Turkish Journal of Electrical Engineering & Computer Sciences

http://journals.tubitak.gov.tr/elektrik/

Research Article

Turk J Elec Eng & Comp Sci
(2019) 27: 2947 – 2961

doi:10.3906/elk-1805-66

Optimal DG allocation for enhancing voltage stability and minimizing power loss using hybrid gray wolf optimizer

Salah KAMEL[1,2], **Ayman AWAD**[1,3], **Hussein ABDEL-MAWGOUD**[1], **Francisco JURADO**[3,*]

[1]Department of Electrical Engineering, Faculty of Engineering, Aswan University, Aswan, Egypt
[2]State Key Laboratory of Power Transmission Equipment and System Security and New Technology, Chongqing University, Chongqing, China
[3]Department of Electrical Engineering, University of Jaén, Jaén, Spain

Received: 11.05.2018 • **Accepted/Published Online:** 17.09.2018 • **Final Version:** 26.07.2019

Abstract: High penetration of photovoltaic and wind turbine-based distributed generators (DGs) can help reduce carbon emissions which is an important goal for the whole world. DG can be used to improve the voltage stability, present generation reserve/emergency, and consequently, the system power quality can be improved. However, it is very important to select the right size and location of a DG so that the power system can increase the gained benefits of such an installation to the maximum. In this paper, a hybrid optimization technique is proposed to determine the optimal allocation of DG in the standard IEEE 33-bus radial distribution system in order to improve the voltage stability and minimize the total power loss. The proposed hyprid technique is based on the gray wolf optimizer algorithm with loss sensitivity factor. The performance of the system is analyzed without DG installation, then it is compared with the performance of the system when DGs are installed with the predefined optimal sizes and locations. The study is performed by MATLAB M-Files and NEPLAN software.

Key words: Voltage stability, power losses, loadability, distributed generation, gray wolf optimizer, loss sensitivity factor

1. Introduction

In the last few decades, the concept of distributed generation has arisen in the power systems world. This concept briefly means to generate electric power in small scales, and the location of the generators is close to the location of loads, mainly in distribution networks [1,2]. A distribution generator (DG) can be defined as "a small scale electric power generation unit that is installed 'behind the meter', typically at the end-of-use customers' premises and operated for the purpose of totally or partially supply the load" [3,4]. A DG often depends on renewable energy for electric power generation, known as distributed energy resources (DERs), and it includes a variety of generation methods. It can depend on photovoltaic (PV) technology, solar thermal energy, small and microhydros, wind energy, geothermal, biomass, combined heat and power technology (CHP), beside backup generators (gensets), microturbines and energy storage devices [1–5]. Actually, the main concern of the DG technology is the environment. In other words, DER technologies exploit the renewable power resources to reduce the traditional central power plants which depend on organic fuel and nuclear power consumption to produce electric energy so that the greenhouse gas effect is mitigated. However, DG establishments prove that it is very beneficial to power systems, as it is environment-friendly. The main characteristic of DGs is that they are established in the distribution network level, often in load location, so there is no need for long transmission lines, which provides many advantages for such establishments. A DG installation helps in power loss reduction, improves the reliability of the system, enhances the voltage profile and stability, increases the loadability, improves the power quality presented to the customers, mitigates power system instability and presents a spinning reserve for the system for contingencies [1].

As the penetration of DGs in power systems increases, it attracts the interest of many researchers and power system developers, which makes it an important subject. One of the most common issues concerned with DGs is determining the DG size and location that will maximize the benefits from such an installation. Many contributions have been introduced for that issue. In [6–8], particle swarm optimization (PSO) is utilized to determine the optimal location and size of DG. In [6], it was utilized to reduce power losses and improve the voltage profile of IEEE 69-bus distribution system. In [7], it was also utilized to reduce the power losses of IEEE 69-bus system, and the results obtained by PSO are compared with the results obtained by improved analytical method and artificial bee colony. In [8], it was utilized to minimize the power losses of a United Kingdom 15-bus realistic distribution system. Weight-improved particle swarm optimization was introduced in [9] to find the optimum size and location of DG that leads to operation costs reduction and voltage profile improvement of IEEE 13-bus distribution system. Genetic Algorithm was proposed in [10] to obtain the optimum location and size of DGs for power losses minimization of IEEE 14-bus system. In [11], a combination of PSO and Chu-Beasly genetic algorithm was proposed to determine the optimal size and location of DGs so that the power losses are minimized in IEEE 33-bus and IEEE 69-bus systems. Another combination of tabu search and branch exchange optimization techniques was presented in [12] to determine the optimal location and size of DGs so that the power losses are minimized. The gray wolf optimizer (GWO) algorithm was inspired by the hunting behavior of gray wolves in nature. The GWO algorithm proposes the social hierarchy of gray wolves that is divided into four groups: alpha, beta, delta, and omega to implement the hunting mechanism [16,17].

This paper proposes a hybrid optimization technique to determine the optimal size and location of DGs, typically PV and wind generators, in order to improve the voltage stability and minimize the total power loss. The proposed technique is based on GWO and loss sensitivity factor (LSF) in order to reduce the search space. The performance of IEEE 33-bus radial distribution system (RDS) is comprehensively analyzed in five different cases to show the impact of DGs on the system. These cases are: 1) The base case (without DG), 2) One photovoltaic DG, 3) Two photovoltaic DGs, 4) One wind turbine DG, and 5) Two wind turbine DGs. The hybrid optimization code is scripted by MATLAB M-Files. Then, the system is analyzed using NEPLAN software to investigate the impact of optimization process on the system with and without DGs.

2. Problem formulation

2.1. Objective function

This paper aims to determine the optimal size and location of DG in RDSs in order to improve the voltage stability and minimize the total power loss. The representation of equivalent model of RDS is shown in Figure 1. However, the objective function can be formulated as follows:

$$f_t = Min(W_1 f_1) + Max(W_2 f_2), \tag{1}$$

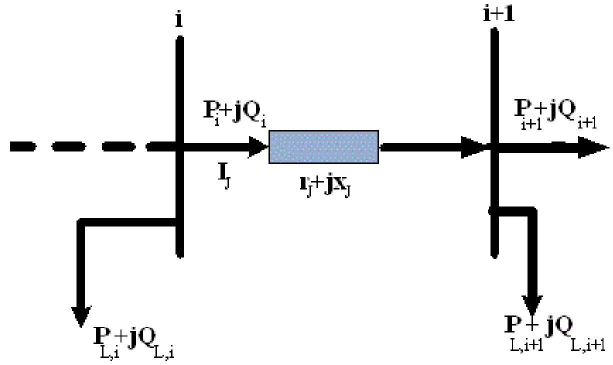

Figure 1. Equivalent model of RDS.

where f_1 represents the power losses, which are desired to be minimized, and it can be expressed as:

$$f_1 = \frac{\sum_{i=1}^{nl}(P_{loss}(i))_{afterDG}}{\sum_{i=1}^{nl}(P_{loss}(i))_{beforeDG}}, \tag{2}$$

where nl is the number of branches of the system.

Voltage stability index (VSI) is an important factor, which indicates the state of the system stability, in optimization problem of the power system. As long as the buses of RDS have low value of VSI, closer to zero, the buses are more stable. VSI values of all buses in RDS can be calculated as follows [18]:

$$VSI_{(j)} = |V_i|^4 - 4(P_jX_j - Q_jR_j)^2 - 4(P_jX_j - Q_jR_j)|V_i|^2. \tag{3}$$

f_2 represents the VSI, which is desired to be maximized, and it can be expressed as:

$$f_2 = \frac{1}{\sum_{i=1}^{nb}(|VSI|(i))_{afterDG}}, \tag{4}$$

where nb is the number of buses of the system.

While $w1$ and $w2$ are weighting factors, the sum of the weighting factors equal 1 (i.e. $|w_1| + |w_2| = 1$).

2.2. Constraints of the optimization problem

2.2.1. Equality constraints

The equality constraints can be set as the power flow equations for active and reactive power, and it can be expressed as:

$$P_{Gi} - P_{Di} - V_i\sum_{j=1}^{Nb} V_j[G_{ij}\cos(\delta_i - \delta_j)] = 0 \tag{5}$$

$$Q_{Gi} - Q_{Di} - V_i\sum_{j=1}^{Nb} V_j[G_{ij}\cos(\delta_i - \delta_j)] = 0. \tag{6}$$

2.2.2. Inequality constraints

The inequality constraints can be expressed as:

Generation constraints:

$$P_G^{min} \leq P_G \leq P_G^{max}, \tag{7}$$

$$V_G^{min} \leq V_G \leq V_G^{max}, \tag{8}$$

$$Q_G^{min} \leq Q_G \leq Q_G^{max}. \tag{9}$$

Security constraints:

$$S_{Li} \leq S_{Li}^{max}, i = 1, 2, ..., nl, \tag{10}$$

$$V_i^{min} \leq V_i \leq V_i^{max}, i = 1, 2, ..., nb, \tag{11}$$

where V_i^{min} and V_i^{max} are given as 0.90 Pu and 1.05 Pu, respectively.

Distributed generators constraints:

$$0.2(\sum P_{Load} + \sum_{j=1}^{Nb} P_{Loss}) < \sum_{k=1}^{n} P_{DG} \leq 0.75(\sum_{i=1}^{nb} P_{Load} + \sum_{j=1}^{Nb} P_{Loss}), \tag{12}$$

$$0.2(\sum Q_{Load} + \sum_{j=1}^{Nb} Q_{Loss}) < \sum_{k=1}^{n} Q_{DG} \leq 0.75(\sum_{i=1}^{nb} Q_{Load} + \sum_{j=1}^{Nb} Q_{Loss}), \tag{13}$$

where Eqs. (12) and (13) express the size of DG, and:

$$PF_{DG,min} \leq PF_{DG} \leq PF_{DG,max}, \tag{14}$$

where n is the number of DG installations, P_{DG} is the power generated by the DG, P_{Load} is the total load demand of the system, and $PF_{DG,min}$ and $PF_{DG,max}$ are the minimum and maximum power factors of DG that are taken as 0.8 and 0.9, respectively.

DG location can be formulated as:

$$1 \leq DGsite_n \leq nb, \tag{15}$$

$$DGsite_1 \neq DGsite_2, \tag{16}$$

where DG site is the location of the DG installation.

Reactive power supplied by DG can be formulated as:

$$Q_{DG} = P_{DG} * \tan(\cos^{-1} pf), \tag{17}$$

where Q_{DG} is the amount of reactive power generated by the DG, and pf is the power factor of DG.

3. Proposed hybrid optimization technique

The proposed hybrid optimization technique is based GWO and LSF to determine the optimal allocation of DG in RDS as discussed below.

3.1. Loss sensitivity factor (LSF)

LSF is used to determine the best buses for DG location in RDS that is based on sensitivity of buses. LSF of each bus is determined by studying the changing in active power loss with respect to the change in reactive power injection at all buses. The buses with high LSF are the best locations for DG installation as shown in Figure 2. LSF gives the best solution with less simulation time of optimization5 technique. LSF can be calculated using Eq. (18) [19–23]

$$LSF_i = \frac{\partial P_{Loss(i,i+1)}}{\partial Q_{i+1}} = R_{i,i+1}\left(\frac{2Q_{i+1}}{|V_{i+1}|^2}\right), \tag{18}$$

where $P_{loss(i,i+1)}$ is the power loss between the bus "i" and the receiving bus "i+1". Q_{i+1} is the injected reactive power at receiving bus "i+1". $R_{i,i+1}$ is the resistance between bus "i" and "i+1". V_{i+1} is the voltage magnitude of bus "i+1".

After power flow solution and LSF calculation, the candidate buses for optimal allocation of PV- and WT-based DGs in distribution system are determined up to 50% of system buses (6, 3, 28, 8, 29, 4, 5, 30, 9, 24, 13, 10, 27, 31, 2, 26 and 23) as shown in Figure 2.

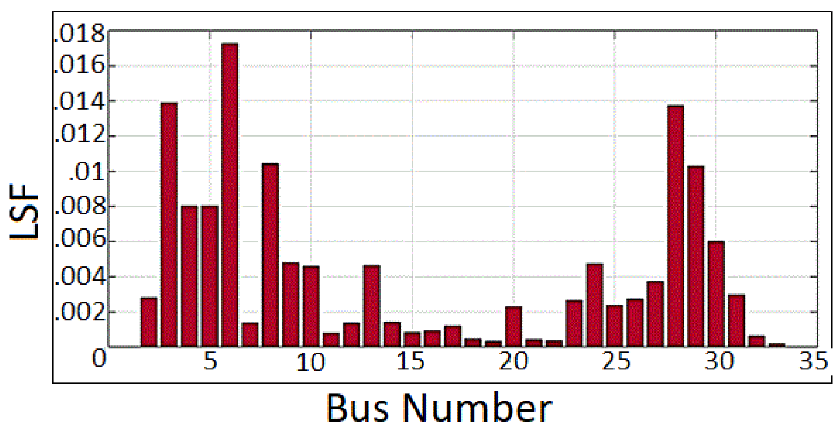

Figure 2. The appropriate buses for DG installation in IEEE-33 bus test system.

3.2. Gray wolf optimizer (GWO)

GWO is a recent optimization technique inspired by the strict hierarchy of gray wolf society. The leaders of the group are a male and a female who are called "alpha", and they are the most responsible for taking decisions for hunting. A sublevel is the level "beta", and they are subordinate wolves who help the "alpha" take the decision. The lowest level is called "omega", and it have to submit to all decisions of the higher levels. The wolves belonging to this hierarchical leadership group work together to hunt their prey according to the following steps:

(1) Tracking and chasing the prey.

(2) Pursuing, surrounding, and harassing the prey until it is no more able to move.

(3) The final attack on the prey.

This behavior is translated into an algorithm that is used in optimization processes [16,17].The implementation of GWO can be described briefly with the following steps:

Step 1: Initialize the gray wolf population between the upper and lower limits of variables as shown below:

$$G(m,v) = rand(U_p(m,v) - L_p(m,v)) + L_p(m,v), \tag{19}$$

where m is the number of wolves and v is the number of variables.

Step 2: The generated solutions are the position of a gray wolf population for chasing and tracking the prey that can be represented as below:

$$G = \begin{bmatrix} G_{1,1} & G_{1,2} & \cdots & G_{1,v} \\ G_{2,1} & G_{2,2} & \cdots & G_{2,v} \\ \vdots & \vdots & \ddots & \vdots \\ G_{m,1} & G_{m,2} & \cdots & G_{m,v} \end{bmatrix}, \tag{20}$$

where m is the number of search agent.

Step 3: Calculate the objective function of each search agent as follows below:

$$OG = \begin{bmatrix} OG_1 & OG_2 & OG_3 & .. & OG_m \end{bmatrix}. \tag{21}$$

Step 4: Determine the first best position (G_α), the second-best position (G_β) and the third best position (G_δ) of grey wolf packs according to its objective function.

Step 5: Calculate the values of b, $\overrightarrow{B}$, and $\overrightarrow{C}$:

$$b = 2 - \frac{2l}{L} \tag{22}$$

$$\overrightarrow{B_1} = 2br_1 - b, \tag{23}$$

$$\overrightarrow{C_1} = 2r_2, \tag{24}$$

$$\overrightarrow{B_2} = 2br_3 - b, \tag{25}$$

$$\overrightarrow{C_2} = 2r_4, \tag{26}$$

$$\overrightarrow{B_3} = 2br_5 - b, \tag{27}$$

$$\overrightarrow{C_3} = 2r_6, \tag{28}$$

where b is linearly decreased from 2 to 0 over all iterations; $r_1, r_2, r_3, r_4, r_5, r_6$ are random numbers between 0 and 1; and l and L are the current iteration and maximum iteration, respectively.

Step 6: Update the position of β and δ as shown below:

$$\overrightarrow{D_\alpha} = |\overrightarrow{C_1} * \overrightarrow{G_\alpha(l)} - \overrightarrow{G}(l)|, \tag{29}$$

$$\overrightarrow{D_\beta} = |\overrightarrow{C_2} * \overrightarrow{G_\beta(l)} - \overrightarrow{G}(l)|, \tag{30}$$

$$\overrightarrow{D_\delta} = |\overrightarrow{C_3} * \overrightarrow{G_\delta(l)} - \overrightarrow{G}(l)|, \tag{31}$$

$$\overrightarrow{G_1} = |\overrightarrow{G_\alpha(l)} - \overrightarrow{B_1} * \overrightarrow{D_\alpha}|, \tag{32}$$

$$\overrightarrow{G_2} = |\overrightarrow{G_\beta(l)} - \overrightarrow{B_2} * \overrightarrow{D_\beta}|, \tag{33}$$

$$\overrightarrow{G_3} = |\overrightarrow{G_\delta(l)} - \overrightarrow{B_3} * \overrightarrow{D_\delta}|, \tag{34}$$

where $\overrightarrow{D_\alpha}$, $\overrightarrow{D_\beta}$, $\overrightarrow{D_\delta}$ are the distance between the best three positions of α, β, and δ with respect to ω respectively, and $\overrightarrow{G_1}$, $\overrightarrow{G_2}$, and $\overrightarrow{G_3}$ are the position of α, β, and δ, respectively.

Step 7: Update the position of ω based on the position of α, β, and δ as follows:

$$\overrightarrow{G}(l+1) = \frac{\overrightarrow{G_1} + \overrightarrow{G_2} + \overrightarrow{G_3}}{3}. \tag{35}$$

Step 8: Calculate the objective function of the updated position of all gray wolf packs.

Step 9: Repeat steps from 5 to 8 until maximum iteration is achieved.

Step 10: Obtain the best position of alpha (optimal locations and sizes of DGs) and its objective function.

4. Analysis of the case study

Standard IEEE 33-bus distribution system is used to validate the proposed hybrid optimization technique. This system is a radial distribution network with 33 nodes. It has a total load demand of 3715 kW and 2300 kVAR, while its nominal voltage is 12.66 kV [24]. Figure 3 shows the system plotted by NEPLAN software.

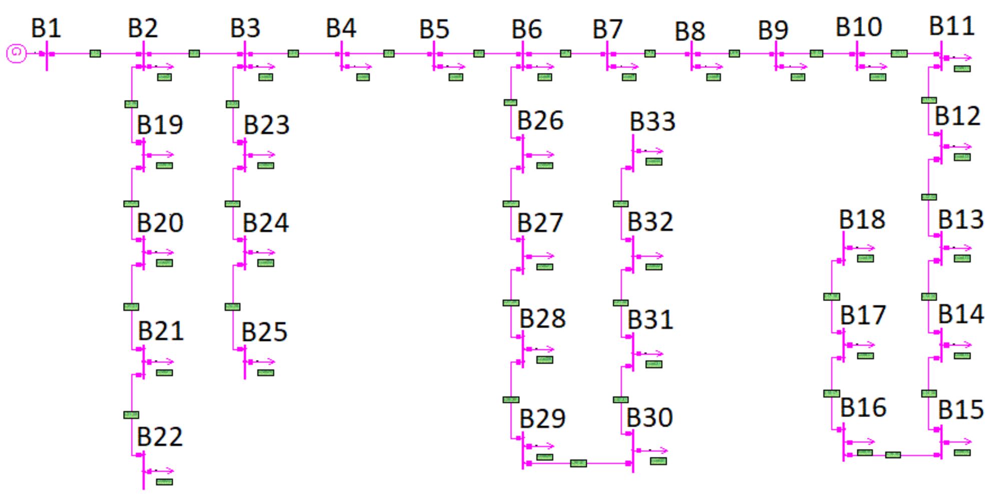

Figure 3. IEEE 33-bus distribution system plotted by NEPLAN.

When applying load flow analysis to the system, it is observed that the total active power losses of the system is 211 kW. It is also observed that the voltage magnitude of bus 18 has the lowest value, as it is the last bus in the system. The voltage magnitude of this bus is 0.9038 pu. Table 1 presents the voltage magnitudes of the system.

Table 1. Voltage magnitudes of IEEE 33-bus distribution system.

Bus no.	Vmag (pu)	Bus no.	Vmag (pu)	Bus no.	Vmag (pu)
1	1.00	12	0.9177	23	0.9793
2	0.997	13	0.9115	24	0.9726
3	0.9829	14	0.9092	25	0.9693
4	0.9754	15	0.9078	26	0.9475
5	0.968	16	0.9064	27	0.945
6	0.9495	17	0.9044	28	0.9335
7	0.946	18	0.9038	29	0.9235
8	0.9323	19	0.9965	30	0.9218
9	0.926	20	0.9929	31	0.9176
10	0.9201	21	0.9922	32	0.9167
11	0.9192	22	0.9916	33	0.9164

As the system is a radial system, the farthest buses from the generator attract more attention, due to the large voltage drop on these buses, compared with the close buses to the generator. On the other hand, Figure 4 shows the PV curves of the system.

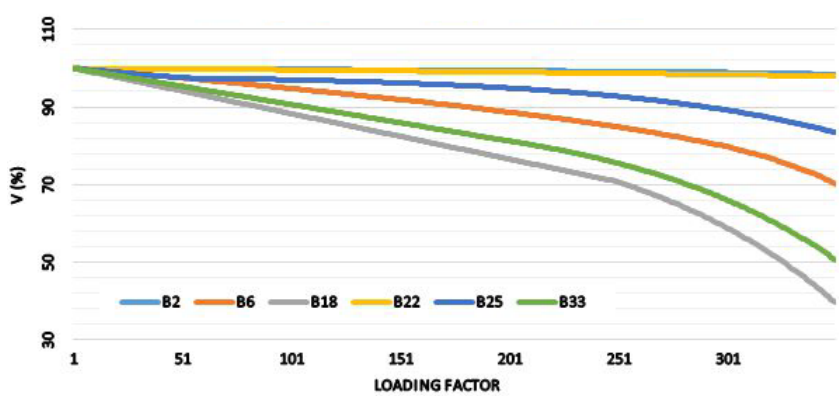

Figure 4. PV curves of IEEE 33-bus distribution system.

From Figure 4, it can be observed that the system's voltages, typically for bus 18, are in margin of the acceptable voltage magnitudes, where it starts to decay to less than 0.9 pu when the loading factor is more than 100%, and the system collapses when the loading factor exceeds 340%.

As mentioned before, the IEEE 33-bus distribution system is analyzed in its normal operating conditions, then DGs are added to the system after determining its optimal sizes and locations using the proposed optimization algorithm. The number of DG installations are even one or two installations, where each model of photovoltaic and wind turbine DGs is installed to the system according to the mentioned DG numbers, and the impact of each model on the system is analyzed. Hence, the system is analyzed in 5 cases: in its normal conditions, and after adding incremental DG installations for both PV and WT models, where the maximum number of DG installations is 2.

Applying hybrid optimization technique on the system to determine the optimal size and location of DG installations, where the objective functions are 1) to maximize the voltage stability index (VSI), and 2) to minimize the total active power loss. The results are shown in Table 2.

Table 2. Optimal sizing and locations of DG installations.

Case	DG no. /DG type	DG parameters			Power loss (kW)	Voltage stability index
		Location	Size(kW)	PF		
Case 1	1/PV	6	2601.77	1	111.029	28.536
Case 2	1/WT	6	2571.3	0.82	67.87	29.845
Case 3	2/PV	13	856.9	1	87.169	29.404
		30	1160.23	1		
Case 4	2/WT	13	824.8	0.88	29.314	31.311
		30	1241.2	0.8		

The convergence characteristics of the proposed hybrid algorithm for single and multiple of PV- and WT-based DG are shown in Figures 5 and 6.

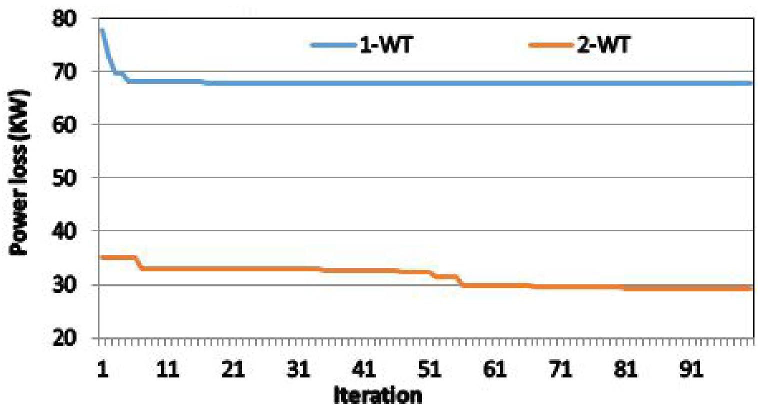

Figure 5. Convergence characteristics of single and multiple of PV-based DG.

From Figure 5, it can be observed that the integration of multiple PVs gives better results than a single PV and the system power loss is reduced to 111.029 KW and 87.169 KW by integrating 1-PV and 2-PVs, respectively. Moreover, the integration of WT in the system reduces the total active power loss to 67.87 KW and 29.314 KW by integrating 1 WT and 2 WTs, respectively as shown in Figure 6. From the comparative study, it is observed that the proposed method obtains the best results when compared with other optimization methods as shown in Table 3.

According to Table 2, DGs are added and the system is analyzed in the following cases.

4.1. Case (1): including one photovoltaic DG

In this case, the proposed optimization algorithm is used to determine the optimal allocation of one photovoltaic DG (optimal size is 2601.77 kW at bus 6). Table 4 presents the voltage magnitudes of the system for this case compared with the base case (without DG).

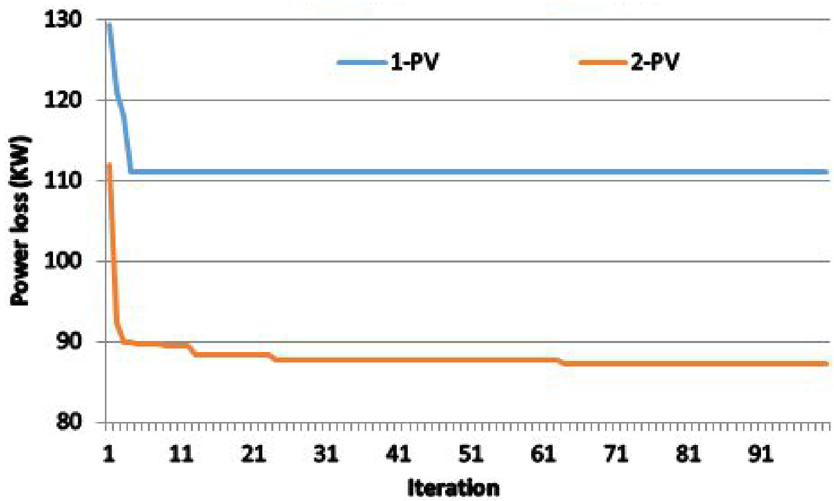

Figure 6. Convergence characteristics of single and multiple of WT-based DG

Table 3. Comparative study of the proposed method with other optimization algorithms.

Case	DG no. /DG type	DG parameters (Size (kW)/PF/Bus no.)			Power losses (kW)		
		Proposed method	BSOA [26]	SOS [27]	Proposed method	BSOA [25]	SOS [26]
Case 1	1/PV	2601.77/1/6	1857.5/1/8	3132.2/1/6	111.029	118.12	115.01
Case 2	1/WT	2571.3/0.82/6	1857.5/0.82/8	-	67.87	82.78	-
Case 3	2/PV	856.9/1/13 1160.23/1/30	880/1/13 924/1/31	2286.1/1/6 836.3/1/28	87.169	89.34	107.39
Case 4	2/WT	824.8/0.88/13 1241.2/0.8/30	777/0.89/13 1032/0.7/29	-	29.314	31.98	red-

Table 4. Buses voltage magnitudes (pu) in Case (1) and base case (without DG)

Bus no.	Case (1)	Base case	Bus no.	Case (1)	Base case	Bus no.	Case (1)	Base case
1	1.00	1.00	12	0.9559	0.9177	23	0.9893	0.9793
2	0.9986	0.997	13	0.95	0.9115	24	0.9827	0.9726
3	0.9929	0.9829	14	0.9478	0.9092	25	0.9794	0.9693
4	0.9916	0.9754	15	0.9464	0.9078	26	0.9845	0.9475
5	0.9907	0.968	16	0.9451	0.9064	27	0.9821	0.945
6	0.9864	0.9495	17	0.9431	0.9044	28	0.9711	0.9335
7	0.983	0.946	18	0.9425	0.9038	29	0.9632	0.9235
8	0.9699	0.9323	19	0.9981	0.9967	30	0.9598	0.9218
9	0.9638	0.926	20	0.9945	0.9929	31	0.9558	0.9176
10	0.9582	0.9201	21	0.9938	0.9922	32	0.9549	0.9167
11	0.9573	0.9192	22	0.9932	0.9916	33	0.9546	0.9164

From Table 4, it can be observed that the voltage magnitudes are greatly improved, where the lowest voltage magnitude occurred at bus 18 with value of 0.9425 pu, and the voltage stability index value of 28.536, while total active power loss is 111.029 kW compared with 211 kW in the system's original case. Figure 7 shows PV curves of Case (1).

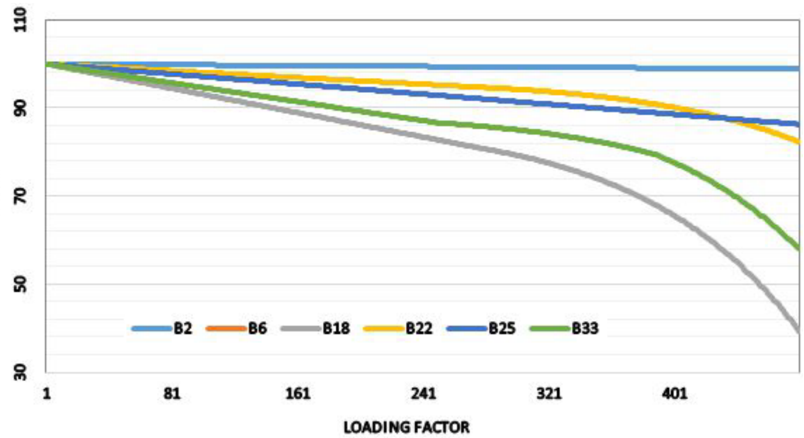

Figure 7. PV curves of IEEE 33-bus distribution system after photovoltaic DG installation.

From Figure 7, it can be observed that the system's loadability is enhanced, where the voltage levels start to decay to less than 0.9 pu when the loading factor is greater than 160%, and it totally collapses when it exceeds 470%.

4.2. Case (2): including one wind turbine DG

In this case, the proposed optimization algorithm is used to determine the optimal allocation of one wind turbine DG (optimal size is 2571.3 kW with power factor $PF = 0.82$ at bus 6). Table 5 presents the voltage magnitudes of the system for this case compared with the base case (without DG).

Table 5. Buses voltage magnitudes (pu) in Case (2) and base case (without DG).

Bus no.	case (2)	Base case	Bus no.	Case (2)	Base case	Bus no.	case (2)	Base case
1	1.00	1.00	12	0.982	0.9177	23	0.9953	0.9793
2	0.9995	0.997	13	0.9762	0.9115	24	0.9887	0.9726
3	0.9988	0.9829	14	0.9741	0.9092	25	0.9854	0.9693
4	1.0012	0.9754	15	0.9727	0.9078	26	1.0098	0.9475
5	1.0041	0.968	16	0.9715	0.9064	27	1.0074	0.945
6	1.0116	0.9495	17	0.9695	0.9044	28	0.9967	0.9335
7	1.0084	0.946	18	0.969	0.9038	29	0.9891	0.9235
8	0.9956	0.9323	19	0.999	0.9967	30	0.9857	0.9218
9	0.9897	0.926	20	0.9954	0.9929	31	0.9819	0.9176
10	0.9842	0.9201	21	0.9947	0.9922	32	0.981	0.9167
11	0.9834	0.9192	22	0.9941	0.9916	33	0.9807	0.9164

From Table 5, it can be observed that the voltage magnitudes are greatly improved; the lowest voltage magnitude occurred at bus 18 and its value is 0.969 pu. The voltage stability index in this case is 29.845, while total active power loss is 67.87 kW compared with 211 kW in the system's original case. Figure 8 shows PV curves of Case (2). From Figure 8, it can be observed that the system's loadability is enhanced; voltage levels start to decay to less than 0.9 pu when the loading factor is greater than 210%, and it totally collapses when it exceeds 520%.

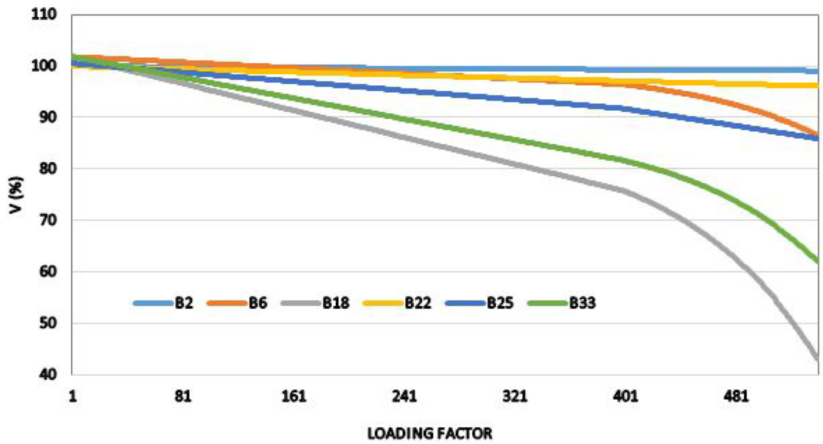

Figure 8. PV curves of IEEE 33-bus distribution system after wind turbine DG installation.

4.3. Case (3): including two photovoltaic DG

In this case, the proposed optimization algorithm is used to determine the optimal allocation of two photovoltaic DGs (optimal sizes are 856.9 kW and 1160.23 kW at buses 13 and 30, respectively). Table 6 presents the voltage magnitudes of the system for this case compared with the base case (without DG).

Table 6. Buses voltage magnitudes (pu) in Case (3) and base case (without DG).

Bus no.	Case (3)	Base Case	Bus no.	Case (3)	Base Case	Bus no.	Case (3)	Base Case
1	1.00	1.00	12	0.9739	0.9177	23	0.9873	0.9793
2	0.9983	0.997	13	0.9761	0.9115	24	0.9807	0.9726
3	0.9909	0.9829	14	0.974	0.9092	25	0.9774	0.9693
4	0.9883	0.9754	15	0.9727	0.9078	26	0.9786	0.9475
5	0.9861	0.968	16	0.9714	0.9064	27	0.9783	0.945
6	0.979	0.9495	17	0.9695	0.9044	28	0.9752	0.9335
7	0.9767	0.946	18	0.9689	0.9038	29	0.9733	0.9235
8	0.9731	0.9323	19	0.9978	0.9967	30	0.9737	0.9218
9	0.9728	0.926	20	0.9942	0.9929	31	0.9698	0.9176
10	0.973	0.9201	21	0.9935	0.9922	32	0.9689	0.9167
11	0.9732	0.9192	22	0.9928	0.9916	33	0.9687	0.9164

From Table 6, it is observed that the voltage magnitudes are greatly improved; the lowest voltage magnitude occurred at bus 18, and its value is 0.9689 pu. The voltage stability index in this case is 29.404, while total active power loss is 87.17 kW compared with 211 kW in the system's original case.

Figure 9 shows PV curves of Case (3). From Figure 9, it is observed that the system's loadability is enhanced; the voltage levels start to decay to less than 0.9 pu when the loading factor is greater than 270%, and it totally collapses when it exceeds 640%.

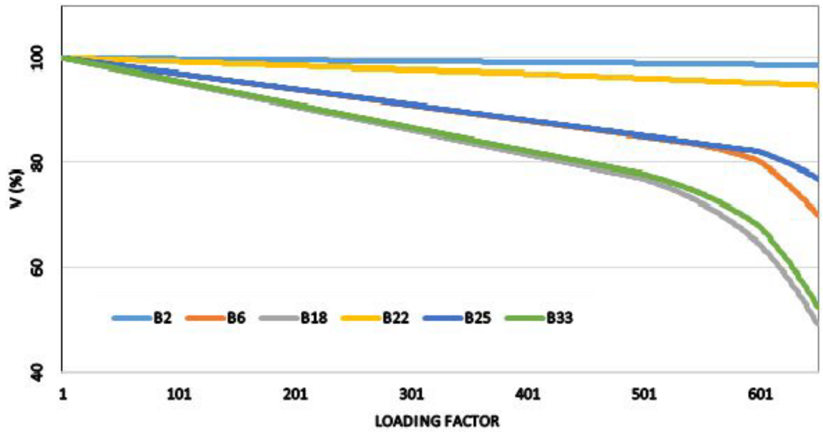

Figure 9. PV curves of IEEE 33-bus distribution system after two photovoltaic DG installations.

4.4. Case (4): including two wind turbine DG installations

In this case, the proposed optimization algorithm is used to determine the optimal allocation of two wind turbine DGs (optimal sizes are 824.8 kW with power factor $PF = 0.88$ and 1241.18 kW with $PF = 0.8$ at buses 13 and 30, respectively). Table 6 presents the voltage magnitudes of the system for this case compared with the base case (without DG).

Table 7. Buses voltage magnitudes (pu) in Case (4) and base case (without DG).

Bus no.	Case (4)	Base case	Bus no.	Case (4)	Base case	Bus no.	Case (4)	Base case
1	1.00	1.00	12	1.0086	0.9177	23	0.9924	0.9793
2	0.9991	0.997	13	1.0151	0.9115	24	0.9858	0.9726
3	0.9959	0.9829	14	1.013	0.9092	25	0.9825	0.9693
4	0.9965	0.9754	15	1.0118	0.9078	26	1.0013	0.9475
5	0.9975	0.968	16	1.0105	0.9064	27	1.0025	0.945
6	1.0004	0.9495	17	1.0087	0.9044	28	1.009	0.9335
7	1.0002	0.946	18	1.0081	0.9038	29	1.0142	0.9235
8	1.0014	0.9323	19	0.9986	0.9967	30	1.0177	0.9218
9	1.0039	0.926	20	0.995	0.9929	31	1.0139	0.9176
10	1.0069	0.9201	21	0.9943	0.9922	32	1.0131	0.9167
11	1.0074	0.9192	22	0.9936	0.9916	33	1.0128	0.9164

From Table 7, it is observed that the voltage magnitudes are significantly improved, where the lowest voltage magnitude occurred at bus 25 and its value is 0.9825 pu. The voltage stability index in this case VSI = 31.311, while total active power losses P_{loss} = 35.948 kW compared with 211 kW in the system's original case. Figure 10 shows the PV curves of Case (4).

From Figure 10, it is observed that the system's loadability is greatly enhanced. The voltage levels start to decay to less than 0.9 pu when the loading factor is greater than 420%, and it totally collapses when it exceeds 800%.

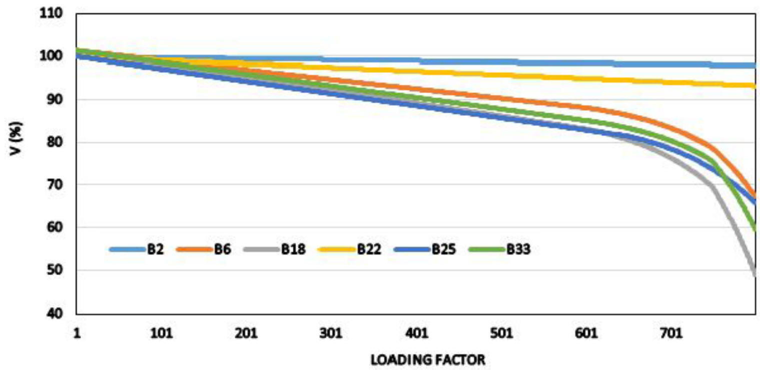

Figure 10. PV curves of IEEE 33-bus distribution system after two wind turbine DG installations.

5. Conclusions

In this paper, the performance of IEEE 33-bus distribution system has been analyzed, then the optimal size and location of DG have been determined using an efficient hybrid optimization technique. The optimal size and location of photovoltaic DGs and wind turbine DGs have been determined in order to improve the voltage stability index and minimize total active power loss. The proposed hybrid optimization technique is based on LSF and GWO. LSF has been used to determine the candidate buses for DGs installation in RDS while GWO algorithm has been developed to determine the optimal locations and sizes of DGs. The system's performance has been analyzed after the installation of DGs of each model, where the number of DG installations in the system increments until '2'. From simulation results, it is observed that the system power loss is reduced to 67.87 KW and 29.314 KW by integrating 1 WT and 2 WTs, respectively, while it is reduced to 110.029 kW and 87 kW by integrating 1 PV and 2 PVs, repectively. The analyses indicate the tremendous impact of the DGs after optimization on the system's voltage stability, loadability, and power losses. They show the poor performance of the system without the optimized DG installations and show a significant improvement on the system's performance with the optimized DG installations.

References

[1] Mahmoud MS, Al-Sunny FM. Control and Optimization of Distributed Generation Systems. 1st ed. Switzerland: Springer, 2015.

[2] Dulău LI, Abrudean M, Bică D. Effects of distributed generation on electric power systems. Procedia Technology 2014; 12: 681-686.

[3] Basak P, Chowdhury S, nee Dey SH, Chowdhury SP. A literature review on integration of distributed energy resources in the perspective of control, protection and stability of microgrid. Renewable and Sustainable Energy Reviews 16: 5545-5556.

[4] Khan UN. Distributed generation and power quality. International Conference on Environment and Electrical Engineering, Karpacz, Poland: IEEE; 2009. pp. 145.

[5] Singh SN. Distributed generation in power systems: an overview and key issues. 24th Indian Engineering Congress. Surathkal, Mangalore: 2009. pp. 1-8.

[6] Zareiegovar G, Fesaghandis RR, Azad MJ. Optimal DG location and sizing in distribution system to minimize losses, improve voltage stability, and voltage profile. In: Electrical Power Distribution Networks, 2012 Proceedings of 17th Conference. Tehran, Iran: IEEE; 2012. pp. 1-6.

[7] Dahal S. and Salehfar H. Optimal location and sizing of distributed generators in distribution networks. In: 2013 North American Power Symposium. Manhattan, KS, USA: IEEE; 2013. pp. 1-6.

[8] Khairuddin NA, Cipcigan LM. Optimal placement and capacity of distributed generators in medium voltage generic UK Network. In: Power Engineering Conference, 2016 51st international universities. Coimbra, Portugal: IEEE; 2016. pp. 1-6.

[9] Arulraj R, Kumarappan N, Vigneysh T. Optimal location and sizing of DG and capacitor in distribution network using weight-improved particle swarm optimization algorithm (WIPSO). In: Automation, Computing, Communication, Control and Compressed Sensing, 2013 International Multi-Conference. Kottayam, India: IEEE; 2013. pp. 759-764.

[10] Shivarudraswamy R, Gaonkar DN, Jayalakshmi NS. GA based optimal location and size of the distributed generators in distribution system for different load conditions. In: Power Electronics, Intelligent Control and Energy Systems, IEEE International Conference. Delhi, India: IEEE; 2016. pp. 1-4.

[11] Grisales LF, Grajales A, Montoya OD. Optimal location and sizing of Distributed generators using a hybrid methodology and considering different technologies. In: Circuits and Systems, 2015 IEEE 6th Latin American Symposium. Montevideo, Uruguay: IEEE; 2015. pp. 1-4.

[12] Hemdan NG, Deppe B, Pielke M, Kurrat M, Schmedes T et al. Optimal reconfiguration of radial MV networks with load profiles in the presence of renewable energy based decentralized generation. Electric Power Systems Research. 2014; 116: 355-366.

[13] Carr JA, Balda JC, Mantooth HA. A survey of systems to integrate distributed energy resources and energy storage on the utility grid. In: Energy 2030 Conference 2008. Atlanta, GA, USA: IEEE; 2008. pp. 1-7.

[14] Schwartfeger L, Santos-Martin D. Review of distributed generation interconnection standards. In: Electricity Engineer's Association Conference and Exhibition; 18–20 June 2014; University of Canterbury, Auckland, New Zealand, pp. 1-13.

[15] Begovic M, Kim I, Novosel D, Rohatgi A. Integration of photovoltaic distributed generation in the power distribution grid. In: System Science, 2012 45th Hawaii International Conference. Maui, HI, USA: IEEE; 2012. pp. 1977-1986.

[16] Emary E, Yamany W, Hassanein A, Snasel V. Multi-objective gray-wolf optimization for attribute reduction. Procedia Computer Science 2015; 65: 623-632.

[17] Mirjalili S, Mirjalili SM, Lewis A. Grey wolf optimizer. Advances in Engineering Software. 2014; 69: 46-61.

[18] El-Fergany A. Optimal allocation of multi-type distributed generators using backtracking search optimization algorithm. International Journal of Electrical Power and Energy Systems 2015; 64: 1197-1205.

[19] Arya LD, Koshti A, Choube S. Distributed generation planning using differential evolution accounting voltage stability consideration. International Journal of Electrical Power and Energy Systems 2012; 42: 196-207.

[20] Oda ES, Abdelsalam AA, Abdel-Wahab MN, El-Saadawi MM. Distributed generations planning using flower pollination algorithm for enhancing distribution system voltage stability. Ain Shams Engineering Journal 2017; 8: 593-603.

[21] Murthy V, Kumar A. Comparison of optimal DG allocation methods in radial distribution systems based on sensitivity approaches. International Journal of Electrical Power and Energy Systems 2013; 53: 450-467.

[22] Chakravorty M, Das D. Voltage stability analysis of radial distribution networks. International Journal of Electric Power and Energy Systems 2001; 23: 129–135.

[23] Ali ES, Abd Elazim SM, Abdelaziz AY. Ant lion optimization algorithm for renewable distributed generations. Energy 2016; 116: 445-458.

[24] McDonald JD, Wojszczyk B, Flynn B, Voloh I. Distribution systems, substations, and integration of distributed generation. Encyclopedia of Sustainability Science and Technology. New York, NY, USA: Springer; 2013. pp. 2976-3022.

[25] El-Fergany A. Optimal allocation of multi-type distributed generators using backtracking search optimization algorithm. International Journal of Electrical Power and Energy Systems 2015; 64: 1197-1205.

[26] Nguyen TP, Vo DN. Optimal number, location, and size of distributed generators in distribution systems by symbiotic organism search based method. Advances in Electrical and Electronic Engineering 2018; 15: 724-735.