Optimal expansion model of renewable distributed generation in distribution systems

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Introduction
Introduction

• **Distributed generation (DG)** is an electric power source connected directly to the distribution network or on the customer side of the meter.

• The benefits of DG are:
  – Voltage profile improvement
  – Increment of the overall energy efficiency
  – Improvement of power quality
  – Fuel cost reduction
  – Transmission and distribution cost savings
  – CO$_2$ emission reduction
Introduction

• This work presents an optimal model of expansion, integration and allocation of distributed renewable generation in distribution networks.
Introduction

Distributed Generation Planning (DGP) problem

- Optimal location
- Optimal sizing

provides

Aims at

- Minimizing distribution system costs

How?

- Renewable DG Investment
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Renewable production models

- Photovoltaic Technology

\[ T_{cell} = T_{amb} + \left( \frac{NOCT - 20}{800} \right) G \]

\[ P^{Ph} = P^{STC} \left\{ \frac{G}{1000} \left[ 1 + \delta(T_{cell} - 25) \right] \right\} \]

![Diagram of voltage and current for different power densities and temperatures.](image)
Renewable production models

- **Wind Generation Technology**

\[
P_{wd} = \begin{cases} 
0, & v < v_l \\
\frac{P_R}{v_R - v_l} v + P_R \left(1 - \frac{v_R}{v_R - v_l}\right), & v_l \leq v < v_R \\
\frac{P_R}{v_R - v_l} v + P_R \left(1 - \frac{v_R}{v_R - v_l}\right), & v_R \leq v < v_O \\
0, & v \geq v_O 
\end{cases}
\]

![Graph showing power output vs wind speed](image)
Renewable production models

- **Scenarios**

  - Historical hourly data
    - Spring
      - Work day: Scenario 1
      - Saturday: Scenario 2
      - Sunday: Scenario 3
    - Summer
      - Work day: Scenario 4
      - Saturday: Scenario 5
      - Sunday: Scenario 6
    - Fall
      - Work day: Scenario 7
      - Saturday: Scenario 8
      - Sunday: Scenario 9
    - Winter
      - Work day: Scenario 10
      - Saturday: Scenario 11
      - Sunday: Scenario 12
Renewable production models

• Uncertainty modeling: a six-step procedure

• Step 1: A separation of values into two groups of seasonal data (winter and summer) is done. Data are divided into peak demand, wind speed and irradiation.

• Step 2: The demand curve is built sorting data in descending order keeping the hourly correlation between demand, wind power and PV production.

• Step 3: Time blocks are set to model the impact of these demand values.
Renewable production models

Fig. 1. Demand, wind speed and irradiation curves and levels.
Renewable production models

- Step 4: Wind speed and irradiation are ordered from highest to lowest in each time block. Then, for each time block and type of data, a cumulative distribution function is calculated.

Fig. 2. Cumulative distribution function for the first block of demand factors.
Renewable production models

• Step 5: The distribution function obtained is divided into segments or defined sections. In Figure 2 there is a total of three segments, each one with a probability of 33%. Once the segments are known, the levels are determined with the mean of the data of this range.

• Step 6: The renewable production levels are obtained using the production models presented.
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Problem formulation

The model has the following contributions:

- Formulation as a mixed-integer linear problem.
- Storage systems are included.
- A real insular case is tested.
- Multi-objective problem.
- Renewable DG candidates are considered.
Problem formulation

• The objective function takes into account:

\[
\min \quad J = CINV + COM\]

\[
CINV = CI^{ph}NT^{ph} + CI^{wd}NT^{wd} + CI^{Btt}NT^{Btt}
\]

\[
COM = \sum_{t=1}^{T} 365 \sum_{\omega}^{24} \gamma_{\omega} \sum_{k=1}^{24} \left[ COMG_{k,\omega} + CT_{k,\omega}^{Loss} + \sum_{n \in \Omega^L} (CT_{n,k,\omega}^{Nsup} + \beta^t (COM_{n,k,\omega}^{ph} + COM_{n,k,\omega}^{wd} + COM_{n,k,\omega}^{Btt})) \right]
\]

- Total investment costs (Renewable DG & storage system).

- Costs of energy losses.

- Costs of not supplied energy.

- O&M costs of existing producers.

- O&M costs of new candidates (battery storage is also included).
Problem formulation

• Total investment costs (Renewable DG & storage system) are the purchase cost of different devices.

• O&M costs of new candidates are the maintenance costs, inspection costs and insurance and repair costs.

• O&M costs of existing producers are the fuel consumption, maintenance costs, inspection costs and insurance and repair costs.

• Costs of not supplied energy is the penalty for not supplied energy.

• Costs of energy losses are based on the Joule effect.
Problem formulation

• The existing producers’ costs are:

\[ COMG_{k,\omega} = \sum_{G \in \Gamma} (CF_{G} + CV_{G} S_{G,k,\omega}); \quad \forall (k, \omega) \]

• The cost of losses are:

\[ CT^{Loss}_{k,\omega} = \sum_{n \in \Omega^{N}} \sum_{m \in \Omega^{N}} (Floss^{(n,m)}_{k,\omega} C^{Loss} L^{(n,m)} S_{base}); \quad \forall (k, \omega) \]

• The penalty for not supplied energy is:

\[ CT^{NSup}_{n,k,\omega} = C^{NSup} S^{NSup}_{n,k,\omega}; \quad \forall (n \in \Omega^{L}, k, \omega) \]
Problem formulation

- Operating and maintenance costs of renewable DG candidates and the storage system are defined as:

\[
COM_{n,k,\omega}^{Ph} = CF^{Ph}N_{n}^{Ph} + CV^{Ph}S_{n,k,\omega}^{Ph}; \forall (n \in \Omega^{L}, k, \omega)
\]

\[
COM_{n,k,\omega}^{Wd} = CF^{Wd}N_{n}^{Wd} + CV^{Wd}S_{n,k,\omega}^{Wd}; \forall (n \in \Omega^{L}, k, \omega)
\]

\[
COM_{n,k,\omega}^{Btt} = CF^{Btt}N_{n}^{Btt} + CV^{Btt}I_{base}(IC_{n,k,\omega}^{Btt} + ID_{n,k,\omega}^{Btt}); \forall (n \in \Omega^{L}, k, \omega)
\]
Problem formulation

Constraints:

• Losses linearization
• Power balance at nodes without a substation
• Kirchhoff’s voltage law for feeders
• Feeders’ thermal capacity
• Voltage drop
• Wind turbine constraints
Constraints:

- Power balance at nodes without a substation:

\[
- \sum_{n} \left( F_{k,\omega}^{(m,n)} - F_{k,\omega}^{(n,m)} \right) + I_{m,k,\omega}^{Nsupt} + ID_{m,k,\omega}^{Btt} \\
+ I_{m,k,\omega}^{Ph} + I_{m,k,\omega}^{Wd} = I_{m,k,\omega}^{load} + IC_{m,k,\omega}^{Btt}; \\
\forall (m \in \Omega^L / m \neq n, k, \omega)
\]
Problem formulation

Constraints:

• Wind turbine constraints:

• They are necessary to transform all electrical values to the per-unit system:

\[ S_{n,k,\omega}^{WD} = N_n^{WD} \sqrt{(P_{k,\omega}^{WD})^2 + (P_{k,\omega}^{WD \tan \phi})^2}; \]
\[ \forall (n \in \Omega^L, k, \omega) \]

• Since \( S_{n,k,\omega}^{WD} = V_{n,k,\omega} I_{n,k,\omega}^{WD} \); \( \forall (n \in \Omega^L, k, \omega) \) assuming \( V_{n,k,\omega} \approx 1 \) pu

• Then, \( I_{n,k,\omega}^{WD} = \frac{S_{n,k,\omega}^{WD}}{S_{base}} \); \( \forall (n \in \Omega^L, k, \omega) \)
Problem formulation

Constraints

• Photovoltaic modules constraints
• Power balance in substation nodes
• Substation current limits
• Not supplied current
• Maximum distributed generation
• Storage system constraints
Problem formulation

Constraints:

• Photovoltaic modules constraints:

\[
S_{n,k,\omega}^{Ph} = N_{n}^{Ph} \sqrt{(P_{k,\omega}^{Ph})^2 + (P_{k,\omega}^{Ph} \tan \varphi)^2}; \\
\forall (n \in \Omega^L, k, \omega)
\]

\[
I_{n,k,\omega}^{Ph} = \frac{S_{n,k,\omega}^{Ph}}{S_{base}}; \quad \forall (n \in \Omega^L, k, \omega)
\]
Constraints:

• Storage system constraints:

  • The charge and discharge variables are limited by a maximum value:

    \[ IC_{n,k,\omega}^{Btt} \leq N_n^{Btt} C^{Btt}; \quad \forall (n \in \Omega^L, k, \omega) \]

    \[ ID_{n,k,\omega}^{Btt} \leq N_n^{Btt} C^{Btt}; \quad \forall (n \in \Omega^L, k, \omega) \]
Problem formulation

Constraints:

• Storage system constraints:

  • The equations that relate charge and discharge variables are:

    \[ \text{St}g_{n,1,\omega} = IC_{n,1,\omega} Btt \eta - ID_{n,1,\omega} Btt (1/\eta) + \text{St}g_{\text{initial}}; \]
    \[ \forall (n \in \Omega^L, \omega) \]

    \[ \text{St}g_{n,k,\omega} = IC_{n,k,\omega} Btt \eta - ID_{n,k,\omega} Btt (1/\eta) + \text{St}g_{n,k-1,\omega}; \]
    \[ \forall (n \in \Omega^L, k \neq 1, \omega) \]
Problem formulation

Constraints:

• Storage system constraints:

  • The storage system limit in each node is:

    $$Stg_{n,k,\omega} \leq N_n^{Btt} C^{Btt}; \quad \forall (n \in \Omega^L, k, \omega)$$

    $$NT^{Btt} = \sum_{n \in \Omega^L} N_n^{Btt}$$
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Case study

• Network
Case study

• Scenario construction
Case study

• Scenario data

[Graphs showing load and wind speed average by season: Spring, Summer, Fall, Winter. Each graph includes lines for Work day, Saturday, and Sunday.]
Case study

- Test cases

  - Case 1: Only existing producers
  - Case 2: With non-limited DG
  - Case 3: With limited DG
  - Case 4: With limited DG and increased costs of existing production
## Case study

### Results

<table>
<thead>
<tr>
<th>Results</th>
<th>Cases</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Total system costs [€]</td>
<td>16,400,370</td>
</tr>
<tr>
<td>DG renewable investment cost [€]</td>
<td>-</td>
</tr>
<tr>
<td>Existing technologies O&amp;M costs [€]</td>
<td>16,225,780</td>
</tr>
<tr>
<td>System loss costs [€]</td>
<td>174,590</td>
</tr>
<tr>
<td>Not supplied energy [MW]</td>
<td>0</td>
</tr>
<tr>
<td>Wind turbine power &amp; location</td>
<td>-</td>
</tr>
<tr>
<td>Photovoltaic power &amp; location</td>
<td>-</td>
</tr>
<tr>
<td>Battery units &amp; location</td>
<td>-</td>
</tr>
</tbody>
</table>
Case study

• Case 2

Wind turbines
PV Modules
Battery units

Feeders type
- - - - 1
- - 2
- - - 3
- - - - 4

59.5 kW
3.60 kW

42 kW
4.16 kW

101.5 kW
1.29 kW

140 kW
1 unit
Case study

• Case 3

Wind turbines
PV Modules
Battery units

Feeders type

1
2
3
4
Case study

• Case 4

Wind turbines
PV Modules
Battery units

Feeders type

1
2
3
4
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Conclusions

• Our model reduces the total cost of the distribution system.

• Decreases dependence on non-renewable traditional producers.

• The optimal allocations are in the farthest nodes of the distribution system.

• Storage units are necessary to avoid uncertainty in production.
Future work

- Substation expansion.
- Uncertainty modelling in load and production levels.
- Production’s reliability.
Optimal Expansion Planning in Distribution Networks with Distributed Generation

Thank you very much for your attention!