Optimal Number, Location, and Size of Distributed Generators in Distribution Systems by Symbiotic Organism Search Based Method

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Abstract. *This paper proposes an approach based on the Symbiotic Organism Search (SOS) for optimal determining sizing, siting, and number of Distributed Generations (DG) in distribution systems. The objective of the problem is to minimize the power loss of the system subject to the equality and inequality constraints such as power balance, bus voltage limits, DG capacity limits, and DG penetration limit. The SOS approach is defined as the symbiotic relationship observed between two organisms in an ecosystem, which does not need the control parameters like other meta-heuristic algorithms in the literature. For the implementation of the proposed method to the problem, an integrated approach of Loss Sensitivity Factor (LSF) is used to determine the optimal location for installation of DG units, and SOS is used to find the optimal size of DG units. The proposed method has been tested on IEEE 33-bus, 69-bus, and 118-bus radial distribution systems. The obtained results from the SOS algorithm have been compared to those of other methods in the literature. The simulated results have demonstrated that the proposed SOS method has a very good performance and effectiveness for the problem of optimal placement of DG units in distribution systems.*

Keywords

Distributed generators, loss sensitivity factor, optimal placement, power loss, radial distribution system, symbiotic organism search algorithm.

1. Introduction

Distributed Generation (DG) units are small generating plants directly connected to distribution systems or to the customer side of the meter. DG units may be synchronous generators, induction generators, reciprocating engines, micro-turbines, combustion gas turbines, fuel cells, solar photovoltaic, wind turbines, and other small power sources [1]. The installation of DG units is becoming more popular in distribution systems due to their overall positive impacts on power systems. Some major advantages of DG units integrated into distribution systems are reducing power losses, improving voltage profiles, reducing emission impacts, and improving power quality. Because of these benefits, utility companies have started to change their infrastructure to adapt to the presence of DG units in their distribution systems. Based on the mentioned benefits, many problems in DG placement and operation have been also posed. The typical Optimal DG Placement (ODGP) problem deals with the determination of the optimal locations and sizes of DG units to be installed into existing distribution systems subject to the electrical network operating constraints, DG operation constraints, and investment constraints. The ODGP problem is a complex mixed-integer nonlinear optimization problem [1]. Apart from the optimal location and size of DG units, the optimal number of DG units should be also considered since a large number of DG units in a distribution system may cause a negative impact on the system like overvoltage, conductor overloading, and losses increment. Therefore, the problem of optimal location and sizing of DG units has attracted the attention of many researchers.

Several conventional methods have been proposed for solving the ODGP problem such as gradient-based method [2], linear programming (LP) [3], Non-Linear

Programming (NLP) [4], Sequential Quadratic Programming (SQP) [5], and Dynamic Programming (DP) [6]. In general, these conventional methods can easily find the optimal solution for a small-scale optimization problem in a very short time. However, the main disadvantage of them is that they suffer from difficulty when dealing with large-scale problems due to large search space, leading time-consuming or no convergence.

In addition, many researchers have implemented analytical approaches for solving the ODGP problem. In [7], an analytical approach was used to determine the optimal location for placing DG in both radial and meshed systems so as to minimize power losses in the system. In [8], the authors used an analytical expression and a methodology based on the exact loss formula for optimal sizing and location of DG for minimizing the total power losses. In [9], the authors employed a loss sensitivity factor based on the equivalent current injection for finding the optimal location and sizing of DG to minimize the total power losses by an analytical method without using the admittance, impedance or Jacobian matrix. A novel index known as Power Stability Index (PSI) was proposed to identify the most critical bus in the system for DG location, and a search algorithm was used for finding the optimal size of DG at the identified bus to minimize the system losses as in [10]. Analytical methods are easy to implement and fast to execute. However, their results are only indicative since they make simplified assumptions including the consideration of only one power system loading snapshot [1].

Recently, meta-heuristic search methods have become popular for solving the ODGP problem due to their advantages of simple implementation and ability to find the near-optimal solution for complex optimization problems. Various meta-heuristic methods have been applied for solving the problem such as Genetic Algorithm (GA) [11], [12] and [13], Particle Swarm Optimization (PSO) [14], Teaching-Learning Based Optimization (TLBO) [15], Tabu Search (TS) [16], Ant Colony Optimization (ACO) [17], Cuckoo Search (CS) [18], Harmony Search Algorithm (HSA) [19], Grey Wolf Optimizer (GWO) [20], Bacterial Foraging Optimization Algorithm (BFOA) [21], Flower Pollination Algorithm (FPA) [22], Gravitational Search Algorithm (GSA) [23], Bat Algorithm (BA) [24], and Symbiotic Organism Search (SOS) [25]. Some of the researchers have applied GA for optimal location and sizing of DG units in distribution systems as in [11], [12] and [13]. In addition to the single methods, hybrid methods have been also widely implemented for solving the problem such as hybrid PSO and OPF [26] and hybrid GA and PSO [27] to improve the performances of the single methods. The hybrid methods often obtain better solution quality than the single methods, but they also suffer from longer computational time and more complex implementation due to handling many control parameters.

The above discussed methods have gained encouraging results in finding the optimal location and size of DG units. However, most of the mentioned researches did not consider the optimal quantity of DG units. Therefore, the present work is to develop a novel and fast computation technique to find the optimal number of DG units for active power loss minimization in distribution systems. In this paper, an SOS based approach is proposed for optimal determination of sizing, siting, and number of DG units in distribution systems. The SOS algorithm is a new meta-heuristic optimization method developed by Cheng and Prayogo in 2014 [28]. This method is based on the interactive behavior observed among organisms in nature. It is robust to solve and easy to implement various numerical optimization problems because it does not require any control parameters. For the implementation of the proposed method to the problem, a Loss Sensitivity Factor (LSF) is used to determine the most sensitive bus for DG installation and the proposed SOS algorithm is employed to minimize the objective function by determining the optimal size of DG units at candidate locations. The proposed method has been tested on the IEEE 33-bus, 69-bus, and 118-bus systems and the results obtained by the proposed method have been compared to those from other methods in the literature.

2. Problem Formulation

The objective of the ODGP problem is to minimize the total active power loss while satisfying various operational constraints. Mathematically, the ODGP problem is formulated as follows.

2.1. The Objective Function

The objective function for minimization of the total active power loss in a distribution system is expressed as follows:

$$F = \min(TPL), \tag{1}$$

where TPL is the total active power loss of the system.

2.2. Constraints

The optimal location and sizing of DG need to satisfy all of the operational constraints such as the power balance constraints, limitation of bus voltages, limitation of DG capacity, and limitation of DG penetration as follows.

1) Power Balance Constraints

The power flow equations are defined as equality constraints in the ODGP problem. The mathematical formulation is given by:

$$P_{Gi} - P_{Li} = |V_i| \sum_{j=1}^{N} |Y_{ij}| |V_j| \cos(\delta_i - \delta_j - \theta_{ij}), \quad (2)$$

$$Q_{Gi} - Q_{Li} = |V_i| \sum_{j=1}^{N} |Y_{ij}| |V_j| \sin(\delta_i - \delta_j - \theta_{ij}), \quad (3)$$

where P_{Gi} is the active power of DG at bus i; P_{Li} is the active power of load at bus i; Q_{Gi} is the reactive power of DG at bus i; Q_{Li} is the reactive power of load at bus i; V_i and δ_i are the voltage magnitude and angle at bus i; V_j and δ_j are the voltage magnitude and angle at bus j; Y_{ij} and θ_{ij} are the modulus and angle of i^{th} element in the admittance matrix of the system related to bus i and bus j; and N is the number of buses in the system.

2) Bus Voltage Limits

The voltage magnitude at each bus must be maintained in their lower and upper limits:

$$V_{i,\min} \le V_i \le V_{i,\max}; \quad i = 1, \ldots, N, \quad (4)$$

where $V_{i,\min}$ and $V_{i,\max}$ are the minimum and maximum voltage levels at bus i.

3) DG Capacity Limits

The used DG must have the allowable size as the following range:

$$S_{DG_i}^{\min} \le S_{DG_i} \le S_{DG_i}^{\max}; \quad i = 2, \ldots, N, \quad (5)$$

where $S_{DG_i}^{\min}$ and $S_{DG_i}^{\max}$ are the minimum and maximum power output limits of DG at bus i and S_{DG_i} is the power output of DG at bus i.

4) DG Penetration Limits

This constraint is to limit the total amount of DG power output to be installed in the distribution system expressed by:

$$\sum_{i=1}^{n_{DG}} S_{DG_i} \le S_{DG}^{\max}, \quad (6)$$

$$S_{DG}^{\max} = S_L, \quad (7)$$

where S_{DG_i} is the power output of the i^{th} DG; $S_{DG}^{\max}$ is the total allowed power of DG that can be installed in the system; S_L is the total load of the system; and n_{DG} is the number of DG units.

3. Loss Sensitivity Factor for DG Installation

The locations for the DG installation can be found based on the LSF [29]. The advantage of using this method is the reduction of the search space of the problem during the optimization process.

An example of a two-bus distribution system is shown in Fig. 1. The LSF at the line section between bus p and bus q can be determined by following equation:

$$LSF(p,q) = \frac{\partial P_{lineloss}}{\partial Q_{eff}} = \frac{2Q_{eff}(q)\,R(k)}{(V(q))^2}, \quad (8)$$

where $Q_{eff}(q)$ is the total effective active power supplied beyond the bus q; $R(k)$ is the resistance of the k^{th} line; and $V(q)$ is the voltage at bus q.

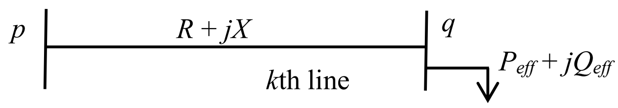

Fig. 1: Sample of two-bus distribution system.

4. Symbiotic Organism Search Optimization Algorithm

The SOS algorithm is a new meta-heuristic algorithm based on the symbiotic relationships observed among organisms in an ecosystem developed by Cheng and Prayogo in 2014 [28]. Unlike other meta-heuristic algorithms, SOS does not use control parameters, which lead to enhancing performance stability of the method. In order to seek the optimal solution in the search space, the SOS algorithm uses a population of organisms, in which each organism is considered as a candidate solution for the corresponding problem. The new solutions are created based on the symbiotic relationships among organisms in the population. The symbiotic relationships in the SOS algorithm are known as mutualism, commensalism, and parasitism phases. The detail of these three phases can be described in detail as follows.

4.1. Mutualism Phase

This phase denotes a symbiotic relationship between two different organisms in which both organisms are mutually benefited.

In the mutualism phase, $\vec{X}_i$ represents the i^{th} organism of the ecosystem and another organism $\vec{X}_j$ is randomly chosen from the ecosystem to interact with

$\vec{X}_i$. In order to enhance the mutual survival advantage in the ecosystem, both organisms engage in a mutualistic relationship. Based on the mutualistic symbiosis between both organisms, the new candidate solutions $\vec{X}_{inew}$ and $\vec{X}_{jnew}$ are calculated by:

$$\vec{X}_{inew} = \vec{X}_i + \text{rand}(0,1) \cdot (\vec{X}_{\text{best}} - \vec{M}_{\text{vector}} \cdot BF1), \quad (9)$$

$$\vec{X}_{jnew} = \vec{X}_j + \text{rand}(0,1) \cdot (\vec{X}_{\text{best}} - \vec{M}_{\text{vector}} \cdot BF2), \quad (10)$$

where $\text{rand}(0,1)$ is a vector of random numbers generated between 0 and 1; $\vec{X}_{\text{best}}$ represents the highest degree of adaptation; $\vec{M}_{\text{vector}}$ represents the relationship between $\vec{X}_i$ and $\vec{X}_j$; $BF1$ and $BF2$ are the benefit factors and their values are randomly determined as either 1 or 2. These factors represent the level of benefit to each organism.

The value of $\vec{M}_{\text{vector}}$ in Eq. (9) and Eq. (10) is determined by:

$$\vec{M}_{\text{vector}} = \frac{\vec{X}_i + \vec{X}_j}{2}. \quad (11)$$

4.2. Commensalism Phase

In the commensalism phase, the symbiotic relationship is established between two different organisms in which one benefits and the other one is unaffected.

Like the mutualism phase, an organism $\vec{X}_j$ is also randomly selected from the ecosystem, which is used to interact with $\vec{X}_i$. Organism $\vec{X}_i$ attempts to benefit from the interaction and other organism $\vec{X}_j$ is unaffected or neutral from this interaction. The new candidate solution $\vec{X}_{inew}$ is determined as follows:

$$\vec{X}_{inew} = \vec{X}_i + \text{rand}(-1,1) \cdot (\vec{X}_{\text{best}} - \vec{X}_j), \quad (12)$$

where term $(\vec{X}_{\text{best}} - \vec{X}_j)$ represents the beneficial advantage provided by $\vec{X}_j$ to help $\vec{X}_i$ increasing its survival chance in the ecosystem.

4.3. Parasitism Phase

The parasitism phase describes a symbiotic relationship between two different organisms in which one benefits and other is affected.

In this phase, an organism $\vec{X}_i$ is selected and it creates an artificial parasite called $\overrightarrow{Parasite\_Vector}$ by duplicating organism $\vec{X}_i$, and then a random number is used to modify the randomly selected dimensions. Organism $\vec{X}_j$ is randomly selected from the ecosystem and serves as a host to the parasite. If $\overrightarrow{Parasite\_Vector}$ has a better fitness value, then it will kill organism $\vec{X}_j$ and take over its position in the ecosystem. In the contrary, if the fitness value of $\vec{X}_j$ is better, $\vec{X}_j$ will replace the $\overrightarrow{Parasite\_Vector}$ and the parasite will no longer survive in the ecosystem.

5. Implementation of SOS Algorithm to Find Optimal DG Sizes

This section describes the application of the SOS algorithm for the ODGP problem to minimize the total active power loss in distribution systems. The overall procedure of SOS for the ODGP problem is presented in the following steps:

Step 1: Select the parameters of SOS including population size (NP) and the maximum number of fitness function evaluations (max_fit_eval).

Step 2: The initial population is represented as $\mathbf{X} = \left(\vec{X}_1, \vec{X}_2, \ldots, \vec{X}_{NP}\right)^T$, where each organism in the population $\vec{X}_i = (S_{DGi,1}, S_{DGi,2}, \ldots, S_{DGi,k}, \ldots, S_{DGi,ND})$, where $i = 1, 2, \ldots, NP$, represents the power output of DG units. The power output of each DG unit is initialized by:

$$S_{DGi,k} = \text{rand}(0,1) \cdot \left(S_k^{\max} - S_k^{\min}\right) + S_k^{\min}, \quad (13)$$

where $S_k^{\min}$ and $S_k^{\max}$ are the minimum and maximum power outputs of the k^{th} DG unit.

Step 3: The initialized population is evaluated by using a fitness function defined by:

$$FF = F + \lambda_v \sum_{i=1}^{N} \left(V_i - V_i^{\lim}\right)^2 + \lambda_p \left(S_{DG} - S_{DG}^{\lim}\right), \quad (14)$$

where λ_v and λ_p are penalty factors. The penalty factors used in this study are set to 100000. The constraint violations belonging to the dependent variables are expressed as the following equations:

$$V_i^{\lim} = \begin{cases} V_{i,\max} & \text{if } V_i > V_{i,\max}, \\ V_{i,\min} & \text{if } V_i < V_{i,\min}, \\ V_i & \text{if } V_{i,\min} < V_i < V_{i,\max}, \end{cases} \quad (15)$$

$$S_{DG}^{\lim} = S_{DG}^{\max} \quad \text{if } S_{DG} > S_{DG}^{\max}. \quad (16)$$

The fitness value of each organism is determined by performing the power flow to find the total active power loss of the distribution system. In this paper, the Newton-Raphson algorithm is used for the power flow. The bus voltages and DG penetration limits are also considered in this step. The evaluation of organisms is done via choosing the best fitness value having minimum value among the fitness values of all organisms, and the corresponding organism is chosen as the best organism $\vec{X}_{\text{best}}$.

Step 4: The main loop.

The outer loop (Steps 4–9) continues until preset iteration value is reached. The inner loop (Steps 5–

8) continues until the last member of ecosystem is reached.

Step 5: Mutualism phase.

Choose organism $\vec{X}_j$ randomly where $\vec{X}_j \neq \vec{X}_i$.

Modify organisms $\vec{X}_i$ and $\vec{X}_j$ using Eq. (9) and Eq. (10).

The fitness value is calculated for the new organisms $\vec{X}_{inew}$ and $\vec{X}_{jnew}$. If the new organisms are better than the previous ones, they will replace the previous ones.

Step 6: Commensalism phase.

Choose organism $\vec{X}_j$ randomly where $\vec{X}_j \neq \vec{X}_i$.

Modify organism $\vec{X}_i$ with the help of $\vec{X}_j$ using Eq. (12).

The fitness value is calculated for the new organism $\vec{X}_{inew}$. If the new organism gives better fitness evaluation, it is updated in the ecosystem.

Step 7: Parasitism phase.

Choose organism $\vec{X}_j$ randomly where $\vec{X}_j \neq \vec{X}_i$.

$\overrightarrow{Parasite\_Vector}$ is created by mutating organism $\vec{X}_i$. If $\overrightarrow{Parasite\_Vector}$ gives a better fitness value than $\vec{X}_j$, it is replaced by $\overrightarrow{Parasite\_Vector}$.

Step 8: Repeat for population size length.

Find the minimum fitness value, and the corresponding organism is taken as the new best organism.

Go to *Step 5* if the current $\vec{X}_i$ is not the last member of the ecosystem. Otherwise, proceed to the next step.

Step 9: In the proposed SOS method, the stopping criterion for the algorithm is based on the difference of the fitness function. The algorithm is terminated when the difference of the fitness function is smaller than the initial value set. Otherwise, return to *Step 4* and start the next iteration.

The optimal number of DG units can be found by investigating the effects of the number of DG units on the active power losses. For optimal location and size of DG units, the top ND buses from the priority list are picked, and the optimal sizes of DG units are found using the SOS algorithm. The sizing of the DG units varies in discrete steps at the specified location during the optimization process. The number of DG units, which results in the smallest active power loss, is considered as the optimal number of DG units.

6. Numerical Results and Discussion

The proposed method has been tested on the IEEE 33-bus, 69-bus, and 118-bus radial distribution systems [30], [31] and [32]. For the parameters of the SOS, only the population size and maximum number of fitness function evaluations are selected for each test system. To investigate the effect of the population size on the optimal solution, different population sizes have been used for the test systems, and the population size corresponding to the minimum value of the fitness function will be selected for SOS to find the optimal solution. The proposed method runs 20 independent trials for each system to obtain the best solution. In this research, both the fixed number of DG units and the optimal number of DG units for installation in test systems are considered. For the case with the fixed number of DG units, the results obtained by SOS for the systems have been analyzed and compared to those from other methods in the literature. For the case with the optimal number of DG units, the PSO method has been also implemented to solve the problem for result comparison. The control parameters of PSO are selected as follows: $NP = 100, c_1 = c_2 = 2, w_{\max} = 0.9, w_{\min} = 0.05$ and the maximum number of fitness function evaluations is 10000 for all three test systems. The PSO has been also performed in 20 independent runs for obtaining the best solution.

6.1. The IEEE 33-Bus Radial Distribution System

This test system consists of 33 buses and 32 branches from [30]. The total active and reactive power loads of the system are 3.715 MW and 2.300 MVAr. The maximum and minimum DG power outputs are 3.4952 MVA and 0.2 MVA, respectively. The DG penetration limit is set at 4.369 MVA. The base voltage of this system is 12.66 kV. The active and reactive power losses in the system calculated from power flow are 210.99 kW and 143.13 kVAr, respectively. The potential buses for the DG location are found based on LSF indicators. The values of LSF for all buses are given in Tab. 1.

For the optimal selection of population size of SOS, different population sizes have been used for the system from 30 to 110 with a step of 20. As a result, the optimal population size is 50 corresponding to the best fitness function value among the others corresponding to other population sizes. Therefore, the population size of 50 and the maximum number of fitness function evaluations of 10000 are used for SOS to find the optimal solution for the test system in this section.

Tab. 1: The values of LSF for the 33-bus system.

$\frac{\partial P_{lineloss}}{\partial Q_{eff}}$ (descending order)	**Bus No.**	norm$(i) = V(i)/0.95$	**Base Voltage**	**Flag of DG**
0.0173317	6	0.9994401	0.9494681	1
0.0139407	3	1.0346128	0.9828821	0
0.0138088	28	0.9826654	0.9335321	1
0.0103590	29	0.9740129	0.9253122	1
0.0103237	8	0.9813551	0.9322874	1
0.0080811	5	1.0188907	0.9679462	0
0.0080733	4	1.0267079	0.9753725	0
0.0060512	30	0.9702674	0.9217540	1
0.0047535	9	0.9746892	0.9259547	1
0.0047501	24	1.0238154	0.9726247	0
0.0045614	13	0.9595139	0.9115382	1
0.0045149	10	0.9685237	0.9200975	1
0.0037555	27	0.9947096	0.9449741	1
0.0030365	31	0.9658863	0.9175920	1
0.0028204	2	1.0494889	0.9970145	0
0.0027433	26	0.9974088	0.9475384	1
0.0026717	23	1.0308381	0.9792962	0
0.0023800	25	1.0203152	0.9692995	0
0.0022880	20	1.0451668	0.9929084	0
0.0013972	14	0.9571033	0.9092482	1
0.0013803	7	0.9957298	0.9459433	1
0.0013538	12	0.9660146	0.9177139	1
0.0011808	17	0.9519908	0.9043912	1
0.0009111	16	0.9541467	0.9064393	1
0.0008107	15	0.9556014	0.9078213	1
0.0007965	11	0.9676092	0.9192287	1
0.0006456	32	0.9649225	0.9166764	1
0.0004473	18	0.9513452	0.9037779	1
0.0004155	21	1.0444252	0.9922039	0
0.0003599	22	1.0437542	0.9915665	0
0.0003317	19	1.0489327	0.9964861	0
0.0002027	33	0.9646238	0.9163927	1

1) Fixed Number of DG Units

For the cases with the fixed number of DG units, the proposed method has been implemented for solving the problem with a predetermined number of DG units of 1, 2, and 3. The obtained results from the proposed method have been compared to those from other mature methods such as HSA [19], GA [27], PSO [27], and TLBO [33] as shown in Tab. 2.

As observed from the table, the proposed method has better performance for this system via finding less total losses than the other methods. For the case of one DG unit fixed, the proposed method can obtain a total loss of 115.01 kW for the system compared to 144.23 kW from HSA with different DG location and size. For the case of two DG units fixed, the total loss obtained by the proposed method is 107.39 kW compared to 141.14 kW from HSA. The DG location and size for this case are also different. For the case of three DG units fixed, the total power loss of the system obtained by the proposed method is 104.26 kW which is less than a total power loss of 135.69 kW from HSA, 106.3 kW from GA, 105.35 kW from PSO, and 124.695 kW from TLBO. In this case, the DG location and size from different methods are also different. Therefore, the proposed SOS based method is effective for dealing with the problem for the test 33-bus system.

2) Optimal Number of DG Units

In this case, the optimal number of DG units is obtained via investigation of different numbers of DG units for installation in the system. Therefore, the problem is solved many times with each corresponding to a fixed number of DG units. The effect of the different numbers of DG units on the active power loss has been investigated by testing the different numbers of DG units from 1 to 21, and the number of DG units which results in the minimum power loss among the different numbers of DG units is considered as the optimal number of DG units for the system.

Among the values of the active power loss by different number of DG units, a minimum active power loss of 76.967 kW is obtained corresponding to the number of DG units is 12. Therefore, the optimal number of DG units for the 33-bus system is 12 yielding a total active power loss of 76.967 kW.

Table 3 shows the optimal result found by PSO and SOS from the optimal number of DG units. In this case, both the methods can obtain the same optimal number of DG units and the total power loss obtained by the proposed method is slightly less than that from the PSO method. Therefore, the proposed SOS based method can be effective for finding the optimal location, size and number of DG units for the IEEE 33-bus radial distribution system.

Tab. 3: Results by SOS and PSO for the 33-bus system with 12 DG units.

Power loss (kW)		**Total DG power output (MW)**	
PSO	**SOS**	**PSO**	**SOS**
77.033802	76.967104	2.509317482	2.509000089

The voltage profile curves after installation of the optimal number of DG units by the PSO and SOS methods are shown in Fig. 2. From the figure, it may be observed that both methods can give the same effect to voltage profiles.

Tab. 2: Comparison of results for the 33-bus system with fixed number of DG units.

Method	Number of DG Units	Optimal result			
		DG size in MW (location)			Loss
		DG1	DG2	DG3	(kW)
HSA [19]	1	0.8491 (18)	-	-	144.23
	2	0.2012 (18)	0.6932 (17)	-	141.14
	3	0.1913 (18)	0.2133 (17)	0.5927 (16)	135.69
GA [27]	1	-			
	2	-			
	3	1.5 (11)	0.4228 (29)	1.0714 (30)	106.3
PSO [27]	1	-			
	2	-			
	3	0.9816 (13)	0.8297 (32)	1.1768 (8)	105.35
TLBO [33]	1	-			
	2	-			
	3	1.1826 (12)	1.1913 (28)	1.1863 (30)	124.695
SOS	1	3.1322 (6)	-	-	115.01
	2	2.2861 (6)	0.8363 (28)	-	107.39
	3	2.2066 (6)	0.2 (28)	0.7167 (29)	104.26

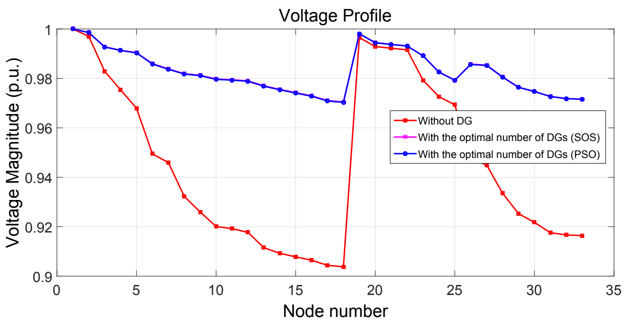

Fig. 2: Voltage profile at buses of the 33-bus system with the optimal number of DG units.

6.2. The IEEE 69-Bus Radial Distribution System

The second test system is the 69-bus radial distribution system from [31] with a total load demand of 3.80 MW and 2.69 MVAr. The active and reactive power losses of this test system are 225 kW and 102.16 kVAr, respectively. The minimum and maximum power outputs of DG units are 0.2 MVA and 3.7248 MVA, respectively. The DG penetration limit is 4.656 MVA, and the base voltage of this system is 12.66 kV.

The best population size of SOS for the system is tuned by using different population sizes to investigate the values of the fitness function where the population size of SOS is considered from 30 to 110 with an increment of 20. Based on the obtained results, the best population size of SOS for this test system is 50 which is corresponding to the minimum fitness function value among the different population sizes. Therefore, a population size of 50 and the maximum number of fitness function evaluations of 10000 are used for SOS to find the optimal solution for this test system.

1) Fixed Number of DG Units

For the case that the number of DG units is fixed in advance, the proposed method has been implemented for solving the problem with the number of DG units of 1, 2, and 3. The obtained results from the proposed method have been compared to those from other methods such as HSA [19], GA [27], PSO [27], and TLBO [33] as shown in Tab. 4. As observed from the table, the proposed method can obtain lower total power loss than that from other methods except the HSA for the cases with 1 and 2 DG units. For the case with 1 DG unit, the proposed method has obtained a total power loss of 118.62 kW, which is higher than a total power loss of 112.1 kW from HSA method. For the case with 2 DG units, the proposed method has obtained a total power loss of 102.92 kW, which is higher than that of 96.56 kW from HSA. For the case with 3 DG units, the proposed method has obtained a total power loss of 82.07 kW, which is less than that of 86.66 kW from HSA, 89.0 kW from GA, 83.2 kW from PSO, and 82.172 kW from TLBO. In general, the proposed SOS can be an effective method for the problem with a higher number of DG units.

2) Optimal Number of DG Units

For the case of finding the optimal number of DG units, the proposed method has been investigated on the effect of the different numbers of DG units on the active power loss and the obtained total power losses corresponding to the different numbers of DG units from 1 to 22.

Among the values of power loss with the investigated number of DG units, the minimum active power loss of 71.444166 kW is obtained when the number of DG units is 8.

Tab. 4: Comparison of results for the 69-bus system with fixed number of DG units.

Method	Number of DG Units	Optimal result DG size in MW (location) DG1	DG2	DG3	Loss (kW)
HSA [19]	1	1.4363 (65)	-	-	112.10
	2	0.0544 (65)	1.5932 (64)	-	96.56
	3	0.0149 (65)	0.1416 (64)	1.6283 (63)	86.66
GA [27]	1	-			
	2	-			
	3	0.9297 (21)	1.0752 (62)	0.9925 (64)	89.0
PSO [27]	1	-			
	2	-			
	3	0.9925 (17)	1.1998 (61)	0.7956 (63)	83.2
TLBO [33]	1	-			
	2	-			
	3	1.0134 (13)	0.9901 (61)	1.1601 (62)	82.172
SOS	1	2.087 (57)	-	-	118.62
	2	0.3612 (57)	1.6948 (58)	-	102.92
	3	0.2588 (57)	0.2 (58)	1.5247 (61)	82.07

The result obtained from the proposed approach for the optimal number of DG units is compared to that from the PSO method as shown in Tab. 5. As observed from the table, the SOS method can find a better total power loss than the PSO method for the system with the optimal number of DG units. With the optimal number of DG units, the active power losses obtained by SOS and PSO methods are 71.444166 kW and 71.579433 kW, respectively.

Tab. 5: Comparative results of 69-bus system for 8 DG units.

Power loss (kW)		Total DG power output (MW)	
PSO	SOS	PSO	SOS
71.579433	71.444166	2.501615430	2.437403138

The voltage profile at buses of the system after installation of the optimal number of DG units by PSO and SOS methods are shown in Fig. 3. From the figure, it can be seen that both methods result in a significant improvement of voltage at buses and the voltage improvement at buses from the PSO and SOS is nearly the same.

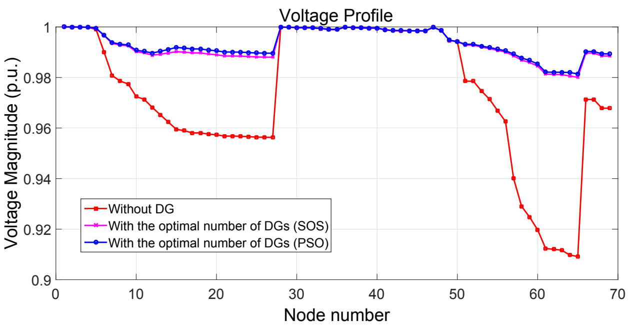

Fig. 3: Voltage profile at buses of the 69-bus system with the optimal number of DG units.

6.3. The IEEE 118-Bus Radial Distribution System

To illustrate the applicability of the proposed method in large-scale distribution systems, it is applied on the 118-bus radial distribution system. This is the large-scale distribution system without tie lines and the used base values are 100 MVA and 11 kV. The total power loads are 22.7097 MW and 17.0411 MVAr. The initial active and reactive power losses are 1298.0911 kW and 978.7358 kVAr, respectively. The test system data such as line and load data are taken from [32]. The minimum and maximum power outputs of DG units are 0.2 MVA and 22.7139 MVA, respectively. Maximum penetration of DG is limited at 28.3924 MVA.

To analyze the effect of population size parameter, the maximum number of fitness function evaluations is set to 10000. The SOS method runs 20 independent trials and the population size is chosen from 20 to 60. Based on the analysis, the best value of the population size of SOS for this system is 30 which is corresponding to the best fitness function value among the others corresponding to other population sizes.

1) Fixed Number of DG Units

For the cases with a fixed number of DG units, the proposed method has been implemented for solving the problem with a predetermined number of DG units of 1, 3, 5, and 7. For investigation of the effectiveness, the results of SOS are compared with those of other methods such as HSA-PABC [34] and SA [35] as shown in Tab. 6. From this table, it can be observed that the performance of the SOS is better compared to HSA-PABC and SA in terms of the quality of solutions. For the case with 1 DG unit, the proposed method has obtained a total power loss of 1021.0898 kW, which is slightly less than that of 1021.09 kW from HSA-

PABC. The total power loss for the case with 3 DG units obtained from the proposed SOS method is found to be 875.2687 kW (i. e. 29.1113 kW) less than the best result of 904.38 kW from the HSA-PABC based method. For the case with 5 DG units, the total power loss of the system obtained by the proposed method is 800.3249 kW which is less than a total power loss of 858.8133 kW from SA. For the case with 7 DG units, the total power loss obtained by SOS is 795.6951 kW compared to 900.1885 kW from SA. For all the test cases of the system, the proposed method can obtain better total power loss than the others. Therefore, the proposed SOS is very effective for this system.

Tab. 6: Comparison of results for the 118-bus system with fixed number of DG units.

Method	Number of DG units	Optimal result	
		DG size in MW (location)	Loss (kW)
HSA-PABC [34]	1	3.050 (70)	1021.09
	3	2.6 (80) 6.8 (30) 4.7 (64)	904.38
SA [35]	5	2.1318 (75) 0.7501 (116) 1.1329 (56) 4.5353 (36) 4.9452 (103)	858.8133
	7	2.8246 (75) 0.4606 (116) 3.6739 (56) 7.4673 (36) 5.0803 (103) 2.2979 (88) 0.7109 (48)	900.1885
SOS	1	3.0482 (70)	1021.0898
	3	2.3788 (70) 4.7958 (104) 1.2591 (68)	875.2687
	5	2.5979 (70) 0.7936 (104) 0.9665 (68) 0.5095 (106) 2.4469 (108)	800.3249
	7	2.5018 (70) 0.6784 (104) 0.2 (68) 0.7226 (106) 2.2610 (108) 0.2 (69) 0.8759 (67)	795.6951

2) Optimal Number of DG Units

For finding the optimal number of DG units, the problem is solved with different numbers of DG units, and the optimal number of DG units is determined corresponding to the case with the minimum total power loss obtained. The effect of the different numbers of DG units on the active power loss has been investigated. Among the values of the active power loss, a minimum active power loss of 485.439990 kW is obtained corresponding to the number of DG units is 34, this being the global optimum. Therefore, the optimal number of DG units for the 118-bus system is 34 yielding a total active power loss of 485.439990 kW.

The results obtained from the proposed approach for 34 DG units are compared to that from the PSO method as shown in Tab. 7. As observed from the table, the SOS method can find a better total power loss than the PSO method for the system with the optimal number of DG units. With the optimal number of DG units, the active power losses obtained by SOS and PSO methods are 485.439990 kW and 493.175799 kW, respectively.

Tab. 7: Comparison of results of 118-bus system for 34 DG units.

Power loss (kW)		Total DG power output (MW)	
PSO	SOS	PSO	SOS
493.175799	485.439990	16.068533	15.924957

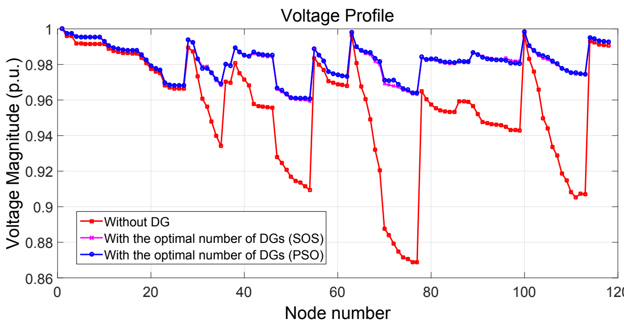

Fig. 4: Voltage profile at buses of the 118-bus system with the optimal number of DG units.

The voltage profile at buses of the system after installation of the optimal number of DG units by PSO and SOS methods are shown in Fig. 4. From the figure, it can be seen that both methods result in a significant improvement of voltage at buses and the voltage improvement at buses from the PSO and SOS is nearly the same.

7. Conclusion

In the paper, the proposed SOS based method has been effectively implemented for dealing with the optimal placement of distributed generators in distribution systems. In this paper, the considered problem includes the determination of the optimal location, size, and number of DG units in a radial distribution system. For the implementation of the SOS based method for solving the problem, the loss sensitivity factor is used to find a priority list of the potential locations where DG units can be installed and then the SOS method is applied to find the optimal size of DG units with a predetermined number of DG units. For finding the optimal number of DG units, the problem is solved with different numbers of DG units, and the optimal number of DG units is determined corresponding to the case with the minimum total power loss obtained. The proposed method has been tested on the IEEE 33-bus, 69-bus, and 118-bus radial distribution systems and the obtained results have been verified via comparing to those from other methods in the literature. The comparisons of results have indicated the proposed SOS based method is effective for solving the problem of optimal placement of distributed generators.

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