Optimal Multi-type DGs Placement in Primary Distribution System by NSGA-II

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Abstract: The study proposes a multiobjective optimal placement of multi-type DG for enhancement of primary distribution system performance. A Pareto-based non-dominated sorting genetic algorithm II (NSGA-II) is proposed to determine locations and sizes of specified number of Distributed Generator units (DG) within the primary distribution system. Three objective functions are considered as the indexes of the system performance: average Load Voltage Deviation (LVD) minimization of the system real power loss and minimization of the annualized investment costs of DG. A fuzzy decision making analysis is used to obtain the final trade off optimal solution. The proposed methodology is tested on modified IEEE 33-bus radial system. Test results indicate that NSGA-II is a viable planning tool for practical DG placement and useful contribution of DG in improving the steady state system performance of the distribution system by the optimal allocation, setting and sizing multi-type DG.

Keywords: Distributed Generation (DG), Load Voltage Deviation (LVD), multi-objective optimization, non-dominance sorting genetic algorithm II (NSGA-II)

INTRODUCTION

Distributed Generators (DG), based on renewable energy technologies are becoming popular as they address climate change and energy security issues to some extent. Renewable energy based DGs do not contribute to GHG emission and also diversity of sources also increases due to different renewable energy options that address energy security concerns. Apart from climate change and energy security concerns, there are other driving forces for increasing penetration of DG in distribution system (Student Member and Member,). There are a number of technical benefits that the DG can bring such as better voltage profile, loss reduction and reliability improvement.

The share of DGs in primary distribution systems has been fast increasing in the last few years. Studies have indicated that inappropriate selection of the location and size of DG may lead to greater system losses than losses without DG (Mithulananthan et al., 2004; Griffin et al., 2000). By optimum allocation, utilities take advantage of a reduction in system losses, improved voltage regulation and an improvement in the reliability of supply (Mithulananthan et al., 2004; Reliability, 2003). It will also relieve the capacity of transmission and distribution systems and hence defer new investments which have a long lead-time. In addition, the modular and small size of the DG will facilitate the planner to install it in a shorter time frame compared to the conventional solution. It would be more beneficial to install in a more decentralized environment where there is a larger uncertainty in demand and supply. However, given the choices, they need to be placed in appropriate locations with suitable sizes. Therefore, analysis tools are needed to be developed to examine locations and the sizing of such DG installations. Several approaches to solve the DG siting and sizing problem in distribution system have been proposed. In Bharathi Dasan et al. (2009), they use evolutionary programming approach for optimal placement and size of DG in a radial feeder. The objective is minimize the system real power loss, hybrid distributed generation for a mixed realistic load model is considered. A technique to determine optimal location and sizing of DG units in a MG based on loss sensitivity factor and priority list compare with analytical approach is developed by Acharya Mahat and Mithulananthan (2006). A simple methodology for placing a distributed generator with the view of increasing the loadability of the distribution system is presented in Mithulananthan and Oo (2006). In Parizad et al. (2010), they use exact loss formula for optimal placement and size of DG in radial distribution system. The objective is minimizing the system real power loss, loadability and voltage stability index. A Genetic Algorithm (GA) combined with power analysis to evaluate DG impacts in system power losses and voltage profile for radial network. A fuzzy model in optimal siting and sizing of DG for loss reduction and improvement voltage profile in power distribution is presented in Shayeghi and Mohamadi (2009). In Ramirez-rosado and Dominguez-navarro (2006), DG siting and sizing problem is fulfilled to compromise multi-objective function consisting of energy not-supplied cost,
improving cost of network and energy loss cost. In Sookananta and Kuanprab (2010); Prommee and Ongsakul (2008), DG siting and sizing problem in distribution network are analyzed to improve only power loss by particle swarm.

From the previous works, we can conclude that most of the problem of optimal location and sizing of DG is generally formulated as a mono-objective optimization problem. Unfortunately, the formulation of DG location and sizing problem as a mono-objective optimization is not quite practical. While, planners the power systems aim to take advantage of multi-type DG considering several objectives at the same time.

This study proposes a multi-objective optimal placement of multi-type of DG for enhancement of primary distribution system performance. A Pareto-based NSGA-II is proposed to find locations and sizes of a specified number of DG within distribution system. Multiobjective functions include LVD, minimize system real power loss and annualized investment cost. The final decision will be made by the fuzzy method to find the trade off solutions among three different objective functions.

**METHODOLOGY**

**DG planning problem formulation:** The multi-objective optimization technique to determine the optimal locations and sizes of DG units within primary distribution system is as follows:

- **Multi-objective:**
  
  \[ \text{Min } f(x, u) = [f_1(x, u), f_2(x, u), f_3(x, u)] \]  

  where, \( f_1, f_2 \) and \( f_3 \) represent average load voltage deviation, system real power loss and annualized investment, cost respectively.

- **Minimize the average load voltage deviation:**

  \[ \text{Min } f_1(x, u) = \sum_{k=1}^{N} \left( \frac{V_k^{\text{ref}} - V_k}{V_k^{\text{ref}}} \right)^2 \]  

- **Minimize the system real power loss:**

  \[ \text{Min } f_2(x, u) = P_L \]  

  Minimize the annualized Investment Cost:

  \[ \text{Min } f_3(x, u) = \sum_{i=1}^{N_{DG}} AF_i \times UC_i \times C_{DG,\text{max}} \]  

  The annualized investment cost of DG unit \( i \) is assumed to be proportional with the maximum rating of DG (Buayai et al., 2011), where the unit cost \( UC_i \) is in ($/KVA). The \( UC_i \) is different for different type of generating units. The total of investment cost is transformed to cash value in the beginning of the planning period by using economical expression (i.e., annual cost based on certain interest rate and life span). \( AF_i \) is the annualized factor associated with the installation cost (annual cost based on certain interest rate ‘\( i \)’ and life span ‘\( T \)’) as shown in (5):

  \[ AF_i = \frac{(i/100)(1+i/100)^T}{(1+i/100)^T-1} \]  

  **Dependent and control variables:** In the three objective functions, \( x \) is the vector of dependent variables such as slack bus power \( P_{G1} \), load bus voltage \( V_L \), generator reactive power outputs \( Q_{G1} \) and apparent power flow \( S_G \). \( x \) can be expressed as:

  \[ X^T = [P_{G1}, V_{L1}, \ldots, V_{LN}, Q_{G1}, S_1, \ldots, S_{NL}] \]  

  Furthermore, \( u \) is a set of the control variables such as generator real power outputs except at the slack bus \( P_{G1} \), generator reactive power outputs except at the slack bus \( Q_{G1} \), the locations of DG units, \( L \) and their setting parameters. \( u \) can be expressed as:

  \[ u^T = [P_{G2}, \ldots, P_{GNF}, Q_{G2}, \ldots, Q_{GNF}, L_1, \ldots, L_{NF}] \]  

  where, \( NF \) is the total number of DG devices to be optimally located within distribution system. The equality and inequality constraints of the load flow problem incorporating DG are given bellow.

  **Equality constrains:** These constraints represent the typical load flow equations as follows:

  \[ \begin{align*}
  \sum_{i=1}^{N} P_{Gi} &= \sum_{i=1}^{N} P_{LDi} + P_L \\
  \sum_{i=1}^{N} Q_{Gi} &= \sum_{i=1}^{N} Q_{LDi} + Q_L 
  \end{align*} \]  

  where, \( N \) is the number of buses, \( P_{Gi} \) and \( Q_{Gi} \) are real power reactive power generated by generating unit \( i \) (including slack bus), respectively, in MW.

  **Inequality constrains:** The inequality constraints are limits of control variables and state variables. Generator active power \( P_G \), reactive power \( Q_G \) and voltage \( V_G \) are restricted by their limits as follows:
\begin{align*}
& P_{\text{DG}, \text{min}} \leq P_{\text{DG}} \leq P_{\text{DG}, \text{max}} \\
& Q_{\text{DG}, \text{min}} \leq Q_{\text{DG}} \leq Q_{\text{DG}, \text{max}} \\
& |V|_{\text{min}} \leq |V| \leq |V|_{\text{max}} \\
& |P_{\text{bi}}| \leq P_{\text{bi}, \text{max}}
\end{align*}

\textbf{Distributed generation model:} DG units are modeled as synchronous generators for small hydro power, geothermal power, combined cycles and combustion turbines. They are treated as induction generators for wind and micro hydro power. DG units are considered as power electronic inverter generators such as micro gas turbines, solar power, photovoltaic power and fuel cells (Puttgen \textit{et al.}, 2003). In general, DG can be classified into four types:

- \textbf{Type 1:} DG capable of injecting constant P only (PV)
- \textbf{Type 2:} DG capable of injecting both P and Q (Gas Turbine)
- \textbf{Type 3:} DG capable of injecting constant P but consumes Q (Wind Turbine)
- \textbf{Type 4:} DG capable of delivering Q only (Synchronous condenser)

\textbf{NSGA-II for DG placement:} A NSGA-II combined with distribution load flow NRPF based on MATPOWER (Zimmer and Deqiang, 1997) is used to solve multi-objective optimization to identify appropriate sizes and locations of a specified number of DG unit within distribution system. The final trade off solution is determined by the fuzzy method. The fitness function for the above problem can be written as:

\begin{equation}
\mathbf{f}(x, u) = [f_1(x, u), f_2(x, u), f_3(x, u)]
\end{equation}

The final trade off solution is determined by the fuzzy method.

\textbf{NSGA-II algorithm:} In case of multiple conflicting objectives, there may not exist one solution which is the best compromise for all objectives. Therefore, a “trade-off” solution is needed instead of a single solution in multi-objective optimization. Non-dominated Sorting Genetic Algorithm (NSGA) uses non-dominated sorting and sharing has not been widely used mainly because of:

- High computational complexity
- Nonelitism approach
- The need for specifying a sharing parameter

NSGA-II is developed to overcome these difficulties (Deb, 2003; Deb \textit{et al.}, 2002)

NSGA-II is one of the most efficient algorithms for multiobjective optimization on a number of benchmark problems (Deb \textit{et al.}, 2002). In addition, with NSGA-II based approach, the multiobjective of DG planning is retained without the need for any tunable weights or parameters. As a result, the proposed methodology is applicable to solving distributed generation planning in a distribution network. NSGA-II has been developed to determine locations and sizes of DG units within distribution system. The NSGA-II procedure can be found in Deb \textit{et al.} (2002).

\textbf{Load flow analysis:} The distribution systems are structurally weakly meshed but are typically with a radial structure. The Distribution Load Flow (DLF) based on iterative backward/forward sweep methods had been applied for a radial distribution system (Bompard \textit{et al.}, 2000). The effectiveness of the backward/forward sweep method in the analysis of radial distribution systems has already been demonstrated over traditional NR (Lin and Huang, 1987). Because of high R/X ratio of distribution networks and it radial structure, these equations are commonly based on iterative backward/forward sweep methods. In this case, the method described in Bompard \textit{et al.} (2000) was used:

\begin{equation}
V_{\text{node}} \leftarrow V_{\text{grid}} \\
\text{while } \varepsilon \geq \varepsilon_{\text{max}} \text{ do} \begin{align*}
V_{\text{node}} &= V_{\text{grid}} - Z \cdot I_{\text{line}} \\
\varepsilon &= g_{\text{error}}(S_{\text{node}}, I_{\text{node}}, V_{\text{node}})
\end{align*}
\end{equation}

z and A are the impedance matrix and line current summation matrix, respectively. For simplicity, here, the constant power model is used, but this could be adapted. All current injections are based on a static load model where the power doses not vary with changes in voltage magnitude. It is also known as constant MVA load model (Mithulananthan \textit{et al.}, 2000). The stopping criterion is based on the node-power convergence.

\textbf{Fuzzy method for best compromise solution:} Once the Pareto optimal set is obtained, it is practical to select one solution from all solutions that satisfies different goals to some extent. Such a solution is the best compromise solution. In this paper, a simple linear membership function is considered for each of the objective functions. The membership function is defined as follow (Sakawa and Yano, 1989).
The membership function \( \mu_i(z) \) is varied between 0 and 1, where, \( \mu_i(z) = 0 \) indicates incompatibility of the solution with the set, while \( \mu_i(z) = 1 \) means full compatibility. Figure 1 illustrates the graph of this membership function.

The compromised solution can be found by using the normalized membership function (Sakawa and Yano, 1989). For each non-dominated solution \( k \), the normalized membership function \( \mu^k \) is calculated as:

\[
\mu^k = \frac{1}{\sum_{i=1}^{M} \sum_{k=1}^{N_{obj}} \mu^k_i}
\]

The results were compared with the Repetitive Load Flow (RLF) approach. The computation procedure of RLF is given as follows:

**Step 1:** Run the base case load flow (without MG).
**Step 2:** Place DG at the bus within MG area.
**Step 3:** Change the size of DG in “small” step and calculate loss for each by running load flow.
**Step 4:** Store the size of DG that gives minimum loss.
**Step 5:** Compare the system loss with previous solution. Replace the previous solution if new solution is lower.
**Step 6:** Repeat from Steps 3 to 5 for all buses in MG area.

The procedure above is used to find the best location and size of two or more DG units within distribution system.
minimizing only system real power loss. Assuming DG units will regulate bus voltage for DG type 2, here we set DG bus voltage as equal 1.0 p.u. The best location and size of the first DG is obtained by RLF method. Similarly, the second DG size and location is found by fixing the first DG at the original location and size. For comparison, NSGA-II and RLF system Loss, Load Voltage Deviation (LVD), annualized investment cost and penetration level is considered. The penetration level can be defined as the total DG power generation $P_{DG}$ er the total load demand $P_{LD}$:

$$\text{Penetration level} = \frac{\sum P_{DG}}{\sum P_{LD}} \times 100$$

(14)

Optimal distributed generation placement-type 1: The best configuration plans of DG within 33-bus radial system are found at buses 22 and 27 for peak load level. The optimal DG size at bus 22 is 1.1576 and at bus 27 is 0.852 MW respectively. Figure 3 shows the Pareto front, in the objective function space (objective function load voltage deviation, system real power loss and annualized investment cost) for on peak load level. This set of solutions on the non-dominated frontier is used by the decision maker as the input to select a final compromise solution by using the normalized membership function in (13).

Optimal distributed generation placement-type 2: The best configuration plans of DG within 33-bus radial system are found at buses 22 and 30 for peak load level. The optimal DG sizes at buses (22 and 30) are (0.938, 0.672) MW and (0.744, 0.356) MVAR, respectively.

Optimal distributed generation placement-types 1 and 2: The best configuration plans of DG types 1 and 2 within 33-bus radial system are found at buses 22 and 30.
respectively for peak load level. The optimal DG types 2 and 1 sizes at buses (22 and 30) are (1.048, 0.668) MW and (1.107, 0) MVAR, respectively.

In Table 2, comparison has been made between RLF and NSGA-II method at on-peak load level. The RLF approach is minimizing system real power loss only whereas NSGA-II approach is minimizing three objectives including LVD, system real power loss and annualized investment cost, respectively.

For DG type 1, the system loss of RLF method is slightly more than NSGA-II method but the LVD is smaller than NSGA-II method. This is because the best location and size of the first DG is obtained by RLF method then the second DG size and location is found by fixing the first DG at the original location and size. In contrast, the NSGA-II method is solved the optimal siting and size of two DGs within the system at the same time.

For DG type 2, in NSGA-II method, the LVD, system loss and annualized investment cost are less than RLF method. This is because RLF is optimizing only system loss while regulate bus voltages. NSGA-II method is minimizing for all three objectives by real and reactive power injection control. Thus, NSGA-II method is better
Table 4: Parameter for simulation

<table>
<thead>
<tr>
<th>No</th>
<th>Description</th>
<th>Parameter of simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>DGs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>DG technology</td>
<td>Photo voltaic, Gas turbine (biomass), Wind turbine, Synchronous condenser</td>
</tr>
<tr>
<td>2</td>
<td>DG type</td>
<td>1, 2, 3, 4</td>
</tr>
<tr>
<td>3</td>
<td>Size (MVA)</td>
<td>0.001-3.00, 01-3.0, 0.001-3.0, 0.001-3.0</td>
</tr>
<tr>
<td>4</td>
<td>Unit cost ($/kVA)</td>
<td>5250, 1800, 2150, 700</td>
</tr>
<tr>
<td>5</td>
<td>Fuel</td>
<td>Solar energy, Biogas, Wind, Non</td>
</tr>
<tr>
<td>6</td>
<td>Equipment life (years)</td>
<td>20, 10, 20</td>
</tr>
<tr>
<td>Economic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Interest rate</td>
<td>7%</td>
</tr>
</tbody>
</table>

AF<sub>i</sub> is the annualized factor associated with the installation cost (annual cost based on certain interest rate ‘i’ and life span ‘T’:

\[
AF_i = \frac{(i/100)(1+i/100)^T}{(1+i/100)^T-1}
\]

than RLF method in terms of both system loss and LVD. For DG type 1&2, NSGA-II is far better that RLF method in terms of LVD, system loss and annualized investment cost.

In Table 2, comparison has been made between the three different DG configurations which are solved by NSGA-II method. The NSGA-II approach is minimizing three objectives including LVD, system real power loss and annualized investment cost, respectively.

For DG type 1, the system loss, LVD and annualized investment cost are more than the other types. This is because it is only real power injection to the bus and unit cost (S/kVA) is the highest. The system loss varies as a function of penetration level in a U-shape trajectory. As a penetration increases, loss will decrease until the minimum value and will start increasing as shown in Fig. 4. Similarly, the LVD varies as a function of penetration level in a U-shape trajectory. As DG penetration increases, LVD will decrease until the minimum value and will start increasing as shown in Fig. 4. By contrast, the annualized investment cost linearly increases as a function of the penetration level. Accordingly, the optimal solution NSGA-II would require a high DG penetration level for voltage profile improvement and loss reduction but require a low annualized investment cost.

Figure 5 shows the comparison of system loss reduction, load voltage deviation improvement and annualized investment improvement for the DG type 1, type 2 and type 1&2 for on-peak load level. Obviously, the DG type 2 is the best plan with respect to load voltage deviation improvement of 94.63% and system loss reduction of 82.84% compared to the base case. For economic consideration, DG type 2 is the best plan due to the lowest annualized investment cost. The annualized investment cost for on peak load level is the lowest at 0.355 million $/year.

**CONCLUSION**

This study proposes an efficient multi-objective DG placement methodology. The NSGA-II is used to determine locations and sizes of a specified number of Distributed Generators (DG) within primary distribution system. A fuzzy decision making analysis is used to obtain the final trade off optimal solution. The proposed methodology is tested on IEEE 33-bus radial system. Using the fuzzy method, DG can improve the system performance by trading off the minimize system LVD, minimize system real power loss and minimize annualized investment cost. Moreover the method does not impose any limitation on the number of objectives. This work will be further extended to address the problem of optimal location of multi-type of DG units to enhance system reliability.

**LIST OF SYMBOLS AND ABBREVIATIONS**

- \( A_{fi} \): Annualized factor associated with the installation cost of DG unit i
- \( C_{DG,i, ax} \): Selected capacity of DG unit i for installation within MG (kVA)
- \( f_{i \text{min}} \): Minimum value of the i<sup>th</sup>objective function among all non-dominated solutions
- \( f_{i \text{max}} \): Maximum value of the i<sup>th</sup>objective function among all non-dominated solutions
- \( i \): Interest rate (%)
- \( n \) : Number of buses.
- \( P_i \) : Net real power injection at bus i
- \( P_L \) : System power loss, in kW
- \( P_{Gi} \) : Real power generated by generating unit i (including slack bus), in kW
- \( P_{LDi} \) : Load demand at bus i, in kW
- \( P_{bi} \) : Branch power in branch i, in kW
- \( P_{DGi, \text{min}} \) : Upper real power generating limit of unit i, in kW
- \( P_{PDGi, \text{min}} \) : Lower real power generating limit of unit i, in kW
- \( P_{DGi} \) : The real power injection from DG place at bus i
- \( Q_i \) : Net reactive power injection at bus i
- \( Q_{LDi} \) : Load demand at bus i in kVAR
- \( Q_{bi} \) : Reactive power generated by generating unit i (including slack bus), in kVAR
- \( Q_{DGi} \) : The reactive power injection from DG place at bus i
- \( \delta_i \) : Voltage phase angle at bus i
- \( T \) : Life span in year
- \( u \) : Decision variables for a two-entry vector of DG size and location
UC
k  Unit cost of DG unit ($/kVA)
μk  Normalized membership function
μφ(z) Membership function (varied between 0 and 1)
Vref k Reference value of the voltage magnitude at bus k, in p.u. (usually set to 1.0 p.u.)
Vi Voltage magnitude at bus i
Vk Actual voltage magnitude at bus k, in p.u
x the vector of dependent variables such as slack bus power Pgi, load bus voltage Vli

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