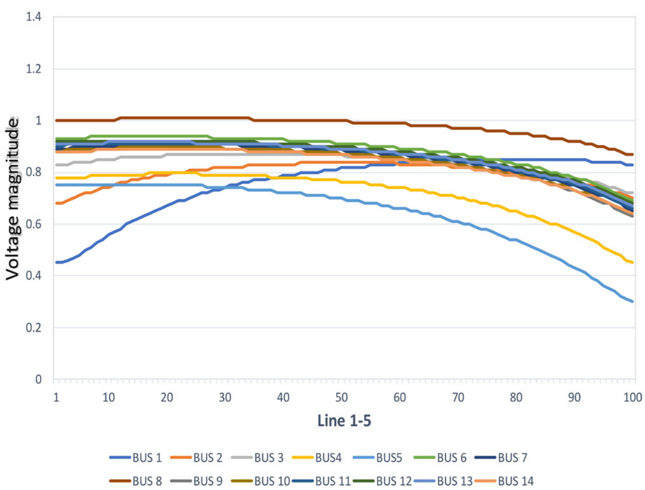

FIGURE 6 Comparison of the bus voltage with the threshold voltage of 0.9 pu due to a fault in line 5–1.

The left side of the expression P(H_i = h | D_j = d) indicates the probability that the voltage drops in the non-monitored bus *i* is *h*, while that in the monitored bus *j* is *d*.

The expression P(H_i = h) is the probability that in non-monitored bus *i*, the number of voltage drops in a given year is *h*; and there is no need to know the monitor bus information. In fact, the information derived from the Monte Carlo method is used.

In this equation, the goal is to obtain the *h* that is most likely to happen; thus, it is not possible to determine the exact probability value of the expression P(H_i = h | D_j = d).

Expression P(D_j = d) in the denominator of the fraction can be ignored because it is the same for all *h* values.

4 | GENETIC ALGORITHM AND PROBLEM FORMULATION

To start the GA for placing STATCOMs on buses, first, the initial population must be created. Each member of the population shows the STATCOMs locations. The population can be formed randomly or by experience. Once the population members are identified, each must be evaluated by the cost function.

$$N = \sum_{k=1}^{n} \lambda \,|\, (0.1 \leq v_k \leq v_{th}) \tag{13}$$

In Equation (13), *n, k*, λ, v_k and v_{th} represent total number of network buses, bus number, number of voltage sags, magnitude of voltage recorded on bus *k*, and threshold voltage, respectively.

The next step is to select the parents to apply crossover and mutation. Parents are selected by the roulette wheel method [28], and for a crossover for more variety, single-point crossover, two-point crossover, and uniform crossover can be used simultaneously; and the mutation operation, which is useful to prevent rapid convergence and help the search algorithm to escape trapping in local minimums, is used. The mutation rate is 0.15, and the combination rate is 0.6. Here, the condition for stopping is the number of repetitions of the algorithm. In this method, the genetic algorithm is executed in such a way that the faults are applied only in the vulnerable areas of the monitoring buses, and by obtaining the SARFI index of these buses, the information of other buses is estimated using the Bayesian method. This reduces the number of study areas and only by having the information of the monitoring buses can be obtained the information of the whole network buses, which is economically and studiously useful. Figure 5 shows the proposed steps for implementing the GA.

5 | CASE STUDY

The described method is tested on the IEEE 14-Bus standard network, which consists of 14 buses, 16 lines, 5 transformers, 5 generators, and a shunt, and on the IEEE 57-Bus system. The simulation is performed in the Digsilent (DSL) power factory environment and the optimization algorithm has been run in MATLAB linked with the DSL. The model of STATCOM is implemented in DSL environment based on the explanations in [29]. The threshold voltage is considered to be 0.9 per unit (pu).

TABLE 3 Part of monitor reach matrix in 14-bus network.

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

5.1 | Determination of monitoring buses

To determine these buses, the worst-case scenario, single phase to ground fault, has been considered. Since this type of fault causes fewer effects on other buses, more monitoring buses are required. As mentioned earlier, the first step is to determine the different segments of the lines by comparing the magnitude of the bus voltage, under a fault condition. For example, Figure 6 shows a comparison of the bus voltage with the threshold voltage of 0.9 pu due to a fault in line 5–1. The monitor reach matrix for this example is given below:

$$M_l \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 0 & 1 & 1 & 1 & 1 & 1 \\ 1 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \\ 1 & 1 & 0 & 0 & 0 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \end{bmatrix} \tag{14}$$

According to this matrix, line 5–1 is divided into 9 sections. For example, bus 6 is triggered only for faults that occur in segments 8 and 9. This should be done for all 16 lines. Therefore, it is only for a part of the IEEE 14-bus network in Table 3.

Considering (5) and (6), buses 11, 13, and 14 are identified as monitoring buses. and in the IEEE 57-bus network, buses 12, 17, 20, 26, 42, 50, and 52 are determined as monitoring buses.

5.2 | Determining AOV

As expressed in the previous section, in the proposed method, faults apply only to the vulnerable areas of the monitoring buses, so these areas should be obtained for all monitoring buses, for example, the 14th bus of the IEEE 14-bus network and the 52nd bus of IEEE 57-bus network, AOV is shown in Figure 7.

5.3 | Establishment of Monte Carlo database and correlation between buses

According to [13], first, the years of fault occurrence for each line must be determined based on the reverse method of the cumulative distribution function (CDF^{-1}). if the mentioned algorithm is used, the database is formed. For example, for buses 3 and 10 in the IEEE 14-bus system and for bus 21 of the IEEE 57-bus system, the information obtained from Monte Carlo is as shown in Figure 8. Such information must be obtained for all buses using the Monte Carlo method.

The interpretation of the diagrams in Figure 8 is that, for example, during 4000 years, only in 810 years in bus 3 and 559 years in bus 10, the number of voltage sags (less than 0.9 pu) is 3. Thus, it can be recognized that how many voltage sags have occurred each year. These data for bus 3, 10, and 14 are given in Table 4; and for bus 21 from the IEEE 57-bus network, 39 years of 4000 years' simulation, the SARFI values are equal to 2.

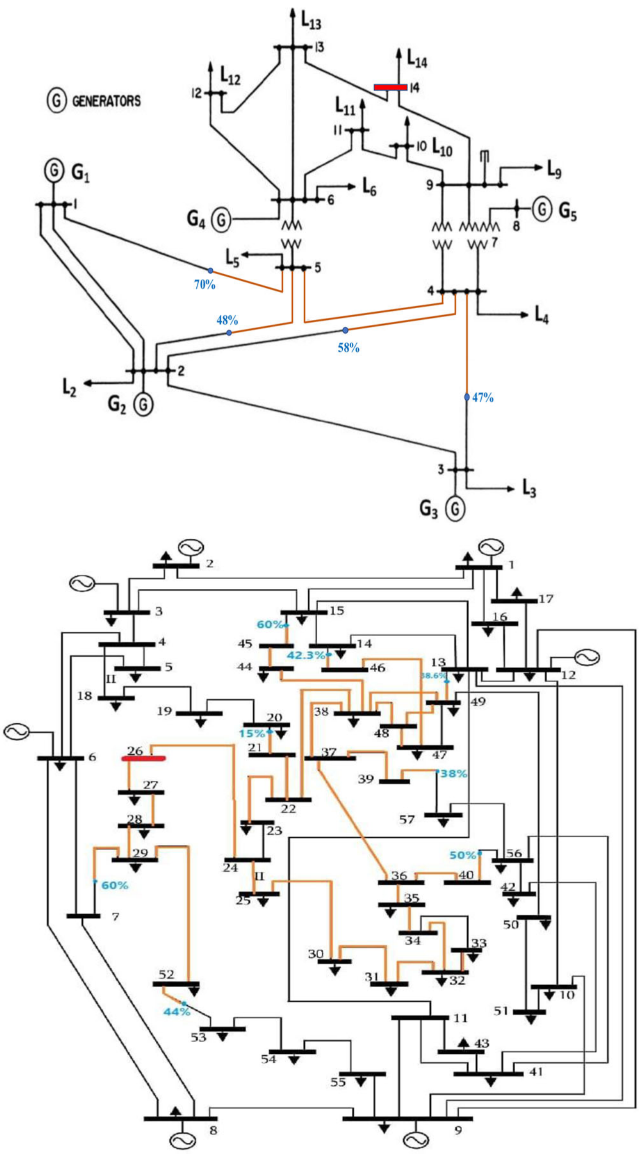

FIGURE 7 AOV of 14th bus in the IEEE-14-bus network and AOV of 52th bus in the IEEE 57-bus network.

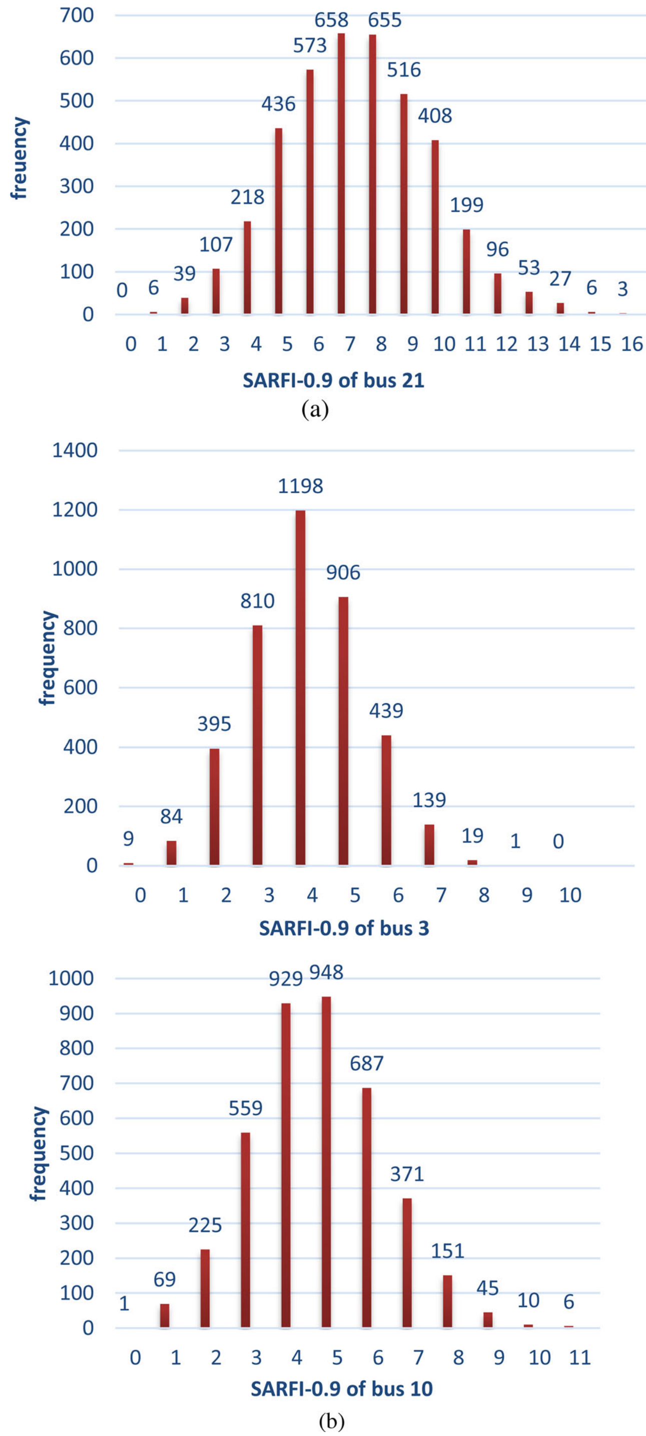

FIGURE 8 Number of SARFI index in Monte Carlo study (a) bus 21 in 57-bus system (b) buses 3 and 10 in 14-bus system.

TABLE 4 SARFI index by year for three buses 3,10 and14.

Year	1	2	4	5	6	…	4000
Bus 3	4	4	2	7	3	…	5
Bus 10	3	6	3	6	5	…	6
Bus 14	3	7	3	6	5	…	8

According to Table 4, we can determine the number of voltage sags per year, for example, in the sixth year, 3 voltage sags occurred in bus3 and 5 voltage sags in buses 10 and 14. The information in this table will be used to estimate the index of non-monitoring buses according to formula (12).

The following table 5 is obtained to determine the correlation between the buses using the expressed method and using the database formed by the Monte Carlo method.

According to this table, it is possible to determine which monitor buses in the Bayesian method can be used to estimate the SARFI index of non-monitored buses. For example, to estimate the number of SARFI in bus 10 buses 11, and 14 information can be used, or to estimate bus 6 index, bus 13 information can be used.

TABLE 5 Correlation matrix of SARFI-90 index of the IEEE −14 bus network.

bus	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	1	0.84	0.75	0.74	0.75	0.42	0.56	0.26	0.56	0.53	0.48	0.42	0.45	0.53
2	0.84	1	0.84	0.82	0.82	0.40	0.62	0.17	0.62	0.60	0.50	0.41	0.44	0.59
3	0.75	0.84	1	0.85	0.82	0.51	0.71	0.33	0.70	0.67	0.57	0.51	0.53	0.67
4	0.74	0.82	0.85	1	0.95	0.60	0.80	0.31	0.78	0.75	0.66	0.58	0.60	0.73
5	0.75	0.82	0.82	0.95	1	0.58	0.76	0.28	0.75	0.72	0.63	0.56	0.57	0.71
6	0.42	0.40	0.51	0.60	0.58	1	0.68	0.33	0.68	0.68	0.76	0.83	0.78	0.68
7	0.56	0.62	0.71	0.80	0.76	0.68	1	0.32	0.88	0.86	0.78	0.67	0.70	0.80
8	0.26	0.17	0.33	0.31	0.28	0.33	0.32	1	0.27	0.27	0.28	0.28	0.28	0.27
9	0.56	0.62	0.70	0.78	0.75	0.68	0.88	0.27	1	0.93	0.79	0.67	0.69	0.87
10	0.53	0.60	0.67	0.75	0.72	0.68	0.86	0.27	0.93	1	0.82	0.68	0.69	0.86
11	0.48	0.50	0.57	0.66	0.63	0.76	0.78	0.28	0.79	0.82	1	0.75	0.77	0.76
12	0.42	0.41	0.51	0.58	0.56	0.83	0.67	0.28	0.67	0.68	0.75	1	0.87	0.74
13	0.45	0.44	0.53	0.60	0.57	0.78	0.70	0.28	0.69	0.69	0.77	0.87	1	0.76
14	0.53	0.59	0.67	0.73	0.71	0.68	0.80	0.27	0.87	0.86	0.76	0.74	0.76	1

TABLE 6 Probability distribution of various fault types.

Fault type	Probability
Single phase to ground	0.8
Line to line	0.05
Double line to ground	0.1
Three phase	0.05

5.4 | Implementation of GA and use of Bayesian method

If three buses are considered for STATCOM installation the following results are obtained by applying 20 faults based on the probability distribution of Table 6 in specified AOV for three monitoring buses:

- Maximum number of iterations: 20
- Number of initial population: 6
- Combination rate: 0.6
- Mutation rate: 0.15
- Determining the best answer in the 12th iteration
- The number of SARFI index of the whole network for the best answer: 45.
- The solution obtained to install STATCOM: buses 10, 13, and 14.

Table 7 shows the number of voltage sags of the IEEE 14-BUS system. The total number of SARFI index, when optimal placement of STATCOM is carried out, is shown in Figure 9.

If we implement the same method in the IEEE 57-bus system for this network:

- Maximum number of iterations: 130
- Number of initial population: 16
- Combination rate: 0.6
- Mutation rate: 0.13

the results of recording the number of voltage sags are as shown in Table 8. According to this table, it is also possible to find out from which of the monitored buses the information of non-monitor buses is estimated. As mentioned in earlier sections, this requires that the correlation between the buses be obtained with information from Monte Carlo.

TABLE 7 Estimated SARFI index in non-monitored buses and result of running GA to install STATCOM.

BUS	SARFI in monitored bus	SARFI in non-monitored bus	Buses for statcom installation
1	–	3	
2	–	4	
3	–	3	
4	–	4	
5	–	4	
6	–	2	
7	–	4	
8	–	1	
9	–	4	
10	–	4	■
11	2	–	
12	–	3	
13	2	–	■
14	5	–	■

TABLE 8 Estimated SARFI index in non-monitored buses and result of running GA to install STATCOM in the IEEE 57-bus system.

Monitored buses	SARFI in monitored buses	Non-monitored buses	estimation
12	2	1	2
		4	2
		8	3
		9	2
		10	3
		23	1
		34	2
17	15	18	15
		19	15
		45	1
20	1	21	7
		54	1
26	11	3	4
		14	15
		24	12
		25	15
		27	11
		36	10
		38	6
42	14	2	3
		5	5
		6	7
		7	4
		11	13
		13	16
		39	14
		40	9
		41	12
		43	15
		44	14
		46	14
50	2	22	4
		48	4
		49	3
		51	1
		55	2
		56	12
		57	1
52	14	15	16
		16	17
		28	17
		29	18
		30	17
		31	16
		32	15
		33	17
		35	17
		37	14
		53	14

For the 57-bus network, the STATCOM locations are: 9, 14, 15, 22, 26, 31, 33, 36.

It is worth mentioning that meta-heuristic methods are an excellent approach to finding global minimization. A meta-heuristic is a higher-level heuristic that provides a sufficiently good solution to an optimization problem. Using a meta-heuristic algorithm assures us not to stick to a local minimum instead of a global minimum.

By installing STATCOMs in the specified buses, the improvement rate of the SARFI index in the IEEE 14-bus network is as shown in Figure 10.

6 | CONCLUSION

This paper has described a method for finding the optimal location of STATCOM is to reduce the number of voltage sags. The main purpose of this paper is to reduce the amount of calculations by applying faults in specific and limited areas for determining the optimal location of STATCOM.

For this purpose, by determining the monitoring buses and AOV of these buses, the areas, and buses under study are limited. Then, to obtain the information of non-monitor buses to evaluate the whole network with a GA, first, the amount of correlation between the buses is determined by the Pearson coefficient that applied to the data obtained from the Monte

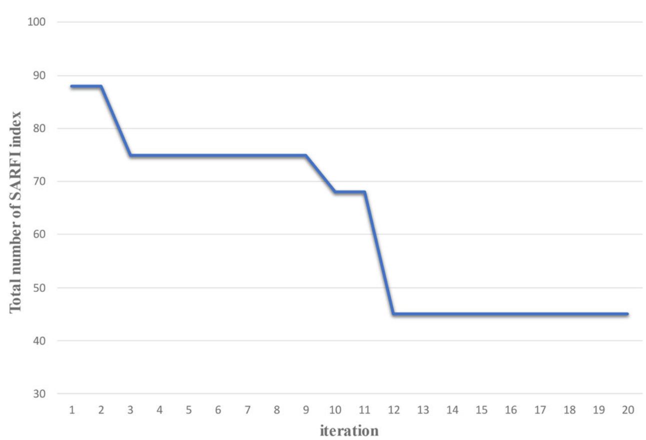

FIGURE 9 Total number of SARFI index with the implementation of GA for optimal placement of STATCOM.

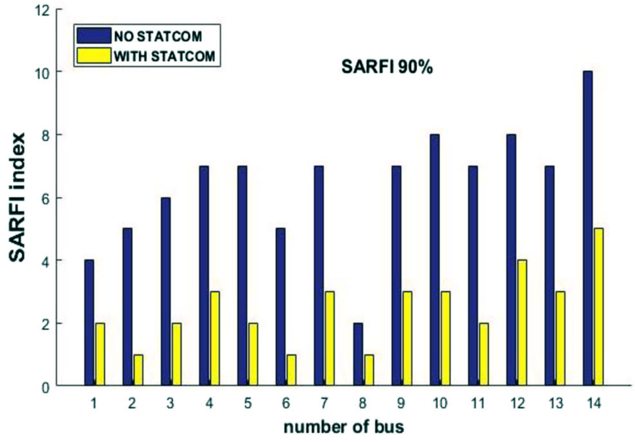

FIGURE 10 SARFI index in IEEE -bus system before and after installing STATCOM.

Carlo method, and then with the Bayesian method, the information of the non-monitor buses is estimated with the information of the monitor buses.

This makes it possible to access the information of all the buses, despite the study and monitoring of a limited number of buses.

AUTHOR CONTRIBUTIONS

All authors have equally contributed to this work. Hamed Jalalat: Simulations, formal analysis, methodology, software, validation, writing—original draft. Sahand Liasi: Simulations, formal analysis, methodology, software, validation, writing-original draft. Mohammad Tavakoli Bina: Conceptualization, formal analysis, methodology, software, supervision, validation, writing-review and editing. Amir Shahirinia: Conceptualization, formal analysis, methodology, software, supervision, validation, writing-review and editing.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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DATA AVAILABILITY STATEMENT

Simulations are the main source of our produced data, the related figures and tables.

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