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Research Article

Multiple Optimal Solutions and Sag Occurrence Index Based Placement of Voltage Sag Monitors

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Abstract: This study presents optimal placement of voltage sag monitors based on new Sag Occurrence Index (SOI) which ensures observability even in case of monitor failure or line outages. Multiple solutions for optimal placement of voltage sag monitors for voltage sag detection have been obtained by genetic algorithm approach such that observability of the whole system is guaranteed. A new Sag Occurrence Index (SOI) is proposed to obtain the severity of voltage sag at all the buses in the system. To obtain the best monitor arrangement in the system, the sum of SOI for each optimal combination is determined. IEEE 24-bus Reliability Test System (RTS) and IEEE 57-bus system were used to demonstrate the effectiveness of the proposed method. The details of implementation and simulation results are also presented.

Keywords: Multiple optimal solutions, power quality, Sag Occurrence Index (SOI), voltage sag, voltage sag monitoring

INTRODUCTION

Voltage sags or voltage dips are sudden reductions in rms voltage (IEC Standard 60050 (International Electrotechnical Commission), 1999; Bollen, 1999; McGranaghan *et al*., 1993). Voltage sag is characterized by its magnitude (the residual voltage) and its duration (the time during which the rms voltage stays below a given threshold (usually 0.9 p.u.). Moreover voltage sags are of a stochastic nature, mostly caused by remote short-circuit faults occurring in transmission and distribution systems and depends on several random factors such as fault position, fault type, pre-fault voltage, etc. In recent years, because of increasing use of sensitive equipment, voltage sags have become the serious power-quality concerns faced by utilities and customers (Juarez and Hernandez, 2006). Maximum number of equipment used in modern industrial process automation, such as process controllers, programmable logic controllers, adjustable speed drives and robotics, are sensitive to voltage sags. Failure or malfunctioning of this equipment can be caused by voltage sags leading to work or production stops with huge financial loss (Baggini, 2008; Dugan *et al*., 2003; Garcia *et al*., 2010; Goswami *et al*., 2009, 2011; McGranaghan *et al*., 1993; McGranaghan and Roettger, 2002; Milanovic and Gupta, 2006a, b; Xian *et al*., 2010).

Voltage sag monitors detect and analyze voltage sag events. Ideally voltage sag monitors must be installed at each bus in a power system to ensure observability of the whole system. However, it is shown in the literature that reducing the number of monitors will reduce the total cost of monitoring (Juarez *et al*., 2009; Olguin, 2005; Olguin *et al*., 2006). Therefore, determination of appropriate monitor placement becomes important. It includes determination of minimum number of monitors required and where these monitors should be installed (Garcia *et al*., 2010).

In Olguin *et al*. (2006) meter placement method using integer programming based modelling is proposed. The formulation based on a matrix expression relating the residual voltage at load buses during faults. A binary matrix Monitor Reach Area (MRA) is introduced to describe all monitor reach areas. The approach proposed in Olguin *et al*. (2006) cannot however assure complete observability since its formulation is based on a limited number of fault positions and is applied to a single type of fault. In Juarez and Hernandez (2006) to overcome this limitation, the proposed approach is based on MRA obtained from solution of analytical expressions which are valid for any location of faults in the power system. An integer linear optimization method is used to solve the optimization problem. A monitor positioning algorithm to determine the optimal placement of power quality monitors in distribution system based on graph

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theory and system topology is proposed (Dong and Seung-II, 2008).

In recent years, evolutionary optimization techniques like Genetic Algorithm (GA), Particle Swarm Optimization (PSO) etc., have become popular. Application of GA and Fuzzy mathematical programming in the design of voltage sag monitoring system is presented in Almeida and Kagan (2009). In Ibrahim *et al.* (2011a) power quality monitor placement method by utilizing quantum inspired particle swarm optimization technique is presented. GA is used to find the minimum number of power quality monitors in the distribution system which can guarantee the observabilty of the whole system in Ibrahim *et al.* (2011b).

In most of the existing literature, no attempt has been made to obtain multiple optimal solutions for monitor placement arrangement. However, in practical power system it is possible to obtain a set of optimal solutions satisfying the constraints, i.e., the number of monitors must be minimum and the obervability of the whole system must be guaranteed for any type of fault at any location.

In this study, multiple solutions of optimal placement of voltage sag monitors have been obtained by genetic algorithm approach. A new Sag Occurrence Index (SOI) has also been proposed. Based on the proposed *SOI* vulnerability to voltage sags at various buses in the network has been investigated. If the monitors are placed at these vulnerable buses then possibility of capturing each and every fault event by at least one or more monitors will be maximum. Therefore the proposed method finds the best arrangement of minimum number of voltage sag monitors which ensures complete observability of the whole system. The applicability of the proposed method has been tested on IEEE 24-bus Reliability Test System (RTS) and IEEE 57-bus system.

THE CONCEPT OF MONITOR OBSERVABILITY

Observability of the entire network means the ability of the voltage sag monitors to capture all voltage sag events below a set threshold value. There is a close relation between the concept of MRA and the concept of monitor observability. The MRA is defined as the area of the network that can be observed from a given meter position. For formulation of MRA, the residual voltage at each bus during all the fault events is required. Therefore, residual voltages during each fault event are to be stored in a matrix which is called as Fault Voltage (FV) matrix. Each column of FV matrix represents buses in the system and each row represents residual voltages during all the fault events. In most of the existing work, while calculating the residual voltage the pre-fault voltages at buses are considered as 1 p.u. This leads to inaccurate residual voltage values (Garcia *et al.*, 2010). Therefore, in this study, all pre-fault voltages are calculated by load flow analysis in order to avoid the above mentioned limitation.

Another important consideration for construction of MRA is monitor threshold (t). Threshold level is the voltage t per unit at which the meter starts recording. A sag monitor detects and captures voltage variations by comparing the measured rms value to a threshold setting. The commonly used voltage sag threshold is 0.9 p.u., (Electromagnetic Compatibility (EMC)-Part2-8: 2002; IEEE Recommended Practice for Monitoring Electric Power Quality, 1995).

Monitor Reach Matrix (MRA): MRA matrix can be obtained by comparing all the FV matrix elements with the set threshold value t. The element of MRA matrix is one if the bus residual voltage at a bus is less than or equal to threshold value t and it is zero if the residual voltage at a bus is greater than threshold t. In this study, the threshold is set at 0.9 p.u. The construction of the MRA matrix is expressed as in Eq. (1):

$$MRA_{(j,k)} = \begin{cases} 1, \mathit{if}\ FV(j,k) \le 0.9\, p.u\, at\, any\, phase \\ 0, \mathit{if}\ FV(j,k) > 0.9\, p.u\, at\, all\, phases \end{cases} \tag{1}$$

A particular row j of matrix $MRA_{(j,\ k)}$ indicates by means of 1 that the fault event can be captured by a meter installed at bus j. Similarly, elements of column k of $MRA_{(j,\ k)}$ indicate the meter positions from which a fault at k can be captured.

OBJECTIVE FUNCTION

In this study, the optimal monitor placement problem consists of two steps. The first step is to determine multiple optimal solutions for number of voltage sag monitors and the second step is to determine the best monitor placement based on *SOI*.

Consider now a decision row vector X. It is a binary vector which indicates whether a monitor is installed at bus j. Binary 1 in vector X indicates that the monitor is installed at bus j whereas, 0 in vector X indicates that monitor is not installed at bus j. The vector X can be described as follows (2):

$$X_j = \begin{cases} 1, \mathit{if}\ monitor\ \ is\ \ needed\ \ at\ j \\ 0, \mathit{if}\ monitor\ is\ not\ needed\ at\ j \end{cases} \tag{2}$$

The objective function of the optimization problem is to minimize the number of voltage sag monitors. This can be mathematically expressed as (3):

$$F = \min \sum_{j=1}^{N} X(j) \tag{3}$$

where,

N = Total number of buses in the system

According to the definition of MRA (1), the non-zero element of column k corresponds to buses where voltage sag for a particular fault event is captured. In order to guarantee the observability, at least one of the non zero elements of column k must correspond to a monitored bus. Therefore, the product of column k of MRA multiplied by the vector X must be equal to or greater than 1 in order to ensure the observability of column k. This condition must be fulfilled for all types of faults, i.e., 3-phase, LL, LG and DLG.

Thus the objective function described in (3) must be modified by including the constraints as (4):

$$F = \min \sum_{j=1}^{N} X(j)$$

Subject to the following constraints:

$$\left.\begin{array}{l} \sum_{j=1}^{N} MRA_{3p}(j,k)\,X(j) \geq 1 \\ \sum_{j=1}^{N} MRA_{LL}(j,k)\,X(j) \geq 1 \\ \sum_{j=1}^{N} MRA_{LG}(j,k)\,X(j) \geq 1 \\ \sum_{j=1}^{N} MRA_{DLG}(j,k)\,X(j) \geq 1 \end{array}\right\} \tag{4}$$

where, MRA_{3p} represents the MRA matrix obtained by considering three-phase balanced faults, MRA_{LL} represents the MRA matrix obtained considering line to line fault, $\mathrm{MRA}_{\mathrm{LG}}$ represents the MRA matrix considering single line to ground fault and MRA_{DLG} represents the MRA matrix obtained considering double line to ground fault.

A GA is used to solve the problem described by (4). GA gives a set of multiple optimal solutions. All the solutions satisfy the constraints given by (4), i.e., monitors are able to capture all the fault events and number of monitors is minimum possible.

Sag Occurrence Index (*SOI*): Residual voltages at all the buses during each fault event are stored in a matrix which is called as Fault Voltage (*FV*) matrix. Each column of *FV* matrix represents buses in the system and each row represents residual voltages during all the fault events. The sum of residual voltages for each fault event at a particular bus indicates the vulnerability to voltage sag for that bus. Low sum of residual voltages indicates that severe voltage sag occurs at that bus for most of the fault events. If voltage sag monitors are placed at these buses then complete observalibility of the network can be guaranteed. Thus, to evaluate the best monitor arrangement in a power system, Sag occurrence Index (*SOI*) is proposed (5). Lowest value of *SOI* will indicate the most vulnerable bus to voltage sag in the system. Placement of voltage sag monitors at most vulnerable buses increases the possibility of capturing each fault event by at least one or more monitors:

$$SOI = \frac{\sum_{k=1}^{TFV} FV}{TFV} \tag{5}$$

where,

TFV = Total number of fault events considering all types of faults (3-p, LL, LG, DLG). Brief introduction of GA is presented in the following section.

BRIEF DESCRIPTION OF GENETIC ALGORITHM (GA) AND ITS IMPLEMENTATION

The GA has become a well-accepted technique for solving complex search problems. It is based on the principles of genetic variation and natural selection and is considered to offer a high probability of finding the global or near global optimum solution of difficult optimization problems with objective functions that do not possess nice properties such as continuity, differentiability etc. The theoretical development of GAs is largely credited to the work of Holland (1975) and Goldberg (1989). Since then, the GA has evolved and found applications in almost every area of optimization, especially those areas involving problems where the search space is not very well understood. The increasing popularity enjoyed by GA can be attributed in part to its simplicity, elegance, ease of implementation and its proven ability to often find good solutions for difficult high-dimensional function optimization or combinatorial problems with continuous or discrete variables (Goldberg, 1989; Haput and Haput, 2004).

There are three phases involved in the GA process, namely selection, crossing-over and mutation. Some of the best chromosomes are selected to be parents for the next generation. Then, the GA operators crossover the randomly chosen parents' chromosomes to generate off-spring chromosomes and then mutate a small part of a randomly chosen off-spring chromosome to get new, better and unique individual chromosomes.

Method of GA implementation: In order to obtain different optimal arrangements of voltage sag monitors, GA is applied to minimize the objective function *F*. The steps involved in finding the optimal monitor placements are given below and its flow chart is shown in Fig. 1:

- Read system data and set GA parameters
- Solve load flow equations and compute pre-fault voltages at all the buses

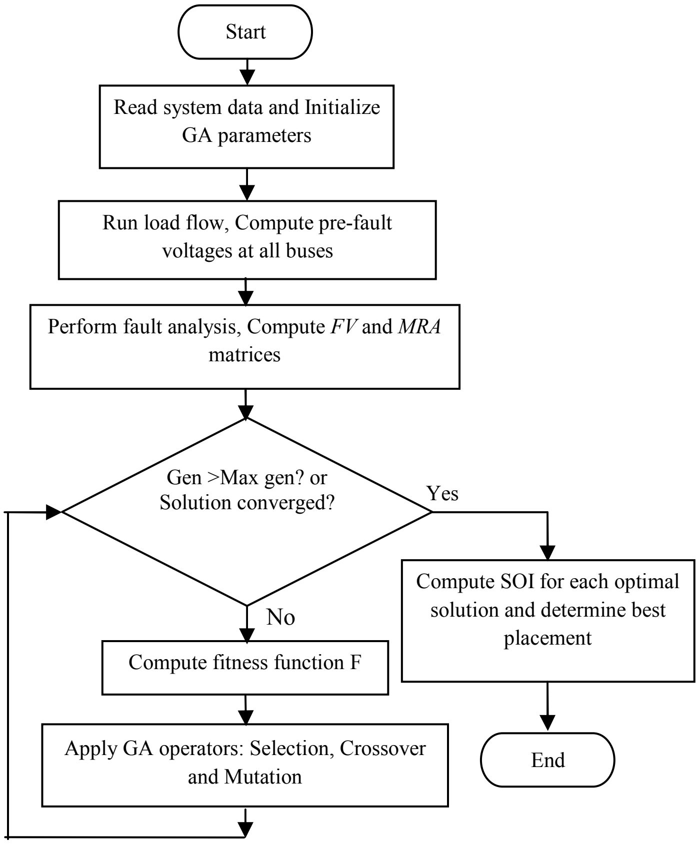

Fig. 1: Flow chart for GA implementation

- Perform fault analysis and calculate residual voltage magnitudes at all the buses of the system by simulating 3-p, LL, LG and DLG faults at all the buses and along all the lines
- Construct Fault Voltage (*FV*) matrix and Monitor Reach Area (*MRA*) matrix
- Compute the objective/fitness function *F* given by (4)
- Solve the constrained optimization problem by applying GA operators: selection, crossover and mutation
- If number of generations is less than maximum no. of generations or if the solution is not converged, repeat steps 5 and 6, else stop
- Obtain multiple optimal solutions for monitor placement using GA
- Calculate SOI for each optimal solution to determine the best monitor placement

RESULTS AND DISCUSSION

The applicability of the proposed method has been tested on IEEE 24-bus Reliability Test System (RTS) and IEEE 57-bus system. The system data are obtained from (IEEE RTS Task Force of the Application of Probability Methods Subcommittee, 1999; Power System Test Archive-UWEE (University of Washington), http://www.ee.washington.edu/research/pstca.). Optimal locations of voltage sag monitors were determined by applying the proposed GA approach. The monitor-reach area matrix was built considering fault events at all the buses as well as all the lines. The algorithm has been implemented using (MATLAB®, http://www.mathworks.com; Houck *et al*., 2008).

IEEE 24-bus Reliability Test System (RTS): The IEEE 24-bus Reliability Test System (RTS) has ten generator buses, ten load buses, five transformers and 33 transmission lines. As the number of buses is 24, total number of binary decision variables in X is 24. Total 198 fault locations were selected at all the buses and along all the lines so as to cover the entire system. Residual voltages during faults along the lines were calculated using analytical method described in Juarez and Hernandez (2006). 3-phase, LL, LG and DLG faults were simulated at these fault locations giving 792 (198×4) fault events. The Constraint for the meter placement is at least one voltage sag monitor should capture the voltage sag for these 792 fault events. Threshold of the meter was taken as 0.9 p.u.

After applying the optimization algorithm it was found that four monitors are enough to completely detect voltage sag occurrences in IEEE 24-bus reliability test system. The GA found 19 different optimal solutions as shown in Table 1. All the solutions

Table 1: Possible monitor combinations in IEEE 24-bus reliability test system

Combination	Bus number			
1	3	6	12	17
2	3	6	12	22
3	3	6	13	17
4	3	6	17	20
5	3	6	17	23
6	3	6	20	22
7	3	6	22	23
8	3	10	12	17
9	3	10	12	22
10	3	10	17	23
11	3	10	20	22
12	6	12	17	24
13	6	12	22	24
14	10	12	17	24
15	10	12	22	24
16	10	13	17	24
17	10	13	22	24
18	10	20	22	24
19	10	22	23	24

Table 2: Number of monitors triggered for all the 792 fault events for combination no. 8

No. of monitors triggered	No. of fault events
One	34
Two	97
Three	269
Four	392
Total fault events	792

satisfy the two constraints, i.e., the monitors are able to cover the entire system and the number of monitors is the minimum possible.

SOI was then computed for all the buses in the system. Figure 2 shows the value of *SOI* for all the buses in IEEE 24-bus reliability test system. It can be observed from the figure that bus no. 14 is the most vulnerable bus to voltage sag with *SOI* equal to 0.7183.

Other vulnerable buses in the system are bus no. 3, 4, 9, 10, 11 and 24 as shown in Fig. 3. In order to obtain the best monitor placement, the sum of *SOI* is calculated for all possible optimal combinations. Figure 4 shows the sum of *SOI* for all 19 combinations in IEEE 24-bus reliability test system. It can be observed from Fig. 4 that the sum of *SOI* is lowest for combination no. 8. If monitors are placed according to this combination the possibility of capturing each fault event will be maximum.

To highlight the reach of different monitors for combination 8 (monitors at bus no. 3, 10, 12 and 17), number of monitors triggered for all the 792 fault events is shown in Table 2. It can be observed that for combination no. 8, for 392 fault events all the four monitors will trigger and for 269 fault events three monitors will trigger. As most of the fault events are captured by three and four monitors, possibility of capturing the fault event even in case of line outage or monitor failure will be maximum.

IEEE 57-bus system: The system consists of seven synchronous machines including three synchronous condensers. Synchronous condensers connected at bus 2, 6 and 9 are used only for reactive power support. Four generators are located at bus no. 1, 3, 8 and 12. There are 80 branches and 57 buses with 42 loads totalling 1250.8 MW and 336.4 MVAR at base case. In this system, total 378 fault locations were selected at all the buses and along all the lines. 3-phase, LL, LG and DLG faults were simulated at these fault locations

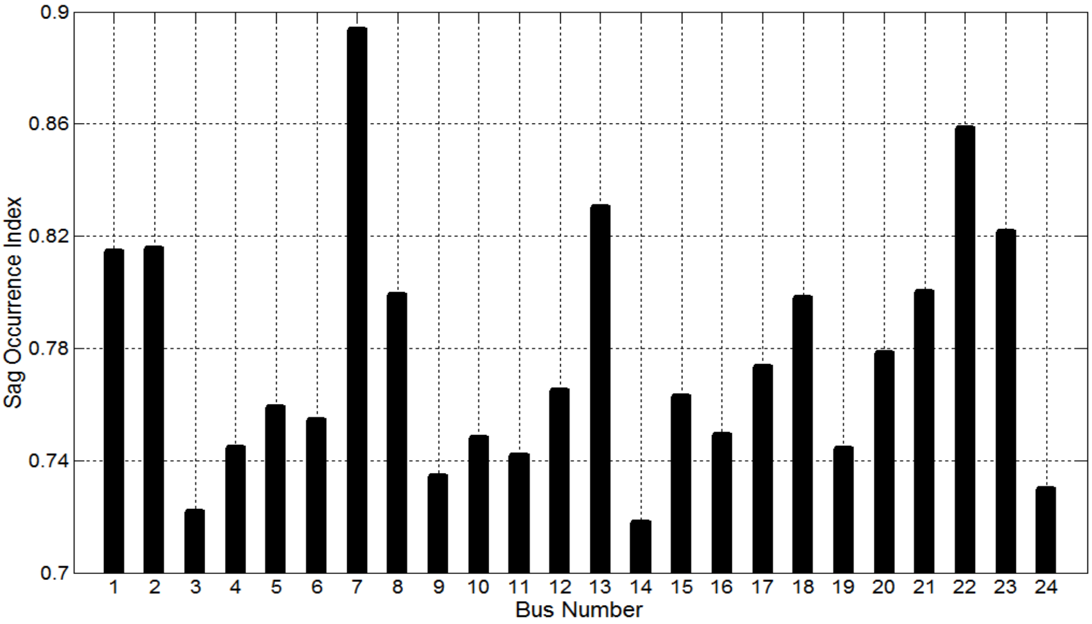

Fig. 2: Sag occurrence index at all buses in IEEE 24-bus system

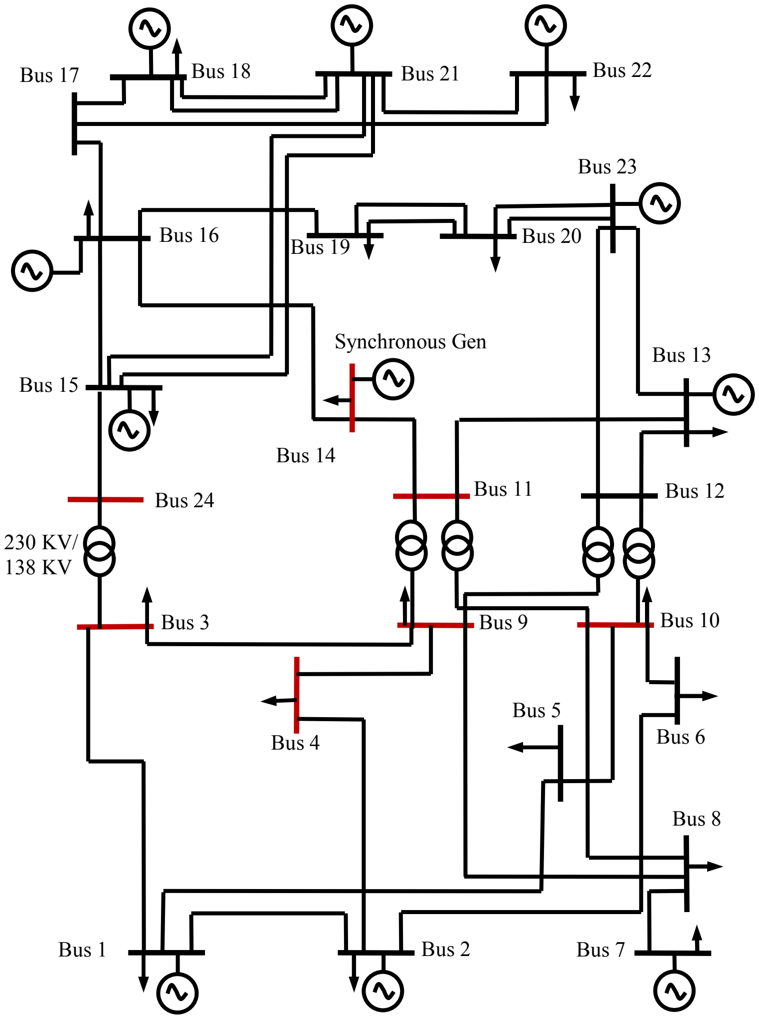

Fig. 3: Most vulnerable buses to voltage sag as per *SOI* in IEEE 24-bus reliability test system

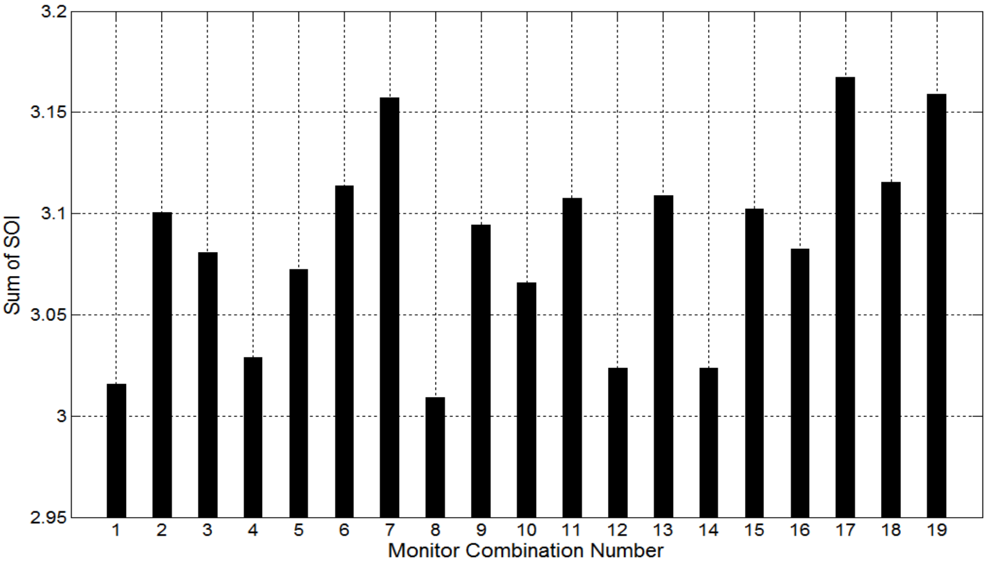

Fig. 4: Sum of SOI for all possible combinations in IEEE 24-bus RTS

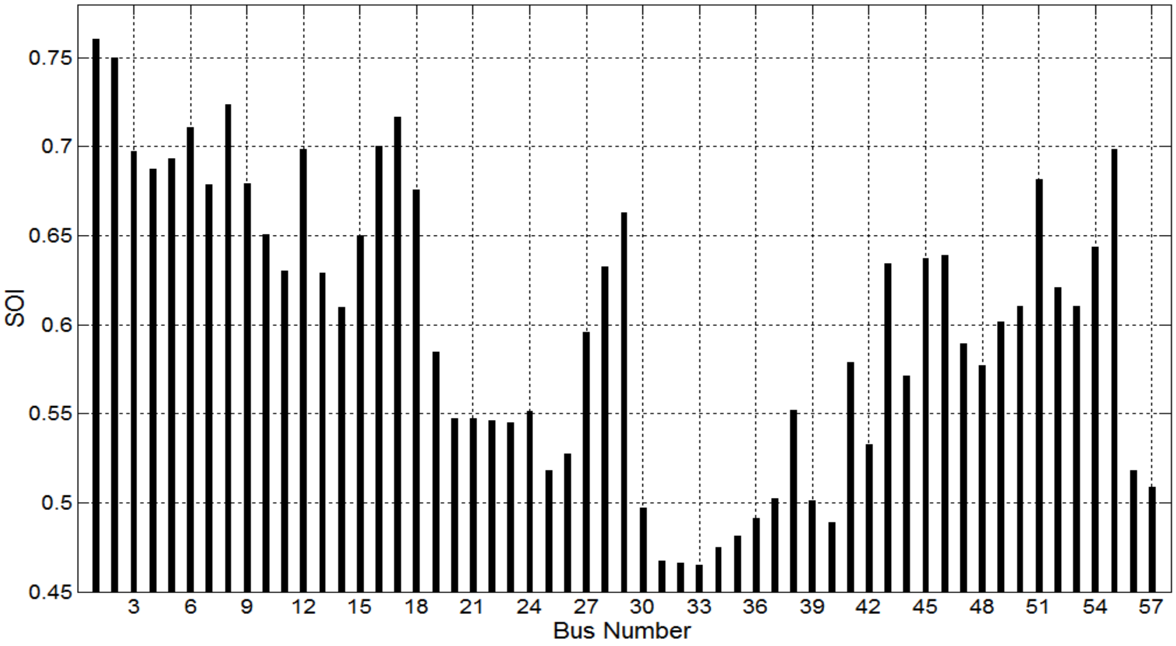

Fig. 5: Sag occurrence index at all buses in IEEE 57-bus system

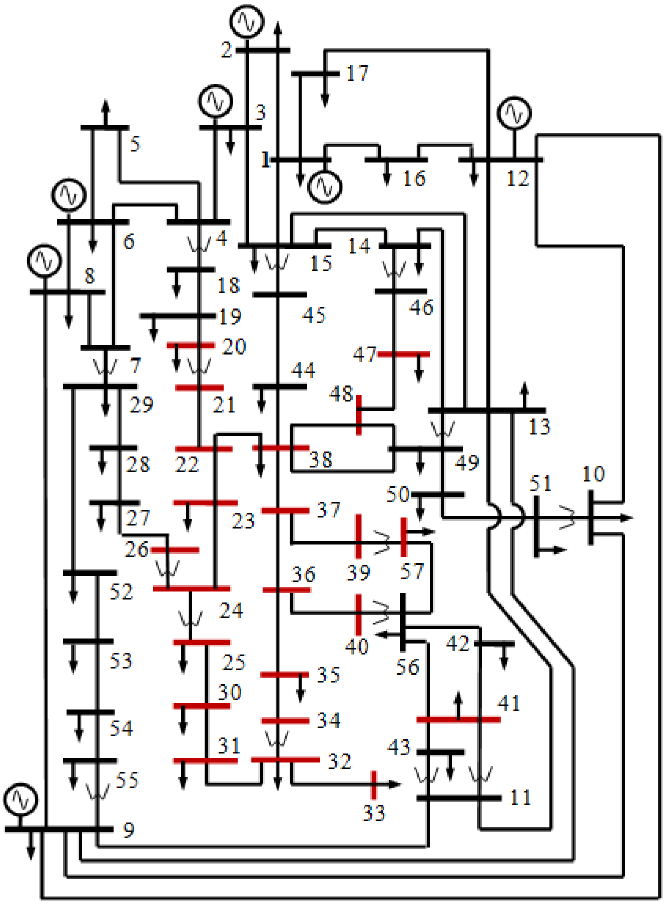

Fig. 6: Most vulnerable buses to voltage sag as per *SOI* in IEEE 57-bus test system

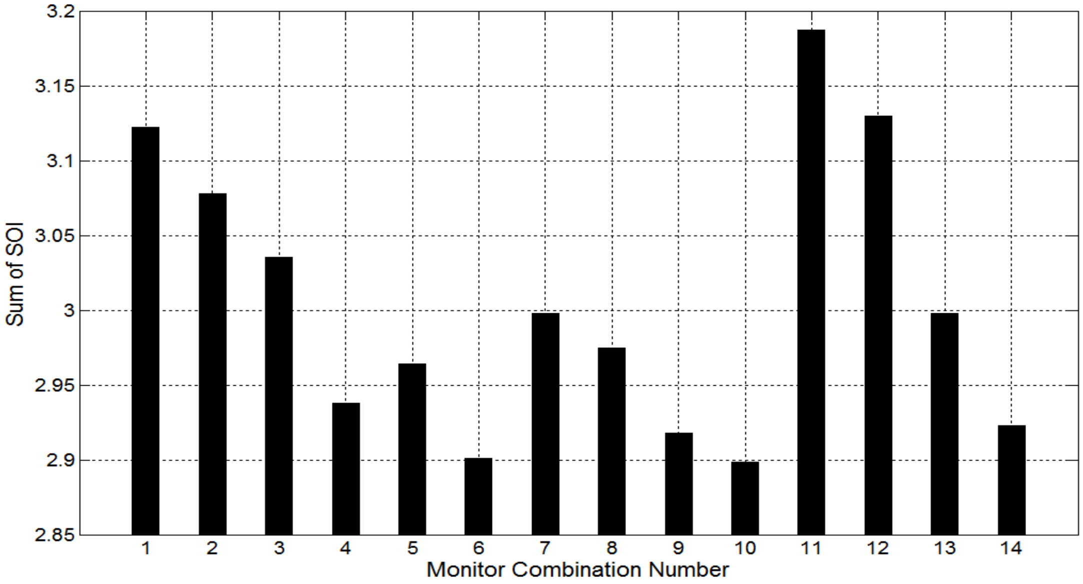

Fig. 7: Sum of SOI for all possible combinations in IEEE 57-bus system

Table 3: Possible monitor combinations in IEEE 57-bus system

Combination	Bus number				
1	1	10	20	33	55
2	10	16	21	35	55
3	12	19	24	37	55
4	12	19	35	38	52
5	12	20	23	34	55
6	12	21	23	32	54
7	12	21	24	37	55
8	12	21	26	37	55
9	12	21	26	39	54
10	12	21	33	48	53
11	16	18	29	32	51
12	16	19	33	51	55
13	16	20	24	39	55
14	16	20	34	37	55

Table 4: Number of monitors triggered for all the 1512 fault events for combination no. 10

No. of monitors triggered	No. of fault events
One	164
Two	104
Three	160
Four	164
Five	920
Total fault events	1512

giving 1512 (378×4) fault events. The Constraint for meter placement is same, i.e., at least one power quality monitor should capture the voltage sag for these 1512 fault events. In this case also threshold of the meter was taken as 0.9 p.u.

GA is used to solve the optimization problem. It was found that five monitors are sufficient to completely detect voltage sag occurrences in IEEE 57-bus test system. GA found 14 different optimal solutions. Again all the solutions satisfy the two constraints, i.e., the monitors are able to cover the entire system and the number of monitors is the minimum possible. Table 3 shows these 14 possible monitor combinations in IEEE 57-bus system.

The value of *SOI* for each bus in IEEE 57-bus system is shown in Fig. 5. It can be observed from the figure that bus no. 33 is the most vulnerable bus to voltage sag with *SOI* equal to 0.4649. Some other vulnerable buses in IEEE 57-bus system are shown in Fig. 6. In order to obtain the best monitor placement the sum of *SOI* is calculated for all possible optimal combinations. Figure 7 shows the sum of SOI for all 14 optimal combinations in IEEE 57-bus test system. It can be observed from Fig. 7 that the sum of SOI is lowest for combination no. 10. If monitors are placed according to this combination the possibility of capturing each fault event will be maximum.

To highlight the reach of different monitors for combination 10 (monitors at bus no. 12, 21, 33, 48 and 53), number of monitors triggered for all the 1512 fault events is shown in Table 4. It can be observed that for combination no. 10, for 920 fault events all the five monitors will trigger. As most of the fault events are captured by all the five monitors, possibility of capturing the fault event even in case of line outage or monitor failure will be maximum.

CONCLUSION

In this study a new approach has been proposed for optimal placement of voltage sag monitors. Multiple optimal solutions for placement of voltage sag monitors have been obtained by applying GA. A new Sag Occurrence Index (*SOI*) has also been proposed to identify the most vulnerable buses to voltage sag in the system. The formulation is based on the use of *MRA* matrix that is obtained by applying an analytical method to calculate the residual voltages caused by 3-phase, LL, LG and DLG faults occurring at all the buses and along all the lines. The proposed method has been applied to IEEE 24-bus and IEEE 57-bus test systems. The proposed methodology can be utilised to minimize the installation cost of voltage sag monitors and also to ensure complete observability even in case of monitor failure or line outages as most of the fault events are captured by many monitors.

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