Optimal Sizing and Placement of DG Units in Radial Distribution System Using Cuckoo Search Algorithm

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Abstract. Due to the evolution of interconnected power systems, the loss reduction in distribution systems has become a subject of major concern. Integration of distributed generation units which are based on renewable energy, provide potential benefits to conventional distribution systems while considering environmental impact. Practice of insertion of DG units in the distribution network system has increased drastically in the recent years because of multidimensional advantages of DG units. It includes the minimization of power loss in network, sharp improvement of bus voltages profile, improvement of reliability and power quality of system. The main objective of this paper is to demonstrate a simple technique to determine appropriate location and size of distributed generation units in the distribution networks in order to reduce real power losses of system. Cuckoo Search Algorithm (CSA) is used as an optimization technique and is implemented on standard IEEE-33 bus radial distribution system to demonstrate the effectiveness of proposed methodology.

Keywords: Distributed Generation; Optimal Allocation and Sizing of DG Units; Power Loss Reduction; Improvement of Voltage Profile; Cuckoo Search Algorithm; IEEE-33 Bus Standard Radial Distribution System.

1 Introduction

Deficiency of centralized power results in energy crisis and large-scale power outage. It is reported that the electric power systems with a single large power source is not able to satisfy the requirement of improved power quality and reliability. Also those traditional electricity generating stations and electric power system are of the order of hundreds to thousands of MW and are located far from the load centers. While the transmission network system transfers the generated electrical power to the distribution systems, a huge amount of transmission losses occur. Since these transmission network systems are quite long and complicated in structure, they create the network congestion in the restructured environment. Conventional power plants that include mainly coal based thermal power plants, nuclear power plants etc, have very high environmental impacts. It has a great contribution behind the ‘Green-House Effect’. Because of the limited resources and aforesaid scenario, power plants (based on non-conventional source of energy) are capturing more attention around the world. The key driving forces behind the increased penetration of DGs can be categorized into three factors, viz. environmental, commercial and regulatory factors. Environmental factor is concentrated to reduce various pollutants. Commercial factor includes the uncertainty in electricity markets that favors small generation schemes and DGs. This offers a very cost effective approach that improves the quality of power and its reliability. The major regulatory drivers include diversification of energy sources in order to enhance the energy security and support. In recent times, DG becomes a clean and efficient alternative to those traditional electric energy sources. Technologies that are adopted make DGs more economically feasible. Giant technological advances in power electronic devices, generators of small range and different energy storage devices for transient backup have increased the penetration of DGs into the electric power plants.

Now-a-days, the field of DGs has included Distributed Energy Resources (DERs) which again include energy storage devices and responsive loads. There have been tremendous research works in the areas of DG technologies that include its allocation and sizing, increased penetration of DG units, economic and financial analysis. Many research works have been done in this area. A teaching learning based technique was proposed for optimal placement and sizing of distributed generation units in the distribution system in [1]. In [2], an optimal distributed generation allocation in a
meshed network was explained. It was done by using evolutionary algorithms. Optimal positioning and sizing of DG units has been solved using differential evolution algorithm in [3].

2 Problem Formulation

In this study, the optimal allocation and sizing of DG units in IEEE-33 bus standard distribution test system is formulated as an optimization problem. Here main objective is to minimize total real power loss while improving the voltage profile of system. First, we have to calculate the loss coefficients by using ‘Exact Transmission Loss Formula’, which is discussed below. The bus power $S_i$ injected into the bus can be represented as generated power minus bus load. While adding the power of all the $N$ buses, we obtain the network losses by subtracting total load from the total generated power. This can be calculated by using (1) and the single-line diagram is shown in Fig. 1.

$$P_i + jQ_i = \sum_{m=1}^{N} S_m = \sum_{m=1}^{N} V_m I_m^* \tag{1}$$

Total real power loss in the power systems is expressed by (2), known as “Exact Loss Formula”.

$$P = \sum_{m=1, n=1}^{N} \left[ a_{mn} \left( P_m - P_n \right) + b_{mn} \left( Q_m - Q_n \right) \right] \tag{2}$$

Where,

$$a_{mn} = \frac{r_{mn}}{V_m V_n} \cos(\delta_m - \delta_n) \tag{3}$$

$$b_{mn} = \frac{r_{mn}}{V_m V_n} \sin(\delta_m - \delta_n) \tag{4}$$

Suffix $m$ and $n$ indicate values at $m^{th}$ and $n^{th}$ nodes respectively.

Four variables associated with each node are as follow:

i). Active power ($P$) ii). Reactive power ($Q$) iii). Bus voltage magnitude ($V$) and iv). Bus Voltage angle ($\delta$).

$V_m, \delta_m$ are bus voltage magnitude and angel at $m^{th}$ bus respectively and $V_n, \delta_n$ are bus voltage magnitude and angel at $n^{th}$ bus respectively. $P_m, Q_m$ are active and reactive power loss at $m^{th}$ bus respectively. $r_{mn}$ denotes resistance of line between $m^{th}$ and $n^{th}$ bus.

In simplified form, total active or real power loss in distribution system with $b$ number of branches can also be written as follow [4]:

$$P = \sum_{m=1}^{b} I_m R_m^2 \tag{5}$$

Above equation (5) can be simplified as:
\[ P_j = \sum_{m=1}^{b} \left( \frac{P_{fm}^2 + Q_{fm}^2}{|V_m|^2} \right) \]  \hspace{1cm} (6)

Where
\[ P_{fm}, Q_{fm} \] are total active and reactive power flow at \( m^{th} \) branch respectively. \( P, Q \) are total active and reactive power loss of the system respectively.

3 Constraints

The aforesaid objective function is mainly subjected to two constraints during optimization process as described below:

3.1 Voltage Constraint

The voltage magnitude must be kept within the specified limits at each bus
\[ V_{m_{\text{min}}} \leq V_m \leq V_{m_{\text{max}}} \] \hspace{1cm} (7)

Where \( V_{m_{\text{min}}} \) and \( V_{m_{\text{max}}} \) define the lower and upper limit of voltage at \( m^{th} \) bus respectively. \( V_{m_{\text{min}}} \) is taken as 0.95 per unit and \( V_{m_{\text{max}}} \) is taken as 1.05 per unit in present study for direct comparison [5].

3.2 Distributed Generator Size Constraint

In order to obtain a reasonable solution, size of distributed generator must not be so small or high with respect to the load value of the system. Here we consider, total power limit of a DG unit should be greater than 10% of total load demand and less than 80% of the total load demand [5].

\[ 10\% \text{of} \left( \sum_{m=1}^{N} S_{Dm} \right) \leq S_{DGm} \leq 80\% \text{of} \left( \sum_{m=1}^{N} S_{Dm} \right) \] \hspace{1cm} (8)

Where \( S_{DGm} \) is the total power generation of \( m^{th} \) DG unit and \( S_{Dm} \) is the total load demand at \( m^{th} \) bus. \( N \) denotes total bus number in system.

3.3 Power Balance Constraint

\[ P_{DGm} = P_{Dm} + P_{loss} \] \hspace{1cm} (9)

Where \( P_{DGm} \) is active or real power generation of \( m^{th} \) DG unit, \( P_{Dm} \) is active power demand from \( m^{th} \) DG unit and \( P_{loss} \) represents total active or real power loss in the system[6].

4 Cuckoo Search Algorithm (CSA)

In 2009, Yang and Deb had proposed Cuckoo Search Algorithm (CSA) [7]. It is an evolutionary algorithm (population based). Its implementation procedure is simple and it has very less control parameters.

To determine the optimal size and location of DG unit, power flow is used to compute the power loss. In Cuckoo Search Algorithm (CSA), mainly the principles that are followed during the optimization process [8]:

- At a time, each cuckoo lays only one egg (designed solution). It will dump its egg in a randomly chosen nest among fixed number of nests (host nests) which are available at that time.
- The best nests which contain the high quality of eggs will be considered in next solution. Those nests are termed as better solution.
- Total number of host nest (available) is considered to be fixed .It is assumed that a host bird can find an alien egg with probability of \( P_a \in [0,1] \).

In order to build a completely new nest at a new location, it can may throw the egg away from the nest or abandon the nest.
After initialization phase, CS comes to a phase (an iterative phase) which consists of following two random walks:

1. Levy Flights Random Walk and
2. Biased or Selective Random Walk.

After the random walks, a better solution is selected based on the fitness value of new generated solutions and current solutions by using a greedy strategy.

### 4.1 Levy Flights Random Walk:

It is a random walk. Its step size is drawn from a Lévy distribution. At the generation \( g \), Levy Flights Random Walk can be written as:

\[
s_{i,g+1} = s_{i,g} + \alpha \odot \text{Levy}(\beta)
\] (10)

Where \( \alpha \) represents a step size. Lévy Flights Random Walk is used to search a new solution around the best solution that is obtained so far. Step size can be found by the equation as follows [9]:

\[
\alpha = \alpha_0 \times (s_{i,g} - s_{\text{best}})
\] (11)

Where \( \alpha_0 \) is termed as scaling factor (\( \alpha_0 \) is generally assigned with a value of 0.01). \( s_{\text{best}} \) represents the best solution that is obtained so far.

\( \text{Levy}(\beta) \) represents a random number. For large steps, it is drawn from a Lévy distribution:

\[
\text{Levy}(\beta) \sim e^{-(1+\beta)}
\] (12)

In implementation, \( \text{Levy}(\beta) \) can be obtained by the following equation [9]

\[
\text{Levy}(\beta) \sim \left(\sigma \times u \right) / |v|^\beta
\] (13)

Where

\[
\sigma = \left( \frac{\Gamma(1+\beta) \times \sin(\Pi \times \beta / 2)}{\Gamma((1+\beta)/2 \times \beta \times 2^{\beta-1}/2)} \right)^{1/\beta}
\] (14)

Where \( \beta \) is a constant and generally set to a value of 1.5. In the software implementation process of CSA [9] \( u \) and \( v \) are random numbers which are drawn from a normal standard deviation of 1. \( \sigma \) is a sigma function and \( \Gamma \) represents a gamma function.

(11) can be rewritten as:

\[
s_{i,g+1} = s_{i,g} + \alpha_0 \left( \frac{\sigma \times u}{|v|^\beta} \right) (s_{i,g} - s_{\text{best}})
\] (15)

In the implementation we consider the values of \( u \) and \( v \) as follows:

\[
u = \text{randn(size(s))} \ast \sigma
\] (16)

\[
v = \text{randn(size(s))}
\] (17)

### 4.2 Biased or Selective Random Walk:

It is generally used to find out the new solutions. It is considered to be far away from current solution (best). At first, a trial solution is built up with a mutation of current solution (as a base vector) and two solutions (randomly selected) as (perturbed vectors). Second, a new solution is generated (by a crossover operator). It can be formulated as follows [9]:

If \( u_u > p_m \) then

\[
s_{i,j,g+1} = s_{i,j,g} + u \left( s_{p,j,g} - s_{q,j,g} \right)
\] (18)

Otherwise
\[ S_{i,j,g+1} = S_{i,j,g} \]  

Where random indexes \( p \) and \( q \) define \( p^{th} \) and \( q^{th} \) solutions in population respectively and \( j \) represents \( j^{th} \) dimension of solution. \( u, u_a \) are random numbers in the range defined as \( [0, 1] \) and \( p_a \) is fraction probability.

### 4.3 Cuckoo Search Algorithm:

Step 1: Read Data: Line and Load Data Network Topology Algorithm parameters.

Step 2: Run load flow analysis to find out initial losses without DG placement. The losses value will be the standard fitness value (\( \text{std}_P_{Loss} \)) of the algorithm.

Step 3: Set all the parameters of Cuckoo Search Algorithm:
- Number of host nests \( n = 30 \)
- Maximum number of iterations \( N_{\text{Total}} = 500 \)
- Probability Index \( p_a = 0.25 \) for the worst nest

By using the best solution (Best nest i.e. DG location and corresponding size) calculate the Active power loss, Minimum bus voltage, Line flow and Branch power losses.

Step 4: Initialize the solutions (termed as nest) randomly.
\[ \text{nest} (i,:)=Lb+(Ub-Lb).*\text{rand(size(Lb))}, \]
where \( Lb \) and \( Ub \) are lower and upper limit of DG location and size respectively. Get the current best for objective function. Minimum and maximum size of DG are taken as described at Constraints section. Lower and upper limit of DG location are considered as 2 and 33 respectively.

Step 5: Again perform the load flow analysis to find out the power loss with DG placement. These losses value will be the first fitness value of the algorithm.

Step 6: Start iterations.

Step 7: By using Lévy Flights Random Walk, initialize new solutions that follow (10) to (20).

Step 8: Again perform the load flow analysis to find out the power loss with DG placement. These losses value will be the second fitness value of the algorithm.

Step 9: Compare both the values and find out the best solution so far.

Step 10: Discovery for the new nest and the process of randomization are:
\[ g=\text{size} \ (\text{nest, 1}) \]
\[ K=\text{rand} \ (\text{size (nest)})>p_a; \]
\[ \text{stepsize} =\text{rand}.*\text{nest} \ (\text{randperm (g,:)})\text{-nest} \ (\text{randperm (g,:)})\); \]
\[ \text{new_nest} =\text{nest}+\text{stepsize}.*K; \]

Step 11: Again perform the load flow analysis to find out the power loss with DG placement. These losses value will be the second fitness value of the algorithm.

Step 12: Find the best objective function (active power loss) so far.

Step 13: Increment the iteration count and if the iteration count does not reach the maximum limit then go to Step 10 again.

Step 14: Repeat the procedure till the end of iterations and find out the value of the objective function that is found to be best so far.

### 5 A Case Study on IEEE 33 bus radial distribution system

In this paper, the proposed algorithm (CSA) is used to determine the optimal location and size of the DG unit and it is carried out on a standard IEEE-33 bus radial distribution network. This network contains total 33 buses, 32 lines. Total load of the system is 3.715 MW and 2.3 MVAR, and its voltage level is 12.66 kV. The standard IEEE 33 bus radial distribution system data are collected from [10].
Table 1 shows the value of active power loss ($P_l$) and minimum bus voltage. The parameters selected for the present work are shown in Table 2. Prior to the installation of DG total real ($P_l$) and reactive power loss ($Q_l$) are 210.0135 kW and 142.3644 kVAR respectively. The results of this paper are shown in Table 3. The results are also compared with loss sensitivity factor simulated annealing (LSFSA) [11] and shown in Table 4. It is found that the proposed algorithm (CSA) can produce more improved results.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active Power Loss (in kW)</td>
<td>210.0135</td>
</tr>
<tr>
<td>Minimum Voltage (in p.u.)</td>
<td>0.9039</td>
</tr>
</tbody>
</table>

Table 2. Cuckoo search algorithm parameters

<table>
<thead>
<tr>
<th>Settings</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of nests</td>
<td>30</td>
</tr>
<tr>
<td>Maximum number of iteration</td>
<td>500</td>
</tr>
<tr>
<td>Discovery rates of alien egg</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Table 3. Results with the installation of DG unit

<table>
<thead>
<tr>
<th>Concerned Parameters</th>
<th>1 DG at unity power factor</th>
<th>1 DG at 0.866 power factor</th>
<th>3 DG at unity power factor</th>
<th>3 DG at 0.866 power factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimal Bus Location</td>
<td>6</td>
<td>6</td>
<td>24, 13, 30</td>
<td>13, 30, 24</td>
</tr>
<tr>
<td>Optimal Size of DG unit (in MW)</td>
<td>2.5820</td>
<td>2.6771</td>
<td>1.2019, 0.7761, 1.3026</td>
<td>0.6202, 1.4413, 1.3676</td>
</tr>
<tr>
<td>Active Power Loss (in kW)</td>
<td>110.8481</td>
<td>68.5723</td>
<td>75.1610</td>
<td>19.7443</td>
</tr>
<tr>
<td>Reduction in Loss (in %)</td>
<td>47.22</td>
<td>67.35</td>
<td>64.21</td>
<td>90.60</td>
</tr>
<tr>
<td>Minimum Voltage (in p.u.)</td>
<td>0.9423</td>
<td>0.9581</td>
<td>0.9712</td>
<td>0.9891</td>
</tr>
</tbody>
</table>

Table 4. Comparison with the installation of DG using LSFSA [11]

<table>
<thead>
<tr>
<th>Concerned Parameters</th>
<th>3 DG at unity power factor</th>
<th>3 DG at 0.866 power factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimal Bus Location</td>
<td>6, 18, 30</td>
<td>6, 18, 30</td>
</tr>
<tr>
<td>Active Power Loss (in kW)</td>
<td>82.03</td>
<td>26.720</td>
</tr>
</tbody>
</table>

The DG unit localization, corresponding sizes, $P_l$ and voltage (in per unit) in the cases without and with DGs using the proposed algorithm (CSA) and analytical approach are summarized in Table 3. While the minimum level of voltage reaches to its minimum value of 0.9039 per unit at bus number 18, but after the installation of one DG with upf (unity power factor) and 0.866 pf (power factor), $P_l$ reduces to 110.8481 kW and 68.5723 kW and bus voltage level improves to a value of 0.9423 per unit and 0.9581 per unit respectively. Similarly, with the implementation of three DG with upf and 0.866 pf, $P_l$ further reduces to 75.1610 kW and 19.7443 kW and bus voltage level improves to a value of 0.9712 per unit and 0.9891 per unit respectively. Fig. 1 shows the $P_l$ is reduced drastically after the installation of DG, operated at optimal pf. In Fig. 2 it is shown that the voltage profile of the system improves while installing DGs operated at optimal pf. It is seen from Fig. 3 that power flow (branch power flow) from branch number 1 to branch number 6 was quite high initially but decreases after the installation of DG.
Fig. 1. Active power loss vs. number of iteration (with and without DG at different power factor)

Fig. 2. Bus voltages vs. bus number (with and without DG at different power factor)

Fig. 3. Branch power flow vs. branch number (with and without DG at different power factor)
6 Conclusion

In this study, optimal sizing and placement of DG Units to reduce the active power loss and improve the voltage profile in radial distribution systems has been carried out using cuckoo search algorithm. Here cuckoo search algorithm is proved to be an efficient technique to find out the optimal location and size of DG unit. It is also observed that with the penetration of DG units operated at optimal pf, active power loss of the system reduces, while voltage profile of system improves sharply. Thus system performance is improved.

References