Assessment of optimal allocation of renewable distributed generator sources in distribution network

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Abstract
The integration of distributed generators (DGs) into distribution networks in optimal allocation is one of the main issues facing power system engineers to ensure improved stability and economic operation. This article presents a detailed analysis of the impacts of the optimal allocation and the number of DGs on both system steady-state and transient performances of distribution networks. An oscillatory particle swarm optimization (OPSO) algorithm was used to find the optimal allocations of DGs via minimizing various objective functions that deal with Total Transmission Losses, Voltage Regulation, and Power Performance Index. The OPSO is used to optimize these functions as a single and as a multiobjective optimization problem. The effectiveness of the method is demonstrated with the IEEE-14 bus as an example of distribution networks with a 50% increase in system loading. Two penetration scenarios have been considered, the optimal sizes and locations of DGs are obtained, and the results are presented. In addition, the impact of the penetration level of Photovoltaic and Wind Energy sources on transient performance is obtained using detailed nonlinear models of both synchronous machines and DGs sources. The system response is then obtained when the system is subjected to a three-phase short circuit fault for six cycles and the results are presented in a comparative form for different penetration levels. The techniques and results presented in the article form a useful base for power system engineers in planning and operating distribution systems with high penetration levels of RDG sources.

Keywords
concentrated and distributed DG (C-DG, D-DG), distributed generation (DG), optimal DG allocations, oscillatory PSO, penetration level.

1 | INTRODUCTION
Fossil fuel resource depletion and environmental interests have encouraged the integration of renewable distributed generator (DG) units (e.g., wind and solar) in distribution networks. These units have offered several advantages such as total loss reduction, improved total system efficiency, voltage stability and voltage profile improvement, enhanced reliability, green-house gas emission reduction and they have a significant impact on the power flow, continuity, short circuit...
level, and power quality.\textsuperscript{1-6} However, the inappropriate choice of locations and sizes of DGs in electric power systems has adverse effects on voltages profile, transmission losses, feeder loading, stability, and system reliability.\textsuperscript{3,7,8} So, there has been a significant rise in interest by researchers to develop methods to find the optimal location as well as the optimal size of DGs integration in the networks. These methods can be classified into analytical, exhaustive, linear programming, optimal power flow, probabilistic analysis and heuristic, and metaheuristic techniques.\textsuperscript{5,9}

In most of the researches, population-based metaheuristic algorithms are used as solution techniques.\textsuperscript{10} This includes genetic algorithm,\textsuperscript{11} evolutionary programming,\textsuperscript{12} particle swarm optimization (PSO),\textsuperscript{13} ant colony optimization,\textsuperscript{14} artificial bee colony optimization,\textsuperscript{9} and tabu search.\textsuperscript{15,16} All these techniques have been used to solve the problem of optimal location and size of DGs. These methods are usually very efficient in finding near-optimal solutions, especially with complex problems. Though heuristic methods necessitate high computational effort, it does not affect their extensive application in solving DG placement and sizing problems. However, these techniques are employed to obtain the locations and sizing of DGs and assess their impacts on steady-state performance only. This, however, neglects the effects of the DGs dynamics and may lead to unrealistic results since DGs are represented only by their active and reactive power. Alternatively, this article considered the DGs impact on both steady-state and transient performance of the system using detailed models of Photovoltaic (PV) and WE sources.

In this article, the oscillatory PSO (OPSO) algorithm was applied to find the optimal allocation of renewable distributed generators (RDGs) in the distribution network considering the minimization of three objective functions; namely Total Transmission Losses (TTL), Voltage Regulation (VR), and Power Performance Index (PPI). The results show a comparison between the steady-state system performance using concentrated and distributed DGs for various penetration levels, illustrating the impacts on transmission losses, VR, and real PPI. In addition, the system transient performance is obtained using a detailed nonlinear model of synchronous machines and RDG sources when the system is subjected to a severe short circuit fault for six cycles. All results have been obtained using the IEEE 14-bus test system, considering a 50% increase in system loads.

\section{SYSTEM UNDER STUDY}

The IEEE 14-bus distribution network is considered in this article as shown in Figure 1. The system consists of 14 buses with 11 load buses, four transformers, 20 branches, and five synchronous generators, three of them are synchronous compensators that are used for reactive power support with the data given elsewhere.\textsuperscript{17,18} However, the original system is modified by increasing all loads in the system by 50% that leads to a load of 388.5 MW, 79.13 MVAR while generation is 422.33 MW and 136.71 MVAR. This modification increases transmission losses from 13.536 to 33.827 MW, VR from 7.9208\% to 8.5471\%, and total real PPI from 8.038 to 18.615 pu. This leads to a deterioration in voltage profile as shown in Figure 2 that illustrates a comparison between voltage profile for the original system and that after a 50% increase in system loading. It is worth mentioning that there is an urgent need to integrate DG in optimal allocation to improve the steady-state and transient performance of the system.
FIGURE 2 Voltage profile of the IEEE-14 bus system

3 | PROBLEM FORMULATION

The objective functions of the optimization problem are used to minimize both TTL, VR and the real PPI. First, each objective is considered as a single objective and then these objectives are resolved as a multiobjective function with different weights:

\[ \text{TTL} = \min \sum_{i,j \in N_b} g_{ij}(V_i^2 + V_j^2 - 2V_iV_j \cos \theta_{ij}) \]  

\[ \text{VR} = \min \left( \frac{V_{\text{max}} - V_{\text{min}}}{V_{\text{min}}} \ast 100 \right) \]  

\[ \text{PPI} = \min \left( \sum_{k=1}^{N_l} w_m \left( \frac{P_{\text{li}}}{P_{\text{max}_m}} \right)^{2n} \right) \]  

\[ J = \min(w_1 \ast \text{TTL} + w_2 \ast \text{VR} + w_3 \ast \text{PPI}) \]

where weight \( w_k \in [0, 1] \), \( \sum_{k=1}^{3} W_k = 1 \). Also, the functions, TTL, VR, and PPI, in Equation (4), are all in pu.

The choice of the weighting factors is crucial since there are no specific criterion to define the relative importance of the various indices TTL, VR, and PPI given in Equations (1)-(3). In this case, the weightings of indices are chosen based on the experience required for system operation in the assessment of the relative importance of each index. In this work, the weight that represents the transmission losses was given a value of 0.50 as transmission losses represent the main concern in introducing DG and has economic impacts on power system operation. The VR was given a weighting value of 0.30 as it is more important than the PPI index, which has a weighting value of 0.20.

Where \( N_b, N_l \) is the number of system buses and lines respectively; \( g_{ij} \) is the conductance of the lines between buses \( i \) and \( j \); \( V_i \) and \( V_j \) are the voltage magnitudes at buses \( i \) and \( j \), respectively; \( \theta_{ij} \) is the angle difference between buses \( i \) and \( j \); \( P_{\text{li}} \) is the active power flow in line \( m \); \( P_{\text{max}_m} \) is the rated active power capacity of line \( m \); \( n \) is the exponent and equals one and \( w_m \) is a real non-negative weighting factor.

The optimization problem is subjected to equality and inequality constraints:

\[ P_{\text{Gi}} + P_{\text{DG}i} - P_{\text{Li}} = V_i \sum_{j=1}^{N_b} V_j(G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij}) \]  

\[ Q_{\text{Gi}} + Q_{\text{DG}i} - Q_{\text{Li}} = V_i \sum_{j=1}^{N_b} V_j(G_{ij} \sin \theta_{ij} - B_{ij} \cos \theta_{ij}) \]
where \( i = 1, 2, 3 \ldots, N_b \).

\[
Q_{Gi}^{\min} \leq Q_{Gi} \leq Q_{Gi}^{\max}, \quad i = 1, 2 \ldots, N_v
\]  

(7)

\[
P_{DGi}^{\min} \leq P_{DGi} \leq P_{DGi}^{\max}, \quad i = 1, 2 \ldots, N_{DGs}
\]  

(8)

\[
Q_{DGi}^{\min} \leq Q_{DGi} \leq Q_{DGi}^{\max}, \quad i = 1, 2 \ldots, N_{DGs}
\]  

(9)

\[
V_i^{\min} \leq V_i \leq V_i^{\max}, \quad i = 1, 2 \ldots, N_b
\]  

(10)

\[
|S_i^{\text{flow}}| \leq S_i^{\max}, \quad i = 1, 2 \ldots, N_L
\]  

(11)

where \( P_{Gi} \) and \( Q_{Gi} \) are the MW and MVAR generated at bus \( i \), respectively; \( P_{Li} \) and \( Q_{Li} \) are the MW and MVAR demand at bus \( i \), respectively; \( P_{DGi} \) and \( Q_{DGi} \) are the active and reactive power generated from the DGs unit at bus \( i \) and \( G_{ij} \) and \( B_{ij} \) are the mutual conductance and susceptance between buses \( i \) and \( j \), respectively; \( N_v \), \( N_{DGs} \) refers to the total number of voltage-controlled and DGs buses, respectively; \( S_i^{\text{flow}} \) and \( S_i^{\max} \) are the apparent power flow and the maximum apparent power (MVA maximum) of the lines and transformers, respectively. Superscripts min and max are the lower and upper limits.

4 | OPSO IMPLEMENTATION

PSO is an algorithm widely used in power system problems because of its simple implementation, it converges to the optimal solution in several problems where most analytical approaches fail to converge and is more effective in preserving the variety of the swarm since all particles use the information related to the most successful particle in order to improve them.25 Due to these features and other features, other techniques of PSO are introduced such as Selective PSO (SPSO) algorithm,25 Improved PSO Based on Success Rate (IPSO-SR),28 Distance-based Intelligent PSO (DbIPSO),29 a Modified PSO (MPSO) algorithm,30 MultiObjective PSO (MOPSO),31 and Binary PSO (BPSO).32 These techniques are used for finding the optimal DG allocation.

Recently, the particle has been derived into oscillatory trajectories such that the search space can be covered more completely from high to low dimensions leading to Oscillatory PSO, which is a modified version of PSO.33 It performs an analysis based on the difference equation to detect conditions that guarantee trajectory oscillation and fast solution convergence. In OPSO, the particle position and velocity are updated using the following difference equation:

\[
x_{j}^{d, T+1} = x_{j}^{d, T} + w \left( x_{j}^{d, T} - x_{j}^{d, T-1} \right) + c_1 \left( P_{b}^{d, T} - x_{j}^{d, T} \right) + c_2 \left( g b_{j}^{d, T} - x_{j}^{d, T} \right)
\]  

(12)

\[
V_{j}^{d, T} = x_{j}^{d, T} - x_{j}^{d, T-1}
\]  

(13)

where \( v_{j}^{d} \) and \( x_{j}^{d} \) are the velocity and position of the particle; \( P_{b}^{d, T} \) and \( g b_{j}^{d, T} \) are the personal best position of individual particle \( j \) and global best position of all particles; \( T \) is referred to iteration number; \( j \) denotes the \( j \)th particle in the swarm of \( M \) particles, \( d \) denotes the \( d \)th dimension of the particle25,33; \( w \) is the inertia weight; \( c_1 \) and \( c_2 \) are random cognitive and social learning factors and often equal 2. More details about the OPSO parameters and updates are given elsewhere.33 The effectiveness of using the OPSO is demonstrated elsewhere.34

Table 1 shows a comparison between the results obtained for the optimal DG location and size for the IEEE 14-bus distribution system using the PSO and OPSO. The results illustrate that both techniques give the same results of the optimization process. Therefore, the OPSO is chosen for this work due to its fast convergence34 and other advantages.33
### Table 1 Comparison between PSO and OPSO

|                  | Without DG | PSO | OPSO | LVIW PSO | TVAC PSO |
|------------------|------------|-----|------|----------|----------|
| DG size (MW)     | —          | 40  | 40   | 40       | 40       |
| DG location      | —          | 3   | 3    | 3        | 3        |
| Total losses (MW)| 13.5       | 8.9 | 8.9  | 8.9      | 8.9      |

Note: LVIW PSO refers to linearly decreasing inertia weight PSO strategy and TVAC PSO refers to time varying acceleration coefficients PSO strategy.

### 5 Steady-State Results and Discussion

The OPSO algorithm is applied to obtain the optimal allocation and the optimal number of the DGs in the modified IEEE 14-bus system considering two scenarios with and without constraints on the penetration level and each scenario includes the following four cases:

**Case 1.** The OPSO is applied to minimize the TTL only, Equation (1) (Single objective)

**Case 2.** The OPSO is applied to minimize the VR only, Equation (2) (Single objective)

**Case 3.** The OPSO is applied to minimize the PPI only, Equation (3) (Single objective)

**Case 4.** The OPSO is applied to minimize, Equation (4), TTL, VR, and PPI (multiobjective)

**Scenario-1:** In this scenario, no limits are imposed on the penetration level and the optimal DG sizes and locations are obtained using the OPSO. The results obtained for the four cases are shown in Table 2, compared with the base case. These results illustrate the performance when penetration occurs at one location (i.e., Concentrated DG, C-DG) or occurs at two or three locations (i.e., Distributed DG, D-DG). These results illustrate the following points:

- Generally, DG penetration improves the steady-state performance, indicated by a substantial reduction in transmission losses and improvements in VR and PPI. Minimizing the TTL reduces both the transmission losses and VR in both D-DG and C-DG.

- Optimal allocation based on minimizing the TTL, Case 1, reduces the total losses by about 76.37% using one unit, 94.02% using two units and 93.91% using three units compared with the base case. VR is reduced from 8.6% to 7.9%. The real PPI was reduced from 18.6 to 12.4 using two units without any significant effect on other cases (one unit and three units).

- Optimal allocation based on minimizing the VR, Case 2, reduces the VR from 8.6% to 7.9% and the total losses and real PPI are also decreased less than the base case.

- Optimal allocation based on reducing the real power performance, Case 3, the PPI is significantly reduced from 18.6 to 7.2. This, however, occurred at the expense of VR. So, the system optimization should be obtained using a multiobjective technique, Case 4, which leads to excellent improvements in system losses, VR, and real power performance.

- The optimal allocation in Case 3 for both C-DG and D-DG is different from the other cases. In this case, the C-DG was found at bus-3 while other cases recommend bus-4 for C-DG. Also, for distributed locations, bus-4 and bus-3 are recommended in most cases.

The results also illustrate that using either VR or PPI as an objective function in the optimization process improves the considered objective at the expense of the transmission losses.

- These results also illustrate that the penetration levels reach higher values especially when the TTL function is used in the optimization process. This, however, exceeds the recommended penetration levels and there is a need to specify an appropriate size of DGs as a constraint in the optimization process that is considered in the second scenario.

**Scenario-2:** Figure 3 shows the transmission losses as a function of the penetration level. The figure illustrates that transmission losses decrease with the increase of penetration level until a minimum value of TTL (point A in Figure 3) and then start to increase again. The results also illustrate that the rate of increase or decrease in TTL about its minimum value is very small within about 20% of penetration level. It is not recommended to introduce more DGs within this region for economic reasons. In the light of these results, it was decided to set a 50% penetration level in the optimization process that is about twice the value recommended for medium voltage systems.
### Table 2: Simulation results of scenario-1

| Cases          | Penetration level (%) | DG location | DGs size | Total losses (MW) | VR (%) | PPI |
|----------------|-----------------------|-------------|----------|-------------------|--------|-----|
| Base           | 0                     | No          | 0        | 33.82             | 8.6    | 18.6|
| Case 1         | One unit (69.28%)     | 4           | 292.57   | 27.87             | 7.99   | 7.9 | 18.6|
|                | Two units (78%)       | 4           | 194.58   | 17.97             | 2.02   | 7.9 | 12.4|
|                |                       | 3           | 134.92   | 100               | 7.9    |    |
|                | Three units (77.3%)   | 4           | 144.16   | 23.62             | 2.06   | 7.9 | 17.3|
|                |                       | 3           | 131.62   | 94.14             |        |    |
|                |                       | 8           | 50.69    | 87.94             |        |    |
| Case 2         | One unit (47%)        | 4           | 198.92   | 20.68             | 10.41  | 7.9 | 16.2|
|                | Two units (43.35%)    | 4           | 158.8    | 90.84             | 11.51  | 7.9 | 12.9|
|                |                       | 13          | 24.32    | 3.5               |        |    |
|                | Three units (62.4%)   | 4           | 26.41    | 18.27             | 8.22   | 7.9 | 16.2|
|                |                       | 6           | 139.93   | 10.12             |        |    |
|                |                       | 9           | 97.18    | 20.16             |        |    |
| Case 3         | One unit (31.6%)      | 3           | 133.53   | 84.53             | 13.29  | 8.3 | 13.8|
|                | Two units (73.1%)     | 3           | 144.6    | 38.86             | 3.86   | 7.9 | 11.8|
|                |                       | 5           | 164.36   | 76.09             |        |    |
|                | Three units (50.4%)   | 3           | 143.51   | 69.26             | 7.01   | 13  | 7.2 |
|                |                       | 6           | 29.68    | 20.54             |        |    |
|                |                       | 14          | 39.66    | 48.14             |        |    |
| Case 4         | One unit (60.5%)      | 4           | 255.66   | 10.32             | 8.38   | 7.9 | 17.4|
|                | Two units (73.1%)     | 4           | 174.96   | 21.5              | 2.15   | 7.9 | 12.1|
|                |                       | 3           | 133.64   | 27.18             |        |    |
|                | Three units (82.2%)   | 4           | 66.13    | 14.2              | 2.74   | 7.9 | 11.0|
|                |                       | 3           | 133.44   | 60.64             |        |    |
|                |                       | 5           | 147.68   | 86.05             |        |    |

**Figure 3:** Total power losses vs DG penetration level
### TABLE 3 Simulation results of scenario-2

| Cases  | No of units | Location | Total losses (MW) | VR (%) | PPI |
|--------|-------------|----------|-------------------|--------|-----|
| Base   | 0           | ___      | 33.82             | 8.6    | 18.6|
| Case-1 | One unit    | 4        | 10.35             | 7.9    | 16.7|
|        | Two units   | 4 3      | 5.82              | 7.9    | 11.9|
|        | Three units | 4 3 8     | 6.23              | 7.9    | 20.7|
| Case-2 | One unit    | 5        | 13.82             | 7.9    | 17.9|
|        | Two units   | 6 8      | 10.99             | 7.9    | 27.0|
|        | Three units | 4 5 6     | 12.04             | 7.9    | 21.1|
| Case-3 | One unit    | 3        | 10.12             | 8.4    | 15.4|
|        | Two units   | 3 4      | 5.82              | 7.9    | 11.9|
|        | Three units | 3 6 9     | 6.72              | 7.9    | 7.6 |
| Case-4 | One unit    | 3        | 10.12             | 8.4    | 15.4|
|        | Two units   | 3 4      | 5.82              | 7.9    | 11.9|
|        | Three units | 3 6 9     | 6.72              | 7.9    | 7.6 |

The cases considered in Scenario-1 are repeated using a 50% penetration level as a constraint. These results are shown in Table 3 for the above-mentioned four cases considering equal sizes of DG units in the distributed DG cases. The results illustrate, when the penetration level is set as a constraint, careful attention should be given to the D-DG case as increasing the number of units may have adverse effects on steady-state performance. In addition, optimization of one function improves this objective at the expense of others as might be extracted from Figure 4 that shows the voltage profile when C-DG is inserted at different busses. This figure illustrates that the voltage, when the C-DG is at bus-4, (Case 1), has the best voltage profile when considering the C-DG case.

**Scenario-3**: This scenario demonstrates a comparison between concentrated DGs and distributed DGs at different penetration levels as shown in Figures 5-7. It has been observed that most of the presented results recommend bus-3 and bus-4 for the concentrated DGs and a combination of these buses and others for distributed DGs. Figure 5 shows the transmission losses and PPI as a function of penetration level when C-DG is at either bus-3 or bus-4. These results illustrate that C-DG at bus-3 is better from the losses point of view when the penetration level is less than 50%. However, this is not the case for PPI at higher values of penetration levels, more than 60%, when the C-DG is at bus-4.

For distributed DGs, Figure 6 illustrates a comparison between the cases of using the DG at various combinations of buses. These results illustrate that increasing transmission losses are reduced by increasing the penetration level using three DGs. However, with the increase of penetration level, the transmission losses decrease until a minimum value and increase again in the case of using two DGs.
Finally, a comparison between concentrated DG and distributed DGs is shown in Figure 7. Apart from the very low value of penetration, the case of D-DG is better than that at C-DG as it has minimum transmission losses and real PPI.

6 | TRANSIENT PERFORMANCE ANALYSIS

This section discusses the impact of integrating wind energy (WE) and PV sources on the transient performance of the modified IEEE 14-bus distribution network using the ETAP software package and connecting the renewable source at bus-4. Each synchronous machine is represented by its detailed $d$-$q$ nonlinear model as in Reference 37, equipped with IEEE Type-1 excitation system and is driven by a steam turbine governor system. The WE sources are modeled by the DFIG detailed model (type-4). The PV plants are modeled using the equivalent model described in References 40 and 41 using the single diode model to simulate each PV cell. The transient performance is studied when the system is subjected to a three-phase short circuit fault at the location, $F$, as shown in Figure 1, and lasts for 120 milliseconds through the subsequent cases.

6.1 | Impacts of DG type

The effects of DG types were studied on the transient performance through the rotor angle deviation of $G_2$ and the bus voltage profile of bus-4 as shown in Figure 8. The results compare the 50% penetration level of wind and PV sources.
**FIGURE 6** Impact of D-DG integration on system performance (A) total active power losses and (B) Real power performance index

**FIGURE 7** Impact of C-DG and D-DG integration on system performance (A) total active power losses and (B) Real power performance index

**FIGURE 8** Effect of DG type on the transient response (A) relative rotor angle of $G_2$ and (B) voltage at bus-4
Figure 9: Effect of DGs penetration levels

Figure 10: Impacts of upgrading the primary control systems

with the base case (0% penetration level) which demonstrates that the PV source penetration has adverse impacts on the transient performance more than wind sources. This is due to the static nature of the PV plants.

6.2 Impacts of DG different penetration Levels

Figure 9 shows the effects of different penetration levels of DGs on the transient performance of the system (relative rotor angle of \( G_2 \)). An important conclusion that can be drawn from Figure 9A,B is that as penetration levels of two types of DGs are increased, the adverse effects on transient performance are significantly reduced in terms of the small oscillatory response of the rotor angle and the system becomes more stable. The impact of WE source is better than that of the PV sources on system transient performance.

6.3 Effect of primary control of synchronous generators

The previous results show the importance of using primary control on the conventional synchronous machines to add more positive damping to reduce the static and stochastic nature of DGs. So, the synchronous generators are equipped with AVR, a governor, and a Power System stabilizer and the results are shown in Figure 10. The results illustrate significant improvements in transient performance using the controller.
7 | CONCLUSION

The objectives of this article are the optimal allocation of renewable DG sources in the distribution network and studying its impacts on steady-state and transient performances. The OPPO algorithm has been used to solve the optimization problem of DG optimal allocation in the IEEE 14-bus distribution network with a 50% increase in loads. The objectives of this optimization problem were minimizing TTL, VR, and real PPI. The results illustrate that each objective was successful to achieve the specified target. However, it is not recommended to use either VR or PPI alone as this may have adverse effects on system losses. Using the multiobjective function offers a good alternative for solving the problem of the allocation of renewable energy sources. The results of the steady-state performance, also, indicate that at low penetration levels there is no significant difference between concentrated DGs and distributed DGs. However, at higher penetration levels, optimal DGs are preferred as that leads to improvements in all steady-state performance.

The results illustrate the adverse effect on transient performance due to the use of PV and WE sources at low penetration levels. The results show that the adverse effects on transient performance due to the use of PV sources are more than that of the WE sources. This is basically due to the inertia-less nature of PV sources. However, the adverse effects of renewable sources on transient performance can be mitigated via upgrading the primary control of the conventional generators in the systems. Further improvements in transient performance, the use of a virtual synchronous generator technique with the PV and WE sources can add further improvements on transient performance. The analysis results and applied techniques introduced in the article are useful for power system engineers, as guidance for upgrading, planning, and operation of power systems including renewable energy sources.

CONFLICT OF INTEREST

The authors declare no potential conflict of interest.

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