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Reliability Improvement in Distribution Systems by Optimal Placement of DSTATCOM Using Binary Gravitational Search Algorithm

Abstract. *In this paper, a new method for improving reliability level of distribution systems is presented by employing optimal placement of DSTATCOM. The binary version of the Gravitational Search algorithm (BGSA) is used to solve the DSTATCOM optimal placement problem. The simulation results show that the proposed method is efficient and feasible for improving the system reliability level by reducing load outages and momentary interruptions.*

Streszczenie. *Przedstawiono nową metodę poprawy niezawodności system dystrybucji energii dzięki optymalizacji DSTATCOM. Optymalne położenie DSTATCOM było określane na podstawie algorytmu BGSA. Uzyskano [poprawę dzięki dedukcji przerw w obciążeniu i chwilowych zaników. (**Poprawa niezawodności systemu dystrybucji energii dzięki optymalnemu ustawieniu DSTATCOM**)*

Keywords: Voltage sag, Reliability, Distribution Systems, DSTATCOM, GSA, Power Quality.
Słowa kluczowe: niezawodność, system dystrybucji energii, DSTATCOM.

Introduction

The unprecedented changes in the technology have changed the customer's expectation about quality and continuity of energy from power utilities. A minute disturbance such as voltage sag may cause large amount of financial loss due to increased level of dependency on electricity in industrial processes. Therefore, utilities have to consider seriously the quality and reliability of the power supply. Reliability is defined as the ability of a system to perform required functions under stated conditions for a given period of time. In power systems, reliability and security have the same implication. For example, a distribution system whose security level is low is said to be unreliable and vice versa. There are many reliability indices which are categorized in three groups, namely, sustained interruption indices, load based indices and momentary indices that are used for reliability assessment [1]. Among them, load based index such as the average system interruption frequency index (ASIFI) and momentary index such as the momentary average interruption frequency index (MAIFI) are most suitable for reliability assessment related to voltage sag problems.

Some researchers have developed suitable algorithms to analyze security of distribution system by predicting the response of the network seen by customers to the expected range of faults [2]. Many algorithms were also introduced on reliability assessment and improvement. An algorithm for reliability improvement using a static series voltage regulator (SSVR) can be found in [3]. The algorithm considers the effects of distributed generation (DG) units, alternative sources, system reconfiguration and load shedding. In a different approach, DSTATCOM was utilized mainly to mitigate voltage sag propagation and avoid process interruption [4]. Voltage sag which is generally caused by short circuits may cause sensitive equipment to malfunction and process interruption. Once the process is interrupted it takes several hours to restart the process, hence affecting the reliability level in distribution systems. Voltage sag is defined as a decrease in rms voltage magnitude between 0.1 and 0.9 pu at duration of 0.5 cycle to 1 min [5]. In a related work, a method was introduced for voltage sag assessment based on whether the equipment will trip or not. As such voltage acceptability curves are introduced as a reliability indicator from the customer's perspective [6-7]. Based on the above discussion, it can be concluded voltage sag causes power supply interruption for many types of loads and reliability level in distribution system is extremely affected by voltage sag performance. In other words, voltage sag mitigation methods can be employed for improving the reliability of distribution systems.

In this paper, a new method for improving reliability of distribution system is presented based on the optimal placement of the DSTATCOM. In the proposed method, an algorithm for reducing the exposed area of voltage sag propagation due to weak area is first developed. Then, DSTATCOM placement is employed for reducing the number of propagated sags throughout the distribution systems. A binary version of gravitational search algorithm (BGSA) is used as heuristic computational optimization tool to determine the optimal DSTATCOM placement [8]. Finally, for reliability assessment, a method for calculating the number of sags which may be experienced at each load point in distribution system is used along with reliability indices such as ASIFI and MAIFI. The proposed method may assist utility engineers in taking the right decision for system reliability improvement.

DSTATCOM Modelling

Electronic-based mitigation devices provide good solutions to voltage sag problems. The installation of these devices can improve not only an individual user's sag performance, but also the voltage sag profile of the entire network [10]. Dynamic voltage restorer and STATCOM are normally employed as solutions for mitigation of voltage sag problem [11]. DSTATCOM is considered as the most popular type of shunt compensation custom power device that may be used for voltage sag mitigation. In this paper, DSTATCOM is considered as a solution for both voltage sag mitigation and reliability improvement.

Before modelling the DSTATCOM, all distribution system components, i.e., lines and cables, loads, transformers, large motors and generators have to be converted into equivalent reactance (X) and resistance (R) on common bases. The main system component models are used in the formulation of impedance matrix for voltage sag calculation [13]. DSTATCOM is treated as a current source in the calculation of the node residual voltages during short circuit analysis by using the impedance matrix method [12]. If Z_{kf} is the transfer impedance between bus k $(k=1, 2, 3. . . N_{bus}$, N_{bus} is the total number of system buses) and fault location, a compensation current of DSTATCOM (I_{sh}) is injected from a compensated bus, c and the transfer impedance between bus, *k* and compensation bus, c is Z_{kc} then the bus voltage magnitude during the fault event can be expressed as in (1), where the compensation is considered.

$$V_k = V_k^{pre-fault} + Z_{kc} * I_{sh} - Z_{kf} * I_f \tag{1}$$

Equation (1) can be generalized for the whole system and the effect of the DSTATCOM compensation can be determined from (2).

$$\begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_n \end{bmatrix} = \begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_n \end{bmatrix}^{pre-fault} + \begin{bmatrix} Z_{11} & \cdots & Z_{1n} \\ \vdots & \ddots & \vdots \\ Z_{n1} & \cdots & Z_{nn} \end{bmatrix} \times \begin{bmatrix} 0 \\ I_{sh} \\ -I_f \\ 0 \end{bmatrix} \tag{2}$$

The maximum size of DSTATCOM can be defined according to the available sizes in the market and the budget of utility investment.

Binary Gravitational Search Algorithm

Gravitational Search Algorithm (GSA) is one of the newest heuristic algorithms that has been inspired by the Newtonian laws of gravity and motion, where its searcher agents are the collection of masses. In GSA, masses are introduced to find the optimum solution by simulation of Newtonian laws of gravity and motion [14]. Detailed description of the GSA can be found in [15].

In binary version of GSA, a sigmoid function is used to transfer the velocity into a probability function. The sigmoid function should be in the interval of (0, 1) [8]. Once the sigmoid function is calculated, the agents will move to next new positions according to the rule of probability. The GSA algorithm is different from other swarm based heuristic algorithm like particle swarm optimization (PSO) algorithm. In both GSA and PSO, optimization is obtained by agents' movement in the search space; however the movement strategies are different [15].

Calculation of Number of Sags

The number of sags must be calculated during the defined reporting period. Based on fault analysis, the affected load points in the exposed area of each fault location can be identified. The problem is to determine which component in the system cause significant voltage sag when faulted, and the probability of its fault occurrence. The voltage sag magnitude depends on fault location in the system, therefore sags farther away are generally less severe [6]. It is important to do calculations for every possible fault is the system. The line faults are considered as main causes of voltage sags. Therefore, it is often convenient to identify the portions of every line which can cause larger exposed area of sag in the system. To estimate the number of sags below a certain magnitude, it is important to define the exposed length of faulted line or portion of the line. The resulting exposed length is multiplied by the fault rate of the line or cable (faults per km per year) to obtain the number of sags per year [6]. The calculation can be done for all possible fault events. The possible events may represent all fault occurrences on lines, bus bars and transformers. If the fault rate of line is λ_L (faults per km per year) and faulted line length is L, the expected number of voltage sags due to faults on distribution lines can be expressed as:

$$L_{sag} = L * \lambda_L \tag{3}$$

In the same manner, the number of sags due to the faulted buses (N_{sag}) and faulted transformers (T_{sag}) can be calculated by using the fault rate of system buses (faults per bus per year) and the fault rate of distribution transformer (faults per transformer per year) respectively. The total expected number of sags ($TNSAG$) due to all fault events can be expressed as:

$$TNSAG = N_{sag} + L_{sag} + T_{sag} \tag{4}$$

Optimization Problem Formulation

The necessity of optimization in this work is to find optimal solution for voltage sag mitigation problem in distribution systems. The formulation of suitable objective function is the main step in optimization. The solution is by determining optimal placement and sizing of DSTATCOM in distribution system. In this work, the objective function of DSTATCOM placement process is formulated to minimize the total number of sags (4). During the searching process, for every change in the device location, the number of healthy buses (N_{hlth}) and system losses (F_{loss}) must be calculated by short circuit analysis and steady state load flow. The calculation must be subjected to system operation constraints, where these constraints can be mentioned as: the nominal bus voltages must be within standard limits, $V_{min} \le V_i \le V_{max}$ where V_{min} is lower limit of nominal voltage magnitude; V_i is voltage magnitude of bus i and V_{max} is the maximum limit of nominal voltage magnitude. The current flows must be within the thermal limits of the lines, $I_i \le I_{imax}$. where Ii is the current of line *i* and I_{imax} is the thermal limit of the line i. The system line loss (Floss) obtained from load flow calculations must also be within acceptable limits.

The number of buses reaching the healthy condition (N_{hlth}) due to the compensation of the DSTATCOM must be calculated. In this case a bus is said to be healthy when its voltage magnitude lies between 0.9 pu and 1.06 pu. If C_i is the healthy condition (0 or 1) for bus i during voltage sag duration, then it can be formulated as:

$$N_{hlth} = \sum_{i=1}^{N_{bus}} C_i \tag{5}$$

$$C_i = \begin{cases} 1 \cdots\cdots 0.9 \le V_i \le 1.06 \\ 0 \cdots\cdots else \end{cases} \tag{6}$$

The calculation must be done before and after each placement process. The minimization of fitness function (4) is further constrained by the increase in system losses (5), where Floss must be calculated before optimization as (F_{loss}b) and during optimization as (F_{loss}a).

In this work, placing a DSTATCOM is suggested as technique of voltage sag mitigation. Here, it is assumed that only a single device based on previously determined weak area need to be optimally installed to compensate voltage sag problem in the distribution system. The best solution can be obtained by changing the location and size of the DSTATCOM in distribution system.

To apply BGSA, some encoding and recording decision variables are required. The encoding technique is a process of translating decision variables into binary string. Meanwhile the decoding technique is opposite to that of encoding and it can be defined as a process of translating binary string into decision variables. Usually the initial population of optimization process is randomly generated. However, the random generation causes the most number of generated strings to be infeasible due to the system constraints. Therefore, an encoding technique is necessary to generate only the suitable strings for feasible solutions.

In the encoding for DSTATCOM placement problem, all system nodes can be considered as feasible locations for DSTATCOM except the substations and main source node, where these nodes must be avoided because of large size required for those locations. DSTATCOM location can be decoded as sum (binary string). If the obtained location represents substation bus, then take other system bus randomly. Meanwhile, the size is selected within limits of maximum value randomly. The developed DSTATCOM placement and sizing algorithm is explained in the flowchart shown in Fig. 1.

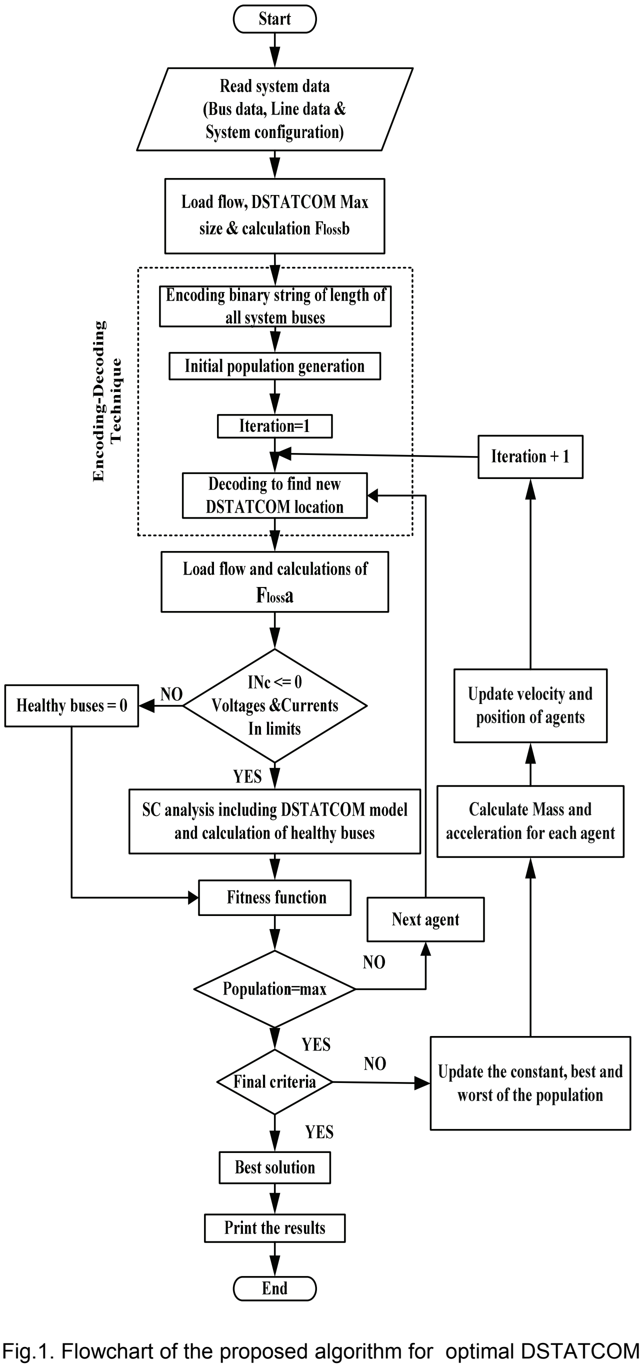

Fig.1. Flowchart of the proposed algorithm for optimal DSTATCOM placement using BGSA for voltage sag mitigation

Reliability Assessment

Improvement in voltage sag performance results in reliability level improvement. If the calculated number of sags can be translated into momentary interruptions and load outages, the corresponding reliability indices can be obtained. The calculation of those indices can be carried out directly by using the number of sags. The sustained interruptions are considered for all downstream loads of the faulted bus. At the same time, all upstream loads of the same faulted bus may experience momentary interruptions due to voltage sags.

The calculation of average system interruption frequency index (*ASIFI*) is based on load outages rather than customers affected, where the voltage sag may cause load outages.

If L_i is the connected kVA load interrupted for each interruption event, and L_T is the total connected kVA load served, the index which indicate the reliability level due to load outages can be expressed as (IEEE Std-1366 2004):

$$(7) \qquad ASIFI = \frac{\sum L_i}{L_T}$$

Meanwhile, the other index indicates the average frequency of momentary interruptions (*MAIFI*) in which its calculation is based on the momentary interruptions of customers due to voltage sags. The index indicates reliability level of customers.

If IMi is number of momentary interruptions for each event, Nm_i is number of interrupted customers for each momentary interruption event during the reporting period and NT total number of customers served for the areas, the index which indicates the reliability level due to customers interruptions can be expressed as [1]:

$$(8) \qquad MAIFI = \frac{\sum IM_i N_{mi}}{N_T}$$

The improvement of reliability level corresponding to the mitigating of voltage sag in distribution systems can be indicated by the calculation of these two indices. The previous developed method of voltage sag mitigation can be evaluated and assessed by using (4) for the total number of propagated sags. In the same manner, the proposed method can assess reliability level improvement by using the reliability indices (7-8). The assessment is done for the base case and before and after optimal placement of DSTATCOM.

Results and Discussion

A practical distribution system shown in Fig. 2 is selected to validate the proposed method. The system is composed of 47 buses and 42 lines supplied by four 132 kV substations connected to buses 2, 17, 34 and 39, respectively. The substations 2 and 17 are fed by 132/11kV, 30MVA transformer, while the substations 34 and 39 are fed by 132/33kV, 45MVA transformer and bus 1 is the swing bus. Seven tie switches (*SWs*) between buses 25-38, 29-38, 24-29, 20-23, 16-18, 4-19 and 4-14 may be used as alternatives to change the configuration of the system in case of contingencies. The selected system represents multi voltage levels such as 132kV, 33kV, 11kV, 6.6kV, 3.3kV and 0.433kV, where various voltage levels are satisfied through 15 transformers of different sizes. The system includes three large induction motors of 2000 kW and these are connected to buses of numbers 9 (3.3kV), 10 (0.433kV) and 21 (3.3kV), respectively. Capacitor banks, each of 2 MVar are connected to buses 42 (33kV) and 38 (11kV), respectively. Two mini hydro power plants of capacities 2000 KVA, 6.6kV and 3000 KVA, 3.3kV are also connected to the buses 32 and 8, respectively. These power plants are used as DG units to control voltage magnitudes of the buses to which are connected.

The fault analyses were performed for all buses rated below 11kV voltage level except the main substations and the buses that are supplied through more than one feeder.

The buses 1, 2, 3, 17, 18, 33, 34, 35, 36, 39, 40, 41, 42, and 43 are excluded from fault analysis simulation, where bus 1 is the main source, buses 2 and 17 are the main substations, buses 3 and 18 are supplied by two feeders, bus 33 is a service bus for local loads and the buses 34, 35, 36, 39, 40 ,41, 42 and 43 are at 33kV voltage level. Fig. 3 is the three dimensions figure, where Y-axis represents the fault locations, the X-axis represents the number of system buses and Z-axis represents the bus voltage magnitudes read according to the degree of darkness. The voltage sag distribution on all system buses for three phase fault with zero fault resistance (Z_f=0) is shown in Fig. 3. It is obvious from the greatest darkness points of voltage sag distribution (Z-axis) that buses 19, 20, 22, 23 and 24 are the most sensitive buses in propagating voltage sag throughout the system. Therefore, this group of buses is considered as a weak area in the system. Among the weak buses (33 in number), bus 22 is considered as the weakest bus in this group and in the system, causing the propagation of voltage sags to most number of system buses.

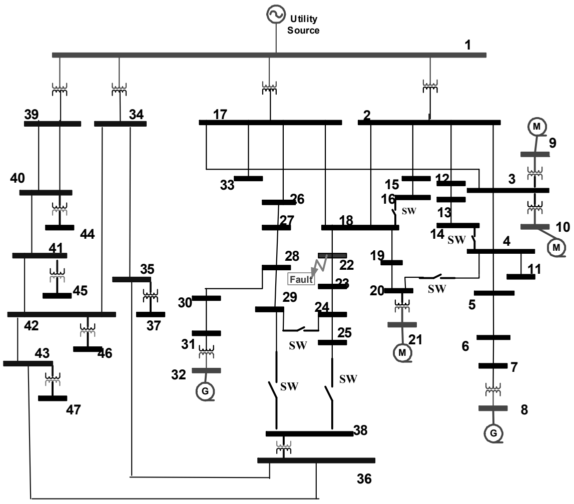

Fig.2. A practical 47-bus test distribution system

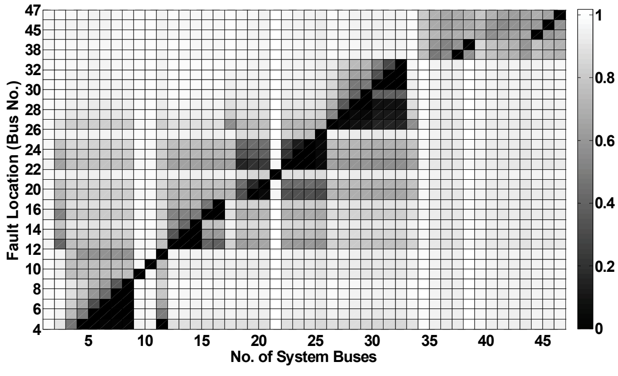

Fig.3. Sag distribution in terms of system buses due to three phase fault at various fault locations

The voltage distribution due to three phase fault at bus 22 is shown in Fig. 4 along with base case voltage profile of the system. From this figure it is clear that all bus voltage magnitudes are within standard limits during base case load flow but causes voltage sag at most buses during a three phase fault at bus 22.

The determination of the weak bus is a significant step in the voltage sag assessment and mitigation because it gives sufficient information to take the right decision to carry out optimal network reconfiguration for the studied system using the proposed binary version of GSA algorithm as an optimization tool. Fig. 5 shows the convergence of the proposed binary GSA algorithm to minimize the objective function (4) and determine optimal placement and sizing of DSTATCOM. The optimum size can be selected by the algorithm within the range 0-40MVA. From Fig.5, it is noted that the converged solution occurs at the no. of sags of 63.4. This solution is achieved when the BGSA identifies bus 31 and 37.30 MVA as the optimal location and size, respectively.

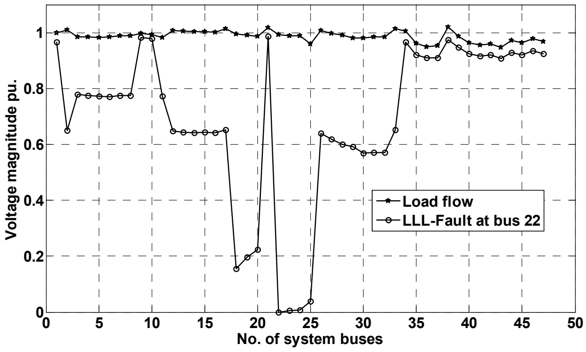

Fig.4. Voltage magnitudes of system buses at base case and during three phase fault at bus 22

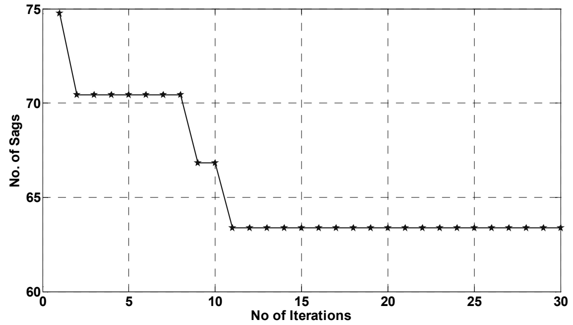

Fig.5. Convergence characteristics of BGSA for optimal placement of DSTATCOM fitness function

Fig. 6 shows the simulation results of short circuit analysis due to a fault at bus 22 along with the base case voltage profile after optimal placement of DSTATCOM. An improvement in the number of healthy buses can be observed as compared with the results of Fig. 4. A successful solution improves the number of healthy buses from 18 to 24 as well as the number of sags for the whole system is minimized from 120.34 even to 63.4 sags / year. Obviously, this optimization improves reliability and saving considerable load outages. In this case, the number of healthy buses is increased up to 24 during three phase fault at weak area as well as other benefits of reduction in the number of sags and improvement of reliability indices. The results of optimization are summarized in Table I. The improvement in optimal placement of DSTATCOM can be observed in the number of healthy buses and number of sags/year for the whole system.

Due to financial losses from load outages and DSTATCOM investment, some compromise must be made between voltage sag mitigation benefits and DSTATCOM investment cost. One of the reliability improvements can be observed by using the load outages index (*ASIFI*) shown in Fig.7. The load outage index (*ASIFI*) is calculated for every fault location, where the generic fault rate data of [16] is adopted in this paper. Other reliability evaluation is curried out by using the index of average frequency of momentary interruptions (*MAIFI*) as shown in Fig. 8. The index *MAIFI* is calculated for each load point. The improvement of reliability level can be observed for the most number of load points.

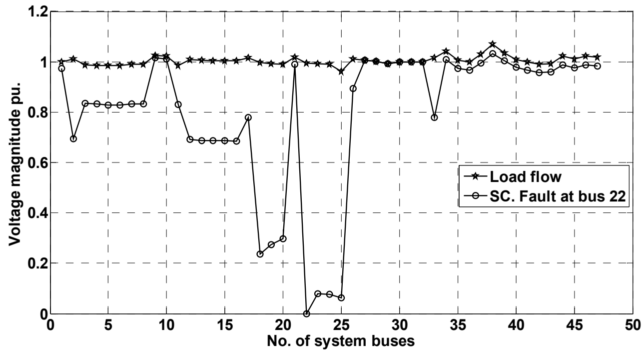

Fig.6. Voltage magnitudes of system buses at base case and during three phase fault at bus 22, after optimal placement of DSTATCOM at bus 31

Table 1. Improvement in the DSTATCOM

Studied Item	Base Case	After DSTATCOM Placement
Number of healthy buses during fault on weak area	18	24
Losses	2.0436 MW	2.1325MW
No. of sags / year	120.4	63.4
ASIFI Index	0.5475	0.3113
MAIFI Index	2.8674	1.5094

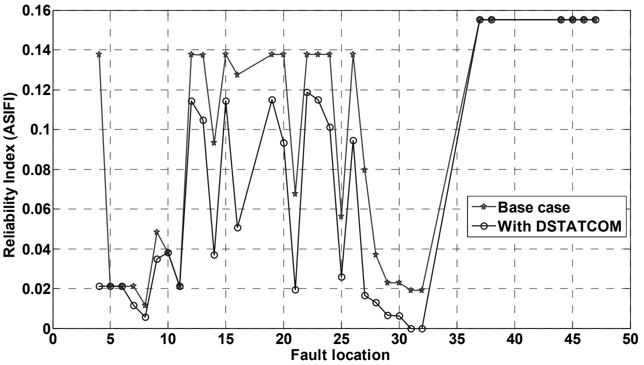

Fig.7. Reliability evaluation by using the ASIFI index at all fault locations of the studied distribution system

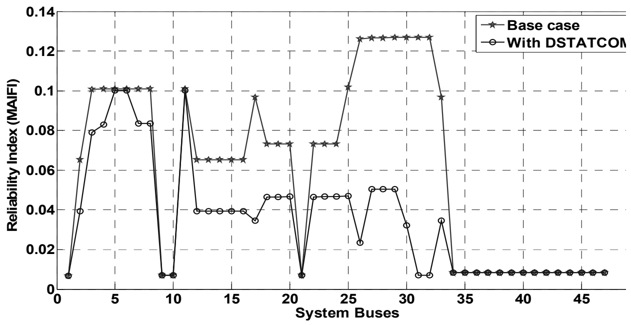

Fig.8. Reliability evaluation using the MAIFI index at all fault locations of the studied distribution system

Conclusion

In this paper, a method for improving the reliability level in distribution systems is presented. The improvement is achieved by employing optimal placement of DSTATCOM as a voltage sag mitigation method. The simulation results show that the proposed technique is efficient to bring significant improvement in voltage sag mitigation in distribution systems. The evaluations using reliability indices (*ASIFI & MAIFI*) show that the presented method of voltage sag mitigation is efficient in improving the reliability level in distribution systems. The application of the proposed optimization method using the BGSA as a heuristic algorithm with the proposed technique of encoding and decoding proves to be accurate.

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