Development of a heuristic algorithm to design stand-alone microgrids for rural electrification projects considering distributed generation

Cañizares F., Kirchhoff H., Gomis O., Ranaboldo M.
1. Introduction
   a. Motivation
   b. Input – Output
   c. Considerations

2. Architecture of the algorithm
   a. Phase I: Initial solution construction
   b. Phase II: Distributed generation incorporation
   c. Phase III: Microgrids expansion

3. Results – Case Study

4. Conclusions and future steps
Motivation

45% of rural areas electrified through mini-grids by 2030 (IEA, 2011)

1. Generation technology
2. Topology of electrical network

Up-front costs of the electrification project

Key
Optimal use of resources and design
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**Input - Output**

1) Consumers' location,
2) Consumers' power and energy demand,
3) Cost and electrical characteristics of potential equipment,
4) Electrical constraints,
5) Local solar radiation.

1) Electrical network design
2) Number and location of DGs
3) Electrical design of DGs
4) Investment cost of the project
Considerations

- AC microgrids,
- Generation points located at consumption points,
- Radial network,
- Generation based on RE (Solar),
- Minimization of upfront investment,
- All generation points with similar power capacities.

Scenario A

- Total power Req: 1.2 kW
- Number Generation points: 2
- Power capacity per GP ≈ 0.6 kW

Scenario B

- Total power Req: 1.2 kW
- Number Generation points: 6
- Power capacity per GP ≈ 0.2 kW
Overview: Main phases

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Phase I: Initial solution construction

Initial point selection

Electrical network construction

Demand concentration index

\[ DI_j = \sum_{j \in N_i} \frac{ED_j}{\max(L_{ij}, L_{min})} \]

(Ranaboldo, 2013)
Phase II: Distributed generation incorporation

\[ \text{Cost} = \min \left( \sum_{i=1}^{n} (NG_{gi} \cdot \text{Cost}_{gi} + NB_{Bi} \cdot \text{Cost}_{Bi} + NCC_{CCI} \cdot \text{Cost}_{CCI} + NI_{li} \cdot \text{Cost}_{li} + NC_{Gi} \cdot \text{Cost}_{Ci}) \right) \]
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   c. Considerations

2. Architecture of the algorithm
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   b. **Phase II: Distributed generation incorporation**
   c. Phase III: Microgrids expansion

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4. **Conclusions and future steps**

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**Phase II: Distributed generation incorporation**

- Simulation of scenarios
- Selection of cheapest solution
- Sizing and cost estimation
- Improved Backwards/Forward Sweep
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   c. Considerations

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**Phase III: Microgrids Expansion**

Case A

Case B

Cost A < Cost B?

Selection of final solution
Results – Case Study

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3. Results – Case Study

4. Conclusions and future steps
Sonzapote (Nicaragua)

Cost comparison
SHS – Centralized approach – Proposed Algorithm

<table>
<thead>
<tr>
<th>Reference Scenarios</th>
<th>SHS</th>
<th>Centralized Generation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost [USD]</td>
<td>73,221</td>
<td>63,364</td>
</tr>
<tr>
<td>Cost of Algorithm [USD]</td>
<td>61,510</td>
<td></td>
</tr>
<tr>
<td>Difference between Algorithm and References</td>
<td>-19%</td>
<td>-3%</td>
</tr>
</tbody>
</table>

Cost comparison
Proposed Algorithm – HOMER Pro

Total real HOMER Pro: 59,431 USD
Total Algorithm: 61,510 USD

Difference: 3.7%
• Gap in the design models/software of off-grid systems considering generation and distribution network.
• Use of design algorithms greatly simplify the design process of the electrification process, while achieving investment reductions.
• Similar investment costs found for centralized and distributed generation solutions.
• Implementation of multiple smaller microgrids rather than a bigger one – *Investment reduction*
• Selection of amount of generation points can be solved from a technical/economical perspective.
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   b. Input – Output
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4. Conclusions and future steps

- Inclusion of additional configurations as part of the potential solutions:
  - DC microgrids,
  - SHS,
  - Microgrids with a single generation point.

**Goal:** Electrification projects exploiting the benefits of each possible configuration

- Optimization of the type of cable used for the electrical network.
- In general, increase the efficiency of the algorithm.
Thanks for your attention!

\[ \%VD \approx 2 \cdot (r \cdot \cos \phi + x \cdot \sin \phi) \cdot \frac{\sum_{n=1}^{N} L_{n} (km) \cdot P_{n} (kW)}{E^2 \cdot \cos \phi} \cdot 10^5 \% \]
Enumerate each node starting from the Slack bus.

Initialize the voltage of the nodes:
\[ V = 1 \text{ p.u.} \angle 0^\circ \]

Initialize the power of the DGs:
\[ S_{DG}(n) = \frac{\sum SD}{\#DGs+1} \]

Calculate \( Y_{bus}(i,j) \)

Starting from the farthest node:
\[ I_k(n) = \left( \frac{S_n}{V_k} - 1 \right) \]

Starting from the farthest node:
\[ I_k(n) = \sum I_k(n,n+i) \]

Starting from the Slack node:
\[ V_k(n) = V_k(n-1) - Z(n)*I_k(n) \]

Is the required convergence reached?

Recalculation of the slack node power:
\[ S_{DG}(k)(1) = V_k(1)*I_k(1)^* \]

Total active and reactive power is redistributed to all DGs.
\[ P_{DG}(k)(n) = P_{DG}(k-1)(n) + \frac{[P_{DG}(k-1)(1) - P_{DG}(k-1)(n)]/}{(#DGs+1)} \]
\[ Q_{DG}(n) = \text{RPF}^*|\text{imag}(Y_{bus}(i,j))*x(V_k(1)^2-V_k(n)^2)| + S_k(n) \]

Increase Reactive Power Injection Factor (RPF):
\[ \text{RPF}(k) = 0.9154*\text{RPF}(k-1) + 4.3846 \]

Compare reactive power generation of DGs to limit of inverters.
If \( Q_{inv} > Q_{max} \) then \( Q_{inv} = Q_{max} \) —— PQ Node

Is the required convergence reached?

No

Yes

Required convergence of DGs voltage reached? Maximum Q capabilities reached? Maximum iterations reached?

Stop

Improved power flow algorithm – Backwards/Forward Sweep – to solve radial network with multiple generation points
Case Study – Sonzapote (Nicaragua)

- Sonzapote (Nicaragua),
- 345 inhabitants,
- Community composed by households, a school and a church
- Completely un-electrified,
- Demand assessment necessary
- 34 consumption points of the community selected
## Case Study – Details of generation system design

### Microgrid 1

<table>
<thead>
<tr>
<th>DG Location</th>
<th>Devices</th>
<th>Type</th>
<th>Amount</th>
<th>Cost [USD]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>PV Panel</td>
<td>3</td>
<td>8</td>
<td>8016</td>
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<tr>
<td></td>
<td>Inverter</td>
<td>3</td>
<td>12</td>
<td>1110</td>
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<tr>
<td></td>
<td>Batteries</td>
<td>1</td>
<td>23</td>
<td>7485</td>
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<tr>
<td></td>
<td>Charge Controller</td>
<td>2</td>
<td>7</td>
<td>2800</td>
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</table>

### Microgrid 2

<table>
<thead>
<tr>
<th>DG Location</th>
<th>Devices</th>
<th>Type</th>
<th>Amount</th>
<th>Cost [USD]</th>
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</thead>
<tbody>
<tr>
<td>31</td>
<td>PV Panel</td>
<td>3</td>
<td>4</td>
<td>4008</td>
</tr>
<tr>
<td></td>
<td>Inverter</td>
<td>1</td>
<td>11</td>
<td>506</td>
</tr>
<tr>
<td></td>
<td>Batteries</td>
<td>1</td>
<td>11</td>
<td>3580</td>
</tr>
<tr>
<td></td>
<td>Charge Controller</td>
<td>3</td>
<td>2</td>
<td>1442</td>
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</table>

<table>
<thead>
<tr>
<th>DG Location</th>
<th>Devices</th>
<th>Type</th>
<th>Amount</th>
<th>Cost [USD]</th>
</tr>
</thead>
<tbody>
<tr>
<td>28</td>
<td>PV Panel</td>
<td>3</td>
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<td></td>
<td>Inverter</td>
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<td></td>
<td>Batteries</td>
<td>1</td>
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<td>3580</td>
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<tr>
<td></td>
<td>Charge Controller</td>
<td>3</td>
<td>2</td>
<td>1442</td>
</tr>
</tbody>
</table>
## Proposed algorithm – Equipment considered

<table>
<thead>
<tr>
<th>Equipment Type</th>
<th>Capacity</th>
<th>Cost [USD]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Inverters</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type 1</td>
<td>200</td>
<td>46</td>
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<tr>
<td>Type 2</td>
<td>300</td>
<td>70</td>
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<tr>
<td>Type 3</td>
<td>400</td>
<td>92.5</td>
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<tr>
<td>Type 4</td>
<td>1500</td>
<td>444</td>
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<tr>
<td><strong>Batteries</strong></td>
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<tr>
<td>Type 1</td>
<td>1290</td>
<td>325.47</td>
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<tr>
<td>Type 2</td>
<td>2520</td>
<td>693.21</td>
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<tr>
<td><strong>PV Modules</strong></td>
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<tr>
<td>Type 1</td>
<td>55</td>
<td>359</td>
</tr>
<tr>
<td>Type 2</td>
<td>150</td>
<td>800</td>
</tr>
<tr>
<td>Type 3</td>
<td>250</td>
<td>1002</td>
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<tr>
<td><strong>Charge Controllers</strong></td>
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<tr>
<td>Type 1</td>
<td>72</td>
<td>92.5</td>
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<tr>
<td>Type 2</td>
<td>300</td>
<td>400</td>
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<tr>
<td>Type 3</td>
<td>540</td>
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<tr>
<td><strong>Cables</strong></td>
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<td>Type 1</td>
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<tr>
<td>Type 2</td>
<td>100</td>
<td>3.9</td>
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<tr>
<td>Type 3</td>
<td>150</td>
<td>4.5</td>
</tr>
<tr>
<td>Type 4</td>
<td>205</td>
<td>5.4</td>
</tr>
</tbody>
</table>
Scenario solved using the model presented in:
### HOMER Pro - Modeling

**Diagram:**
- AC to DC conversion
- PV system
- Battery storage
- Inverter
- Converter
- Load profile

**Table:**

<table>
<thead>
<tr>
<th>Component</th>
<th>Capacity</th>
<th>Cost (HOMER)</th>
<th>Cost (Real HOMER)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV Array</td>
<td>7368 W</td>
<td>28084 USD</td>
<td>30060 USD</td>
</tr>
<tr>
<td>Batteries</td>
<td>44444 Wh</td>
<td>10080 USD</td>
<td>11391 USD</td>
</tr>
<tr>
<td>Inverter</td>
<td>2666 W</td>
<td>466 USD</td>
<td>647,5 USD</td>
</tr>
<tr>
<td>Cables</td>
<td>--</td>
<td>--</td>
<td>7239 USD</td>
</tr>
<tr>
<td>Charge Controller</td>
<td>--</td>
<td>--</td>
<td>10094 USD</td>
</tr>
</tbody>
</table>

**Total HOMER** 38630 USD

**Total real HOMER** 59431 USD

**Total Algorithm** 61510 USD