Celal Bayar University Journal of Science

Optimal placement of multiple DGs in radial distribution systems to minimize power loss using BSA

Waleed Fadel[1]*, Ulaş Kılıç[2], Sezai Taşkın[3]

[1]Department of Electrical&Electronics, Faculty of Engineering, Girne American University, Mersin 10 – Turkey
[2]Department of Electrical&Electronics, Faculty of Engineering, Ege University, İzmir – Turkey
[3]Department of Electrical&Electronics, Faculty of Engineering, Manisa Celal Bayar University, Manisa –Turkey
*waleedfadel@gau.edu.tr
*Orcid: 0000-0002-5061-6474

Received: 18 September 2020
Accepted: 29 March 2021
DOI: 10.18466/cbayarfbe.796140

Abstract

Distributed generation (DG) sources are becoming more important in electrical networks due to the increase of electrical energy demands. However, DG sources can have a profound effect on network power loss. Hence, optimal placement and size of DGs are extremely important. This study presents an efficient heuristic algorithm based on optimal placement and size of multiple DGs within distribution systems in order to reduce power loss. This algorithm is backtracking search algorithm (BSA). Two main DGs, photovoltaic and synchronous compensator, are integrated in two different radial distribution systems (RDS), IEEE 33-bus system and IEEE 69-bus system. To demonstrate the effectiveness of the proposed method, the results obtained by BSA are compared with a genetic algorithm (GA) as well as other results in the literature.

Keywords: BSA, DG placement, DG size, power loss.

1. Introduction

The integration of a solar power plant in distribution network is an important challenge, and it is one of the ways to reduce the environmental pollution that is produced by fossil fuel-based energy generation. Thus, much research has been concentrated on the optimum integration of solar panels in distribution networks in recent years.

Optimal reactive power flow is necessary to maintain power system reliability. It is achieved by minimizing power losses in the transmission line under the constraints of the physical system, using power flow equations. Valuable articles have dealt with this subject for the purpose of reducing power losses. Kansal et al. [1] proposed particle swarm optimization (PSO) to solve for the placement and size of different types of DG's, taking the power loss as an objective function. Kayal et al. [2] presented different types of DG's with different modes, using PSO. Their objective was power loss minimization and voltage stability improvement. Kollu et al. [3] proposed a harmony search algorithm (HSA) for multi-DG placement to reduce power loss, and enhance the voltage profile. García et al. [4] employed modified teaching–learning based optimization (MTLBO) to solve the problem of placement and sizing of multiple DG's with the single objective of reducing power loss. Injeti et al. [5] used simulated annealing (SA) for a DG placement and size to reduce the power loss, and improve the voltage stability. Manafi et al. [6] presented dynamic PSO for optimal placement of a DG to minimize power loss. Moradi et al. [7] proposed PSO/GA hybrid algorithms as a solution for sizing and placement of a DG to improve voltage regulation, and minimize power loss. Aman et al. [8] employed a PSO algorithm to solve a function with the multiple objectives of maximizing voltage stability and minimizing power losses, and found the optimal DG allocation, weakest link in the network, and the most sensitive voltage bus. Ates et al. [9] examined the impact of hybrid DG on power losses, voltage improvement, and electricity bill in distribution network by using the ETAP. Turan et al. [10] proposed the integration of a solar plant to a PEV parking lot to reduce power consumption and losses considering various operating conditions. Hemeida et. al. [11] implemented a new optimization algorithm to the optimal integration of a DG for power loss minimization. Memarzadeh et al. [12] applied a new approach for DG placement in order to improve voltage stability index and the system reliability. This approach has been tested in various RDS. Kansal et al. [13] proposed a hybrid of heuristic and analytical methods of the PSO (H-PSO) algorithm to determine the optimum places and the best types of DGs.

In this work, we have considered 3 scenarios. In Scenario 1, the tested systems are integrated by active-power DGs (photovoltaic) only, where only one active-power DG can be placed in a given bus. In Scenario 2, one active-power DG and one reactive-power DG (synchronous compensator) are paired and connected together in a bus, where only one pair can be placed in a given bus. In Scenario 3, while in some buses one active-power DG and one reactive-compensator DG are paired and connected as a single pair per bus, in other buses either one active-power DG or one reactive-power DG is placed singly –only one DG per bus. References [2, 5, 6, 7, 8 and 13] dealt only with scenario 1. Ref. [1] dealt with scenarios 1 and 2, but not 3. None of the references used the BSA in their optimizations. In this paper, we applied the BSA on 33-bus as well as 69-bus systems in cases where multiple DGs (up to a total of 16 DGs and 13 buses) are used. As understood from the Ref. [1-8] mentioned above, heuristic algorithms are successfully applied to solve the optimization problem in RDS. In this study, we used the BSA to solve the optimization problem of DG placement and sizing, such as to minimize system power loss in RDS.

This paper is arranged as follows: problem formulation is in Section 2, the proposed algorithm in Section 3, simulation results and discussion in Section 4, and the conclusion in Section 5.

2. Problem formulation

In this paper, active power loss is selected as an objective function. To minimize the objective function, the proposed algorithm is applied in two RDSs under both equality as well as inequality constraints. Minimization of power loss is an optimization problem, mathematical equations of which is well known and is defined as follows,

$$\begin{aligned} &\text{Minimize} && f(x,u) \\ &\text{Such that} && g(x,u)=0 \\ & && h(x,u)\le 0 \end{aligned} \qquad \textbf{(1)}$$

where f, g, and h are the fitness function, the equality constraint, and the inequality constraint, respectively. Here, x is the vector of control variables, while u is the vector of state variables. The control variables are the size and the place of DG active power, and of the reactive compensators. The state variables are active and reactive power of the feeder, load, bus voltage, and the line current.

2.1. Objective Function

In this work, power loss is selected as an objective function. The power loss can be demonstrated as equation (2) [14].

$$P_{loss} = P_{feeder} + \sum_{i=1}^{N_{DG}} P_{DG,i} - \sum_{i=1}^{N} P_{Load,i} \qquad i=1,\ldots,N \qquad \textbf{(2)}$$

2.2. Equality constraints

Load balancing constraint formulas as follows:

$$CDG_i \cdot P_{DG,i} + CF_i \cdot P_{feeder} = P_{Load,i} + V_i \sum_{j=1}^{N} V_j \left(G_{ij}\cos\delta_{ij} + B_{ij}\sin\delta_{ij}\right) \qquad i=1,\ldots,N \qquad \textbf{(3)}$$

$$CSC \cdot Q_{sc,i} + CF_i \cdot Q_{feeder} = Q_{Load,i} + V_i \sum_{j=1}^{N} V_j \left(G_{ij}\sin\delta_{ij} - B_{ij}\cos\delta_{ij}\right) \qquad i=1,\ldots,N \qquad \textbf{(4)}$$

2.3. Inequality constraints

Voltage limits:

The allowable range for all buses is given in equation (5),

$$V_i^{\min} \le V_i \le V_i^{\max} \qquad i=1,\ldots,N \qquad \textbf{(5)}$$

Unit constraints of DGs:
The following constraint is the allowable active power and reactive power sizes of DGs.

$$P_{DG,i}^{\min} \le P_{DG,i} \le P_{DG,i}^{\max} \qquad i=1,\ldots,N_{DG} \qquad \textbf{(6)}$$

$$Q_{sc,i}^{\min} \le Q_{sc,i} \le Q_{sc,i}^{\max} \qquad i=1,\ldots,N_{SC} \qquad \textbf{(7)}$$

Line capacity constraints:

The current limitation of the distribution lines of the system is given by [15].

$$\left|I_{ij}\right| \le \left|I_{ij}^{\max}\right| \qquad i=1,\ldots,N,\; j=1,\ldots,N \text{ and } i \ne j \qquad \textbf{(8)}$$

3. Back-tracking Search Algorithm

BSA is an evolutionary algorithm (EA) introduced by Civicioglu in 2012 [16]. BSA has been applied to solve different optimization problems in various fields such as energy, geophysics, and magnetism [17-19]. The most significant property of BSA that it is not sensitive to the initial values. Selection, mutation, and crossover operators are used in BSA. The MATLAB® code of BSA can be found in [16]. The basic steps of BSA are outlined as follows [17].

Repeat
Selection-1
Generation of Trial-Population
Mutation
Crossover
End
Selection-2
Until stopping conditions are met.

3.1. Initialization

In the beginning, two different populations (Pop and $oldPop$) are formed as follows:

$$Pop_{i,j} \sim Rand(low_j, up_j) \quad i = 1,...,SN \quad j = 1,...., D \tag{9}$$

$$oldPop_{i,j} \sim Rand(low_j, up_j) \quad i = 1,...,SN \quad j = 1,...., D \tag{10}$$

3.2. Selection-I

In this section, the old population ($oldPop$) in the initiation stage is formed using,

$$if \quad a < b, \quad oldPop := Pop \quad end \,|\, a,b \sim Rand(0,1) \tag{11}$$

In equation (11), **:=** is the update operator. This operator randomly transfers the Pop individuals' variables to $oldPop$ individuals' variables. Then, equation (12) is used to randomly change individuals in the $oldPop$.

$$oldPop := Randshuff\,(oldPop) \tag{12}$$

where $Randshuff$ is a random mixing function [15].

3.3. Mutation

The mutation process is formed as

$$mutantPop = Pop + W\,(oldPop - Pop) \tag{13}$$

In equation (13), W controls the amplitude of the search line matrix. $W = 3randn$ is proposed in the Ref.[16]. However, we observed that the performance of 4 is better that of 3. The function " $randn$ " randomly generates numbers between 0 and 1 according to the standard normal distribution [17].

3.4. Crossover

Initialization

In this section, the trial population ($Tpop$) is formed using equation (14). The crossover process consists of two stages. In the first stage, the binary number system is fully valued, and produces $SN * D$ size of a matrix (map). This matrix is used to determine whether or not we have to modify $Tpop$, one row at a time ("*individual by individual*" in heuristic terms). The second stage, the following equation is obtained from the matrix after its formation.

$$if \quad map_{i,j} = 1 \quad then \quad Tpop_{i,j} = Pop_{i,j} \quad else \quad Tpop_{i,j} = mutantPop_{i,j} \quad end \tag{14}$$

3.5. Selection-II

All the "individual" fitness values produced is calculated in this section. Individuals are sorted according to their fitness values, from best to worst. Then, the SN of them are carried to the next iteration Pop . The remaining ones are omitted. In this way, the best "individuals" among the whole population are transferred to the next generation.

4. Simulation Results and discussion

In this work, two types of DG are integrated in two different RDS. These systems are 33 and 69 bus systems. All nodes integrated of DGs are selected as PQ mode. The results are compared with GA and other recent works.

DG resources are divided into 4 types, determined by ability to deliver active and reactive power. The DG types are:

Type I: Generating active power (Photovoltaic system).
Type II: Generating reactive power (Synchronous compensation).
Type III: Generating active and absorbing reactive power (Wind power)
Type IV: Generating active and reactive power (Synchronous generator).
Type I and Type II are performed in our work.

Scenarios and cases
In this study, 3 scenarios and 5 cases are examined. All scenarios are considered under the 5 cases, and the differences between cases, depend on the number of DGs. In the following tables Case1 is base case for IEEE 33- bus system and IEEE 69- bus system.

Scenario1: All DGs are type I, one per bus.

Scenario2: Any pair of DGs (one of type I & one of type II) is connected in the same bus, only one pair per bus.

Scenario3: Some DG pairs (one of type I & one of type II) are connected in the same bus, one pair bus, while single DGs (type-I or type-II) are connected in different buses, one DG per bus.

4.1. IEEE 33-bus system

The IEEE 33-bus system is selected, with a system voltage base of 12.66 kV for all cases, and base apparent power of 100 MVA for all cases. The test system has total active and reactive loads of 3.715 MW and 2.300 MVAr, respectively. The data for the line reactance and resistances, and for the loads connected to buses, are given in [20].

Scenario1: In scenario1, 4 cases are constructed considering DG number. One, two, three and four DGs are integrated in Case2, 3, 4, and 5, respectively, to 33-bus system. In the following tables, all sizes of DGs type I are in (MW), while size of DGs Type II are in (MVAr).

The obtained results using BSA for all cases of Scenario1 are given in Table 1. The power loss for Case2, 3, 4, and 5, respectively are 211, 103.966, 87.1669, 72.7878 and 67.67kW. When we compare power loss of all cases, it is concluded that Case2 is better than Case1, Case3 is better than Case2, Case4 is better than Case3, and Case5 is the best for Scenario1.

Power loss reduction (considering Case1) comparison of the proposed algorithm, GA, and other results for all cases of scenario1 are given in Table 2. It is noticed that, the obtained results by the proposed algorithm for all cases are the best among all results.

Table 1. Results by BSA of all cases in Scenario 1 for IEEE 33- bus system

	Case 1	Case 2	Case 3	Case 4	Case 5
Power loss	211	103.966	87.1669	72.7878	67.76
Placement and size of DG Type I	-	2.5753(6)	0.8516(13) 1.1576(30)	0.8000(13) 1.0880(24) 1.0523(30)	0.8400(7) 0.6468 (14) 0.7307(25) 0.8112(31)

Table 2. Comparison of power loss reduction (%) by BSA and others for Scenario 1 of IEEE 33-bus system

Case	Ref. [1]	Ref. [2]	Ref. [5]	Ref. [6]	Ref. [7]	Ref. [11]	Ref. [13]	GA	BSA
2	45.36	-	-	39.73	-	47.37	47.31	45.6	50.73
3	-	-	-	54.54	-	58.68	58.64	58.65	58.69
4	-	27.82	61.12	56.14	-	65.45	65.46	65.31	65.50
5	-	-	-	-	67.68	-	-	67.50	67.89

Scenario 2: The obtained results using BSA for all cases of Scenario2 are given in Table 3. The power loss for Case2, 3, 4, and 5, respectively are 211, 67.739, 28.593, 12.2118 and 8.5364 kW. When we compare power loss of all cases, it is concluded that Case2 is better than Case1, Case3 is better than Case2, Case4 is better than Case3, and Case5 is the best for Scenario2.

Comparison of power loss reduction of BSA and other for all cases of scenario2 are given in Table 4. It is noticed that the obtained results by BSA for all cases of scenario2 are the best among all results.

Table 3. Results by BSA of all cases in Scenario 2 for IEEE 33- bus system

	Case 1	Case 2	Case 3	Case 4	Case 5
Power loss	211	67.739	28.593	12.2118	8.5364
Placement and size of DG Type I	-	2.5566(6)	0.3964(13) 1.0276(30)	0.8534(13) 0.9229(24) 0.3437(30)	0.4350 (7) 0.7180(14) 1.0174(24) 1.0151(30)
Placement	-		0.7537(13)	0.3676(13)	0.5289(7)

and size of DG Type II		1.7580(6)	0.9009(30)	0.4642(24) 0.1949(30)	0.2477 14) 0.5040(24) 0.8370(30)

Table 4. Comparison of power loss reduction (%) by BSA and others for Scenario 2 of IEEE 33-bus system

Case	Ref. [1]	GA	BSA
2	67.79	67.89	67.89
3	-	86.44	86.45
4	-	93.00	94.21
5	-	95.56	95.95

Scenario 3: The obtained results by BSA for all cases of Scenario3 are given in Table 5. The power loss for Case2, 3, 4, and 5, respectively are 211, 29.8235, 13.8957, 8.7463 and 7.4533kW. When we compare power loss of all cases, it is concluded that Case2 is better than Case1, Case3 is better than Case2, Case4 is better than Case3, and Case5 is the best among all cases in Scenario3.

In Table 5, all values in bold font indicate that DG pairs (one of type I & one of type II) are connected in the same bus, while others are connected in different buses. Power loss reduction of BSA and GA results for all cases of scenario3 are given in Table 6. It is noticed that the obtained results by the proposed algorithm for all cases are better than GA results.

Table 6. Comparison of power loss reduction (%) by BSA and others for Scenario 3 of IEEE 33-bus system

Case	GA	BSA
2	83.28	85.87
3	93.00	93.41
4	94.51	95.86
5	95.67	96.47

Table 5. Results by BSA of all cases in Scenario 3 for IEEE 33-bus system

	Case 1	**Case 2**	**Case 3**	**Case 4**	**Case 5**
Power loss	211	29.8235	13.8957	8.7463	7.4533
Placement and size of DG Type I	-	0.6247(29) **0.6755(14)**	1.0070(24) 0.6972(30) **0.7833(13)** **0.3295(30)**	0.5724 (3) 0.4820(12) 0.4270(27) **0.3781(13)** **0.9094(24)** **0.7673(30)**	0.2647(25) 0.3866(26) 0.3918(31) **0.7962(13)** **0.1000(21)** **0.6283(24)** **0.2068(28)** **0.1734(31)**
Placement and size of DG Type II	-	0.1000(30) **0.3781(14)**	0.2393 (8) 0.1261(14) **0.2076(13)** **0.9685(30)**	0.3194(4) 0.1321(10) 0.3987(31) **0.1000(13)** **0.3871(24)** **0.6595(30)**	0.3439(23) 0.4105(27) 0.5653(30) **0.2732(13)** **0.1393(21)** **0.1000(24)** **0.2093(28)** **0.1000(31)**

4.2. IEEE 69- bus system

The IEEE 33-bus system is selected, with system voltage base of 12.66 kV for all cases, and base apparent power of 100 MVA for all cases. The test system has total active and reactive loads of 3.802 MW and 2.694 MVAr, respectively. The data for the line reactance and resistances, and for the loads connected to nodes, are given in [20].

Scenario 1: The obtained results using BSA for all cases of Scenario1 are given in Table 7. The power loss for Case2, 3, 4, and 5, respectively are 225, 83.0704, 71.567, 69.3767 and 67.84 kW. When we compare power loss of all cases, it is concluded that Case2 is better than Case1, Case3 is better than Case2, Case4 is better than Case3,

and Case5 is the best for Scenario1. Comparison of power loss reduction of BSA and other for all cases of scenario1 are given in Table 8. It is noticed that, the obtained results by BSA for all cases of scenario1 are the best among all results.

Table 7. Results by BSA of all cases in Scenario 1 for IEEE 69-bus system

Celal Bayar University Journal of Science
Volume 17, Issue 2, 2021, p 199-207
Doi: 10.18466/cbayarfbe.796140

	Case 1	Case 2	Case 3	Case 4	Case 5
Power loss	225	83.0704	71.567	69.3767	67.84
Place-ment and size of DG Type I	-	1.8710 (61)	0.5291 (17) 1.7820 (61)	0.5885 (11) 0.3445 (20) 1.7338 (61)	0.5448 (11) 0.3572 (20) 0.7188 (50) 1.7181 (61)

Scenario 2: The obtained results by BSA for all cases of Scenario2 are given in Table 9. The power loss for Case2, 3, 4, and 5, respectively are 225, 23.133, 7.7836, 5.7156 and 2.0784 kW. When we compare power loss of all cases, it is found that Case2 is better than Case1, Case3 is better than Case2, Case4 is better than Case3, and Case5 is the best for Scenario2.

Power loss reduction comparison of the proposed algorithm, GA, and other results for all cases of the scenario2 are given in Table 10. It is noticed that, the obtained results by BSA for all cases are the best among all results.

Table 8. Comparison of power loss reduction (%) by BSA and others for Scenario 1 of IEEE 69-bus system

Case	Ref. [1]	Ref. [5]	Ref. [11]	Ref. [12]	Ref. [13]	GA	BSA
2	62.94	-	63.01	63.02	62.95	63.08	63.08
3	-	-	68.14	-	68.09	68.19	68.19
4	-	65,68	69.14	-	69.09	69.07	69.17
5	-	-	-	-	-	69.80	69.85

Table 9. Results by BSA of all cases in Scenario 2 for IEEE 69-bus system

	Case 1	**Case 2**	**Case 3**	**Case 4**	**Case 5**
Power loss	225	23.133	7.7836	5.7156	2.0784
Placement and size of DG Type I	-	2.0275(61)	0.5280(15) 1.7266(61)	0.3037(19) 1.6533(61) 0.1501(66)	0.2774(11) 0.2575(18) 0.5289(49) 1.1995(61)
Placement and size of DG Type II	-	1.4447(61)	0.4654(15) 1.2207(61)	0.2203(19) 1.1344(61) 0.3391(66)	0.5206(11) 0.3569(18) 0.7771(49) 1.6666(61)

Table 10. Comparison of power loss reduction (%) by BSA and others for Scenario 2 of IEEE 69-bus system

Case	**Ref. [1]**	**GA**	**BSA**
2	89.01	89.72	89.72
3	-	96.23	96.54
4	-	96.48	97.46
5	-	97.37	99.08

Scenario 3: The obtained results by proposed algorithm for all cases of Scenario3 are given in Table 11. The power loss for Case2, 3, 4, and 5, respectively are 225, 7.3167, 4.1776, 3.6989 and 1.8875kW. When we compare power loss of all cases, it is noticed that Case2 is better than Case1, Case3 is better than Case2, Case4 is better than Case3, and Case5 is the best for Scenario3. In Table 11, all values in bold font indicate that DG pairs (one of type I & one of type II) are connected in the same bus, while others are connected in different buses.

In Table 12, comparison of power loss reduction of the proposed algorithm and GA for cases of scenario3 is given. It is noticed that the obtained results by BSA for all cases of scenario3 are better than GA results.

Table 12. Comparison of power loss reduction (%) by BSA and others for Scenario 3 of IEEE 69-bus system

Case	**GA**	**BSA**
2	96.64	96.75
3	97.63	98.14
4	97.94	98.36
5	99.01	99.16

Celal Bayar University Journal of Science
Volume 17, Issue 2, 2021, p 199-207
Doi: 10.18466/cbayarfbe.796140

Table 11. Results by BSA of all cases in Scenario 3 for IEEE 69-bus system

	Case 1	Case 2	Case 3	Case 4	Case 5
Power loss	225	7.3167	4.1776	3.6989	1.8875
Placement and size of DG Type I	-	0.5126(17) **1.7805(61)**	0.4080(17) 0.3148(50) **1.8000(61)** **0.3387(66)**	0.6224(8) 0.1440(17) 0.6551(50) **0.2630(21)** **0.7848(61)** **0.8759(62)**	0.2696(4) 0.3414(19) 0.2383(53) 0.3477 (12) **0.5359 (50)** **0.1000(61)** **1.2000(62)** **0.3674(64)**
Placement and size of DG Type II	-	0.3400(16) **1.2483(61)**	0.1000(15) 0.6084 49) **1.1792(61)** **0.4645(66)**	0.3180(12) 0.2186(40) 0.3273(53) **0.1000(21)** **0.2400(61)** **0.8745(62)**	0.2734(2) 0.1314(15) 0.1757(49) 0.3036(12) **0.3654(50)** **0.3094(61)** **0.5464(62)** **0.3532(64)**

Variation of fitness function versus iteration number of IEEE 33- and 69-bus system for Scenario-3 are shown in Fig.1 and 2, respectively. In Fig.1, the value of fitness nearly at 62nd, 50th, 45th and 52nd iteration for Case2, 3, 4, and 5, respectively; in Fig.2, the value of fitness nearly at 74nd, 46th, 52th and 53th iteration for Case2, 3, 4, and 5, respectively are approached to the optimal solution.

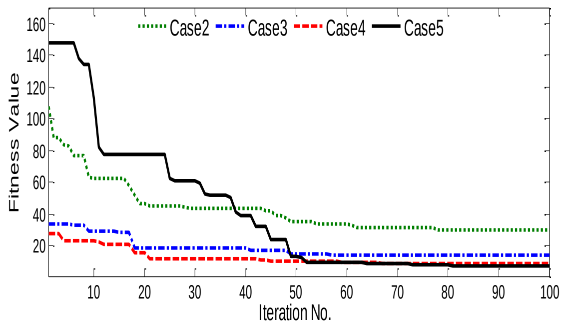

Figure 1. Fitness variation with iteration number for 33 bus system with scenario3

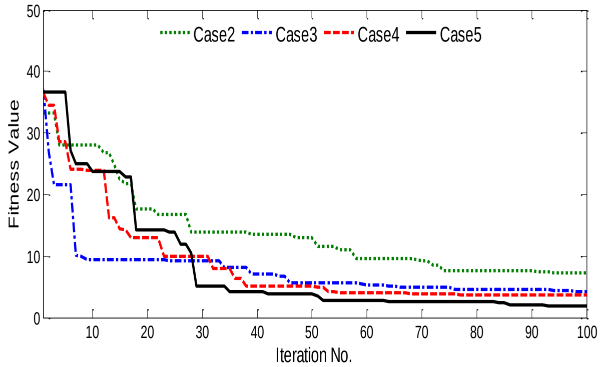

Figure 2. Fitness variation with iteration number for 69 bus system with scenario 3

It can be seen from the figures that all fitness values are reached the optimal solution before 75th iteration and there is no change after that.

Summary: According to the obtained results by BSA for all scenarios and cases of both test systems, it is noted that power loss reduction gradually increases as the number of DGs is increased, as well as by changing the DG type, as shown in Fig. 3 and 4. It is clearly observed that the results of Case 5 of each scenarios offer the greatest power loss reduction for both the IEEE 33- and 69-bus system. The noticeable increase in power loss reduction under Scenario-3 is better than those in other scenarios. So, it is better to integrate some DGs, as in Scenario-3, in order to increase the power loss reduction. The location, size, type, and the number of DGs are the basic steps for planning improvements in system performance, especially the system power loss.

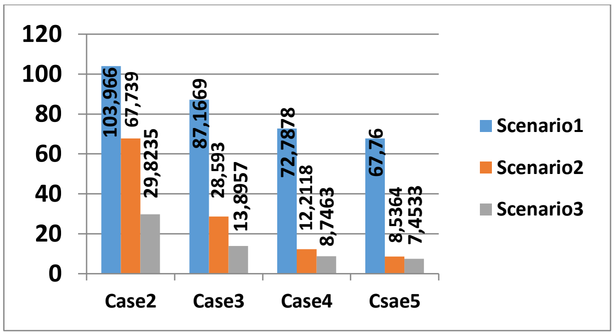

Figure 3. Demonstrate power loss (kW) in each scenario with their different cases for 33 bus system

Celal Bayar University Journal of Science
Volume 17, Issue 2, 2021, p 199-207
Doi: 10.18466/cbayarfbe.796140

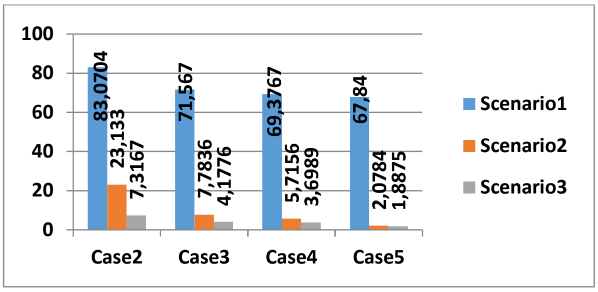

Figure 4. Demonstrate power loss (kW) in each scenario with their different cases for 69 bus system

5. Conclusion

In this work, the BSA is successfully applied in RDS to find optimal size, number, type, and location of DGs. These DGs are connected to the test systems and minimized their power loss. The DGs are integrated under 3 scenarios and 5 cases in each scenario. Under Scenario-3 (Case5), power loss is reduced by 99.16%, 96.47%, respectively for 33 and 69 bus systems. It's noticed that it is better to select suitable DG type to minimize power loss to a considerable amount. But the best way is to put DG type, and number in consideration.

It is concluded that an optimal size, type, number of DG with suitable location can reduce the power losses by considerable amounts.

In future work, Type III: Generating active and absorbing reactive power (wind power) and Type IV: Generating active and reactive power (synchronous generator) will considered by using the BSA.

Nomenclature

DG	Distributed generation
f	Fitness Function
g	Equality constraint
h	Inequality constraint
x	Control variables
u	State variables
P_{loss}	Total power loss
P_{feeder}	Feeder active power
Q_{feeder}	Feeder reactive power
$P_{DG,i}$	DG active power output at i^{th} bus
$P_{Load,i}$	Active load at i^{th} bus
$Q_{Load,i}$	Reactive load at i^{th} bus
N	Total bus number
N_{DG}	Total number of DG
N_{SC}	Total number of SC
CF_i	Status (on/off) of the feeder
CDG_i	Status (on/off) of the distributed generation at i^{th} bus
CSC_i	Status (on/off) of the synchronous compensator at i^{th} bus
V_i	Voltage magnitude at i^{th} bus
δ_{ij}	The voltage angle difference between buses i and j
$Q_{sc,i}$	SC reactive power output at i^{th} bus
G_{ij}	Transfer conductance between buses i and j
SC	Synchronous compensator
SN	Number of population size
D	the number of optimization parameters
$Randshuff$	random mixing function
$Rand(low, up)$	produce a random number between low and up
Pop	Population
$oldPop$	Old population
~	Produce
$Tpop$	Trial population
$P_{DG,i}^{\min}$	Minimum DG active power output at i^{th} bus
$P_{DG,i}^{\max}$	Maximum DG active power output at i^{th} bus
I_{ij}	Current magnitude at branch ij
$I_{ij}^{\max}$	Allowable maximum current magnitude at branch ij
a,b	$Rand(0,1)$
:=	Update operator
mutantPop	Population of mutation
W	Value
$randn$	Generates numbers between 0 , 1
map	Matrix ($SN * D$)
$Q_{sc,i}^{\min}$	Minimum SC reactive power output at i^{th} bus
$Q_{sc,i}^{\max}$	Maximum SC reactive power output at i^{th} bus
B_{ij}	Transfer susceptance between buses i and j

Author's Contributions

Waleed Fadel: Methodology, Software.
Ulas Kilic: Visualization, Investigation, Supervision.
Sezai Taskin: Investigation, Supervision, Writing.

Ethics

There are no ethical issues after the publication of this manuscript.

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