Optimal choice and allocation of distributed generations using evolutionary programming

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SUMMARY

In this paper, evolutionary programming (EP) is proposed to determine the optimal choice and allocation of multi-type distributed generations (DG) to enhance power transfer capability and minimize system power losses in power system. The optimal allocation includes the optimal type, size, and location. Two types of DG including photovoltaic (PV) and wind turbine (WT) are used in this study. The objective function is formulated as maximizing the benefit to cost ratio. The benefit means increasing in the ability to support the load with deducting system losses which is defined as system loadability. The total costs are the investment and operating costs of the selected DG units. Power transfer capability determinations are calculated based on the optimal power flow (OPF) technique. Test results on the modified IEEE 30-bus system show that the proposed EP can determine the optimal choice and allocation of DG units to achieve system loadability enhancement with the highest benefit to cost ratio of the existing power system.

KEYWORDS

Distributed generations, evolutionary programming, optimal power flow, and optimal allocation.

INTRODUCTION

Distributed generation (DG) is an electric power generation unit connected directly to distribution networks or on the customer site [1]. The technologies adopted in DG comprise small gas turbines, micro-turbines, fuel cells, wind, and solar energy, etc [2]. In power systems, DG can provide benefits for the consumers as well as for the utilities, especially in sites where central generations are impracticable or where there are deficiencies in the transmission systems [3]. The optimal allocated DG units can be used to enhance power transfer capability, reduce power system losses, improve voltage profile, increase system reliability, and reduce pollution [4].

Even though DG units have many benefits when they are placed in power systems, the installation of DG units at non-optimal places can result in an increase in system losses, implying in an increase in costs and, therefore, having an effect opposite to the desire [5]-[6]. Therefore, the problem of selection of the best places for installation and the preferable size of the DG units in large power systems is of great importance. However, the optimal choice and allocation of DG is a complex combinatorial optimization problems which conventional optimization methods cannot effectively be used to solve these problems.

At present, evolutionary programming (EP) has been suggested to overcome the above-mentioned difficulties of conventional methods [7]-[9]. In this paper, EP is used to simultaneously determine the optimal type, size, and location of multi-type DG units to enhance system loadability with deducting system losses. Photovoltaic (PV) and wind turbine (WT) generation units are used in the study. The objective function is formulated as maximizing the benefit to cost ratio. The modified IEEE 30-bus system is used as the test system.
PROBLEM FORMULATION

Objective Function

The optimal power flow (OPF) based objective function considering benefits and cost of DG installation in (1) is used to evaluate the maximum feasible loadability value that can be increased in power systems. The benefit means increasing in the ability to support load with deducting system losses as shown in (2). The total cost (TC) is the cost function of investment and operating costs of DG, which can be calculated in (3). DGs are represented by the static model used in load flow calculation [10].

Maximize \[ F = \frac{B}{TC} \]  
\[ B = \left( \lambda_{\text{max}} \left( \sum_{i=1}^{\text{ND}} P_{\text{DG},i}^{\text{max}} \right) \right) \cdot 8,760 \cdot C_e \]  
\[ TC = I_i + j_{\text{Tech}} \sum_{i=1}^{\text{SNK}} I_{C,j} \cdot P_{\text{DG},j} + \sum_{i=1}^{\text{SNK}} \sum_{j_{\text{Tech}}} ^{\text{ND}} \sum_{i=1}^{\text{SNK}} O_{C,j} \cdot P_{\text{DG},j} \cdot a_j \times 8,760 \]  

Where \( F \) is the objective function, \( B \) is benefit from installation of DG units and \( TC \) is total cost of DG installation and operating cost. In (2), \( \lambda_{\text{max}} \) is maximum system loadability, which are considered with base case real power load \( (P_{\text{DG},i}^{\text{max}}) \) at bus \( i \). \( P_{\text{DG},i}^{\text{max}} \) is real power loss at bus \( i \) with maximum loadability condition. \( \text{ND} \) \( \text{SNK} \) is number of load bus in sink area. \( C_e \) is cost of electricity which is defined as 100 $/MWh. In (3), \( I_{C,j} \) and \( O_{C,j} \) are investment cost and operating cost of DG type \( j \). \( P_{\text{DG},j} \) is capacity of the DG type \( j \) at bus \( i \). \( a_j \) is plant factor of DG unit type \( j \). The technical and economic data of DG technologies are shown in Table 1 [10].

System Constraints

System constraints are composed of power balance constraints, real and reactive power limits of generations, voltage limits, transmission line constraints, and maximum installation capacity of DG. Equality constraints are represented in (4) and (5).

\[ P_{G,i} - P_{D,i} - \sum_{j=1}^{N_S} Y_{ij} \cdot V_i \cdot V_j \cdot \cos(\theta_{ij} - \delta_i + \delta_j) = 0 \]  
\[ Q_{G,i} - Q_{D,i} + \sum_{j=1}^{N_S} Y_{ij} \cdot V_i \cdot V_j \cdot \sin(\theta_{ij} - \delta_i + \delta_j) = 0 \]  

Where \( P_{G,i} \) and \( Q_{G,i} \) are real and reactive power generation at bus \( i \). \( P_{D,i} \) and \( Q_{D,i} \) are real and reactive power load at bus \( i \). \( V_i \) and \( V_j \) are voltage magnitudes at bus \( i \) and \( j \). \( Y_{ij} \) is magnitude of the element \( ij \) in bus admittance matrix. \( \theta_{ij} \) is angle of the element \( ij \) in bus admittance matrix. \( \delta_i \) and \( \delta_j \) are voltage angles of bus \( i \) and \( j \).

Inequality constraints are represented in (6) - (10).

\[ P_{G,i}^{\text{min}} \leq P_{G,i} \leq P_{G,i}^{\text{max}} \]  
\[ Q_{G,i}^{\text{min}} \leq Q_{G,i} \leq Q_{G,i}^{\text{max}} \]  
\[ V_i^{\text{min}} \leq V_i \leq V_i^{\text{max}} \]  
\[ |S_{i,j}| \leq S_{i,j}^{\text{max}} \]  
\[ P_{DG,i} \leq P_{DG,i}^{\text{max}} \]  

Where \( P_{G,i}^{\text{min}} \) and \( P_{G,i}^{\text{max}} \) are lower and upper limits of real power generation at bus \( i \). \( Q_{G,i}^{\text{min}} \) and \( Q_{G,i}^{\text{max}} \) are lower and upper limits of reactive power generation at bus \( i \). \( V_i^{\text{min}} \) and \( V_i^{\text{max}} \) are lower and upper voltage magnitudes at bus \( i \). \( S_{i,j}^{\text{max}} \) is apparent power flow loading limit of line \( i \). \( P_{DG,i} \) is injected real power of DG at bus \( i \) and \( P_{DG,i}^{\text{max}} \) is maximum install capacity of DG unit at bus \( i \).

Table 1

<table>
<thead>
<tr>
<th>Type</th>
<th>IC ($/MW-year)</th>
<th>OC ($/MWh)</th>
<th>Commercial size (kW)</th>
<th>Plant Factor (a_j)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photovoltaic</td>
<td>618,000</td>
<td>0.0</td>
<td>100</td>
<td>25</td>
</tr>
<tr>
<td>Wind turbine</td>
<td>206,000</td>
<td>10.9</td>
<td>200, 300</td>
<td>20</td>
</tr>
</tbody>
</table>
EVOLUTIONARY PROGRAMMING

EP is a computational intelligence technique that searches for the optimal solution by evolving a population of candidate solution, starts with random generation of initial individual. Then, the mutation and selection are preceded until the best individual is found. The structure of EP algorithm is shown in Figure 1 [11]. The major steps of the algorithm are explained as follows.

Initialization

The initial population consists of individuals and it is created randomly within a feasible range of each control variable which is calculated by (12).

\[ V_i^k = \left[ P_i, V_i, \lambda_i, Loc_i, Size_i \right] \]  \hspace{1cm} (11)

\[ x_i = x_i^{\min} + \mu \left( x_i^{\max} - x_i^{\min} \right) \]  \hspace{1cm} (12)

Where \( P_i \) is real power generation at bus \( i \) excluding slack bus. \( V_i \) is voltage magnitude of generator at bus \( i \) including the slack bus. \( \lambda_i \) is loadability at bus \( i \). \( Loc_i \) are type and location of DG which \( Loc_{PV} \) and \( Loc_{WT} \) is bus number of PV and WT, respectively. \( Size_i \) is size of DG unit. \( x_i \) is \( i \)th element of the individual in a population that in the range of lower and upper limits, \( x_i^{\max} \) and \( x_i^{\min} \). \( \mu \) is an uniform random number in the interval 0 to 1.

Mutation

Each individual is mutated to generate a new population which is an offspring vector. The new population is generated by the gaussian random variable. The \( k \)th parent create \( k \)th offspring, result from this step is \( 2k \) individuals. Each element is computed by (13) and (14).

\[ x_{i,j} = x_{i,j} + N \left( 0, \sigma_{i,j}^2 \right) \]  \hspace{1cm} (13)

\[ \sigma_{i,j} = \left( x_i^{\max} - x_i^{\min} \right) \left( \frac{f_{i,j} - f_{i,j}^\text{max}}{f_{i,j}^\text{max}} + a \right) \]  \hspace{1cm} (14)

Where \( x_{i,j} \) and \( x_{i,j} \) are \( i \)th element of the \( k \)th offspring and parent individuals. \( N \left( 0, \sigma_{i,j}^2 \right) \) is gaussian random number with mean 0 and standard deviation of \( \sigma_{i,j} \). \( x_i^{\min} \) and \( x_i^{\max} \) are lower and upper limits of the \( i \)th element of the \( k \)th parent individual. \( f_{i,j} \) is fitness of the \( k \)th individual and \( f_{i,j}^\text{max} \) is the maximum fitness of the parent population. \( a \) is a positive constant number slightly less than 1 and \( g \) is iteration counter.

Competition

Each individual in the combined population has to compete with some other individuals to get chance to be transcribed to the next generation. The best \( k \)th individuals with maximum fitness values are retained to be parents of the next generation. A weight value is assigned to the individual according to the competition in (15) and (16).

\[ w_i = \sum_{j=1}^{N_i} w_j \]  \hspace{1cm} (15)

\[ w_i = \begin{cases} 1 & \text{if } f_i > f_r \\ 0 & \text{otherwise} \end{cases} \]  \hspace{1cm} (16)

Where \( w_i \) is weight value of \( k \)th individual in combined population. \( f_i \) is fitness value of \( k \)th individual in combined population and \( f_r \) fitness value of \( r \)th opponent randomly selected from the combined population. \( N_i \) is a number of competitors.

Termination criterion

The termination criterion is set as the maximum number of generations.

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Figure 1 Flowchart of EP-based OPF
CASE STUDY AND SIMULATION RESULTS

The modified IEEE 30-bus system shown in Figure 2 is used to demonstrate the optimal choice and allocation of multi-type DG units using the EP approach. Bus data and line data of the system are taken from [12]. The EP parameters used in the study are shown in Table 2.

Table 2
<table>
<thead>
<tr>
<th>Parameter setting of EP</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population size (popsize)</td>
<td>30</td>
</tr>
<tr>
<td>Maximum number of generation (maxgen)</td>
<td>300</td>
</tr>
<tr>
<td>Constant value in mutation scale (Consta)</td>
<td>0.90</td>
</tr>
<tr>
<td>Number of tournament (Ntour)</td>
<td>15</td>
</tr>
<tr>
<td>Fitness function constant (KF)</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 3
Test results of all case studies

<table>
<thead>
<tr>
<th>Case study</th>
<th>p_DG</th>
<th>l_DG</th>
<th>objective function value</th>
<th>l_max</th>
<th>Avg. time (min)</th>
<th>PV Bus/Size (MW)</th>
<th>Wind Bus/Size (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base PF</td>
<td>164.30</td>
<td>2.42</td>
<td>-</td>
<td>1.000</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Base EP</td>
<td>164.30</td>
<td>2.42</td>
<td>174.75</td>
<td>4.04</td>
<td>1.064</td>
<td>1.38</td>
<td>-</td>
</tr>
<tr>
<td>N DG=1</td>
<td>164.30</td>
<td>2.42</td>
<td>177.79</td>
<td>4.14</td>
<td>142.40</td>
<td>0.92</td>
<td>29/1.0</td>
</tr>
<tr>
<td>N DG=2</td>
<td>164.30</td>
<td>2.42</td>
<td>182.04</td>
<td>3.95</td>
<td>39.96</td>
<td>1.108</td>
<td>17.1</td>
</tr>
<tr>
<td>N DG=3</td>
<td>164.30</td>
<td>2.42</td>
<td>182.70</td>
<td>3.90</td>
<td>45.22</td>
<td>1.112</td>
<td>1.87</td>
</tr>
</tbody>
</table>

Figure 3. System loadability of all case study

Figure 4. The convergence characteristic of the EP approach

Table 3 shows test results from EP approach which group of case study are without and with DG installation. The power transfer of base case system (Base PF) is 164.30 MW. Without DG installation, the system loadability evaluated by EP (Base EP) can be increased from 1.000 to 1.064 resulting in the additional power transfer 10.45 MW. The maximum power transfer can be improved when DGs are placed in the system. For example, the additional 13.49 MW is increased with the maximum number of each DG type is one component (N DG=1). The real power generation of PV installation at bus 29 is 1.00 MW and the real power generation of WT installation at bus 7 is 2.00 MW. The power transfer is increased and total loss is reduced, when maximum numbers of DG are two and three components. However, optimal number of each DG installation is one component all case study to obtain the best objective value. Figure 3 shows graph of loadability that comparing results from base case until total number of each DG type is three components. Figure 4 shows the rapid convergence characteristic of fitness of EP method.
CONCLUSION

In this paper, the proposed EP is implemented to determine the optimal choice and allocation of multi-type DG units to enhance system loadability and reduce power losses in power systems without any violation of system constrains. Test results on the modified IEEE 30-bus system show that the EP approach can simultaneously determine the optimal type, size, and location of photovoltaic and wind turbine DG units to maximize system loadability and minimize power losses with the lowest installation and operating cost of DG. In addition, test results indicate that optimally placed OPF with multi-type DG units by the EP approach could enhance the power transfer value far more than OPF without DG, leading to a higher trading level of energy transactions in a normal secured system.

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BIBLIOGRAPHY


Short Bio-data of Main Author

Rungmanee Jomthong received her B.Eng. degree in Electrical Engineering from Naresuan University, Phitsanulok, Thailand, in 2008. She is currently a master student in Electrical Engineering, Department of Electrical Engineering, Faculty of Engineering, Chiang Mai University, Thailand.
Optimal Choice and Allocation of Distributed Generations using Evolutionary Programming

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Reasons and background of this research

Figure 1. Central vs. distributed generation.
Problems and Limitations of Central Generation

- Capital Cost
- Fuel Cost
- Area
- Pollutions
What is Distributed Generation?

Distributed Generation is the new system would also be able to seamlessly integrate an array of locally installed, distributed power generation. (Definition of Electric Power Research Institute: EPRI.)

Distributed generation is:
  • Not centrally planned.
  • Today not centrally dispatched.
  • Usually connected to the distribution network.
  • Smaller than 50 or 100 MW.
(Definition of International Conference on High Voltage Electric Systems: CIGRE.)
Technology of Distributed Generation.

Distributed Generation Types & Technology

Traditional Generators (Combustion Engines)
- Micro Turbine (MT)
  - Natural Gas Turbine
- Such as Fuel Cell (FC)

Non-Traditional Generators
Consists of
Such as Renewable Devices
- Such as Photovoltaic (PV)
- Such as Wind Turbine (WT)
- Storage Devices
  - Batteries
  - Flywheels

Electrochemical Devices

Figure 2. Type and technology of distributed generation
The optimal solution for optimization of DG.

- Real and reactive power limits of generations
- Feeder transmission capacity
- Maximum install capacity
- Power balance equations
- Voltage limits

Evolutionary Programming

Power Flow

Objective Function

Types
Sizes
Locations

Figure 3. Optimal solution of objective function
Problem Formulation : Objective Function

\[ Maximum \ F = \frac{B}{TC} \]  \hspace{1cm} (1)

Where

\[ B = \text{Benefit from installation of DG units, and} \]

\[ TC = \text{Total cost of DG installation and operating cost.} \]
The benefit from installation of DG units.

\[
B = \left[ \lambda_{\text{max}} \cdot \left( \sum_{i=1}^{\text{ND}_\text{SNK}} P_{Di}^{\text{base}} \right) \right] - \left( \sum_{i=1}^{\text{ND}_\text{SNK}} P_{Li,\lambda_{\text{max}}} \right) \cdot 8,760 \cdot C_e
\]  

Where:

- \( B \) = Benefit from installation of DG units, and
- \( \lambda_{\text{max}} \) = total transfer capability,
- \( P_{Di}^{\text{base}} \) = base case real power load at bus \( i \),
- \( P_{Li,\lambda_{\text{max}}} \) = losses in the line flows at line \( i \),
- \( C_e \) = cost of electricity which is defined as 100 $/MWh, and
- \( \text{ND}_\text{SNK} \) = number of load bus in sink area.
- Total costs of DG installation.

\[
TC = \sum_{i=1}^{ND\_SNK} \sum_{j\in Tech} IC_j \cdot P_{DG,ij} + \sum_{i=1}^{ND\_SNK} \sum_{j\in Tech} OC_j \cdot P_{DG,ij} \cdot a_j \times 8,746
\]

(3)

Where

\[
TC = \text{Total cost of DG installation and operating cost.}
\]

\[
j = \text{DG technologies used in the study,}
\]

\[
IC_j = \text{investment cost of DG type } j,
\]

\[
OC_j = \text{operating cost of DG type } j,
\]

\[
P_{DG,ij} = \text{capacity of the DG type } j \text{ at bus } i, \text{ and}
\]

\[
a_j = \text{plant factor of DG unit type } j.
\]

\[
ND\_SNK = \text{number of load bus in sink area.}
\]
Data of DG technologies.

Table 1. Technical and economic data of DG technologies.

<table>
<thead>
<tr>
<th>Type</th>
<th>IC ($/MW-year)</th>
<th>OC ($/MWh)</th>
<th>Commercial size (KW)</th>
<th>Plant factor (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV</td>
<td>618,000</td>
<td>0.0</td>
<td>100</td>
<td>25</td>
</tr>
<tr>
<td>WT</td>
<td>206,000</td>
<td>10.9</td>
<td>200,300</td>
<td>20</td>
</tr>
</tbody>
</table>

* For more information of in Promotion strategy of clean technologies in distributed generation expansion planning.
Figure 4. Flowchart of EP-based OPF
Figure 5. Diagram of the modified IEEE 30-bus system
### Results

#### Table 1. Test results of all case studies

<table>
<thead>
<tr>
<th>Case study</th>
<th>$P_{Di}^{base}$</th>
<th>$\lambda_{max}P_{Di}^{base}$</th>
<th>Objective value</th>
<th>loadability</th>
<th>Photovoltaic</th>
<th>Wind Turbine</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TTC (MW)</td>
<td>Loss (MW)</td>
<td>TTC (MW)</td>
<td>Loss (MW)</td>
<td></td>
<td>Bus</td>
</tr>
<tr>
<td>Base PF</td>
<td>164.30</td>
<td>2.42</td>
<td>-</td>
<td>-</td>
<td>1.00</td>
<td>-</td>
</tr>
<tr>
<td>Base EP</td>
<td>164.30</td>
<td>2.42</td>
<td>174.75</td>
<td>4.04</td>
<td>1.064</td>
<td>-</td>
</tr>
<tr>
<td>N_DG=1</td>
<td>164.30</td>
<td>2.42</td>
<td>177.79</td>
<td>4.14</td>
<td>142.40</td>
<td>1.082</td>
</tr>
<tr>
<td>N_DG=2</td>
<td>164.30</td>
<td>2.42</td>
<td>182.04</td>
<td>3.95</td>
<td>39.96</td>
<td>1.108</td>
</tr>
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<td>N_DG=3</td>
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<td>182.70</td>
<td>3.90</td>
<td>45.22</td>
<td>1.112</td>
</tr>
</tbody>
</table>
Results

Loadability

Figure 6. System loadability of all case study
Figure 7. The convergence characteristic of the EP approach
Conclusion

- The EP approach can simultaneously determine the optimal types, sizes, and locations of photovoltaic and wind turbine.

- Test results are shown DG units to maximize power transfer and minimize power losses with the lowest cost.

- The test results indicate that optimally placed OPF with multi-type DG units by the EP approach could enhance the power transfer value far more than OPF without DG.