Multi-Criteria Optimization of the Deployment of a Grid for Rural Electrification Based on a Heuristic Method

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Abstract. In order to design electrification systems, recent mathematical models solve the problem of location, type of electrification components, and the design of possible distribution microgrids. However, due to the amount of points to be electrified increases, the solution to these models require high computational times, thereby becoming unviable practice models. This study posed a new heuristic method for the electrification of rural areas in order to solve the problem. This heuristic algorithm presents the deployment of rural electrification microgrids in the world, by finding routes for optimal placement lines and transformers in transmission and distribution microgrids. The challenge is to obtain a display with equity in losses, considering the capacity constraints of the devices and topology of the land at minimal economic cost. An optimal scenario ensures the electrification of all neighbourhoods to a minimum investment cost in terms of the distance between electric conductors and the amount of transformation devices.

1. Introduction

The design of electrification systems, involve recent mathematical models which solve location problems, types of electrification components, and the design of possible distribution microgrids. However, as the amount of demand points increases, the solution to these models require high computational times, which at the same time, become unviable practice models [1], [2]. In order to find the best possible solution to this kind of problem described as NP-Complete, it is necessary to consider the use of heuristics in search of the optimal solution. Heuristics are an algorithm that approximates the solution or a subset of the problem [3]. There are general forms of heuristic algorithms such as Gross Furze, the Random Search algorithms and Smart Search. Combination type problems that are NP-Complete or NP-Hard, have an exponential search space that becomes very large; therefore, it is necessary to approximate a heuristic that is finite, scalable and that seeks an optimal solution [3].

The problem that needs to be solved in this study is an NP-Complete problem that has no defined single optimal solution and therefore we will rely on a heuristic method to find an approximation to the solution. This case study seeks to solve a complex problem of electrification at minimal cost, and reduce losses in electrical circuits in rural areas. The problem has a set of rural developments, in which...
their location is known and will be electrified from known transmission points. The objective is to trace the exact location of the transformation centers in the transmission Grid and its connection with the subtransmission Grid, transformation centers of subtransmission to distribution. All these centers are connected by an optimal route for optimal Grid deployment, considering further losses therein. The system locates the general connection of the entire circuit with one of the candidate points of the transmission grid. Among the restrictions are the following: the grid topology, the ability to locate transformers, location, and losses; finally electrifying the proposed rural areas. The algorithm design allows for a general electrical circuit comprising of transformation centers, and the deployment of transmission and distribution grids, with a location and routing that meets the minimum investment cost and losses in the electricity grid [4], [5].

2. State of the art: Electrification of rural areas

The figure 1 shows the electrification problem raised in the case study, where a group of rural developments with their location will be electrified from an existing transmission point. The goal is to locate a multi-criteria analysis that includes loss and costs, an exact location of the transformation centers, the optimal deployment of the transmission network, its connection with the subtransmission network, and transformation centers of subtransmission to distribution.

![Figure 1. Electric grid for Rural Electrification.](image)

This is due to the dispersal of loads, low expected consumption, lack of road infrastructure and accessibility, topography and environmental setting with many limitations and complications to deploy an air grid, distant electrified points either by transmission or distribution, or inaccessibility to their villages, among many other causes that may arise in the individual analysis of each issue of electrification. For these reasons, it is of vital importance the development of an optimal technical-economic strategy in order to carry out the electrification in rural areas [6], [5].

Most electrification projects of rural areas are based on a design in regards to an economic scope or coverage. Based from this preliminary analysis the design of routing grids and location of processing centers is carried out in compliance with the minimum quality requirements and energy efficiency [7]. Achieving the electrification of these areas at minimal cost is an optimization problem NP Complete the due to the amount of restrictions mainly related to accessibility for the construction of Grids [8]. The best and only solution, is quite difficult to find due to the designs that are based on the experience of the professionals involved, hence, the analysis is done by creating scenarios and comparing them to each other without exploring other possible solutions, leaving the design without a mathematical analysis of feasibility and with more search space [9], [10].
3. Problem Formulation

The biggest problems in electrification are posed in rural areas but with much less impact in urban peripheries. The electrification of rural areas in many countries has reduced levels of coverage and low service quality [10]. Substations must be placed in any cell, including the same cell with an existing neighborhood. The cost of wiring is 1M pesos per km. Distances are measured using a straight line between the cells, which are each 1km apart. For example, the distance between cell A1 and B2 is 1.42 km, losses in distribution circuits is considered one of the biggest problems that electric companies face that should be another important part of the analysis.

Whereas the active power losses are given by [4]:

\[ \Delta P = \sum_{i=1}^{n} I_i^2 \cdot R_i \]  

where: \( n \) is the number of nodes in the system; \( I_i \) corresponds to the value of the current at node \( I \); and \( R_i \) resistance is seen in the same node

3.1. Description of Heuristics

The heuristic model for optimal deployment of a new electric grid that electrifies rural neighborhoods considers cost variables associated with necessary material resources, load capacity and losses. The model is based on a set of algorithms that seek an optimal solution that meet the need for electrification of the grid under the criteria of loss reduction, efficiency, and profitability.

In order to define a first instance of the solution, the k-means algorithm is used, in which the clustering of the sites are defined as houses or neighborhoods. This grouping is based on the basis of Euclidean distances and number of centroids (clusters) proposed that are also defined, based on the allowable capacity that will be projected from transformers in order to assume the charge required to electrify. Once the centroids are defined for neighborhoods with the above characteristics, it is necessary to move them to an appropriate location in an exact coordinate defined by the candidate sites, which must comply with the restriction of not having a home or neighborhood in that location.

This movement is performed through a smart search in candidate sites closest to the centroid point making a comparison between the distances from the centroid to the sites. Once a first approximation of the location of the centroid is defined, as it would be the position of the substation of subtransmission to distribution, a comparison of distances of these centroids is done against the termination sites of the transmission grid that are the candidates to carry out the connection. In this case, those sites are defined with the coordinates of each corner of the map.

By comparing the measurements obtained, the k-means algorithm is again used to select a new centroid between the connection point and the above defined centroids. The new centroid is the transformer transmission to subtransmission which delimits routing grids as which will allow the addition of various functions of cost electric conductor used in transmission, subtransmission and distribution. The position of this centroid is relocated to a candidate site under the same criteria taken for subtransmission substations to distribution. With locations obtained for each transformer, a ratio cost is established between conductors of each voltage level and proceeds to calculate total cost which depends on the amount and type of transformer located based on their capacity and distance and type of electric conductor used to establish the complete connection.

The routing for the deployment of the total grid is achieved using Dijkstra's algorithm which explores all routes declared as feasible in selecting the best weight criteria which are defined by cost and distance. The process consists of finding the optimal solution by making a smart shift of the positions
assigned by minimizing candidates with relocation within the feasible path described by Dijkstra as shorter to deploy an air grid at different voltage levels. Later, a recalculation of the objective function cost and loss is achieved, keeping only the solution that meets the criterion of lowest total cost. Thus the optimal route and location of the processing centers is obtained in order to meet the criteria for the electrification in rural areas.

| Nomenclature | Variables |
|--------------|-----------|
| $C$          | Rural Houses |
| $S$          | Sites |
| $P$          | Transmission |
| $l_i$        | Current in the node $i$ |
| $R_i$        | Resistance in the node $i$ |
| $\text{cap}$ | Capacity \text{Substation} |
| $\text{CostXuC}$ | Cost for a unit distribution cable |
| $\text{CostXuS}$ | Cost for a unit transmission cable |
| $\text{CostoT}_i$ | Total cost |
| $\text{CostoO}$ | Optimal Total Cost |
| $\text{Subest}$ | Optimal location |
| $\text{PuntSal}$ | Substation |
| $\text{slnap}_i$ | Optimal placement of Transformers |
| $\text{Pcand}$ | Candidate sites |
| $\text{Transf}$ | Electric transformers |
| $\Delta p$   | Losses |

**Table 1.** Shows the notation of the variables used in the algorithm in order to achieve a better understanding of it.

**Algorithm 1.** Function $\text{CostoMinDist}$

Step 1 Input: $C(x, y); M; (P)$

Step 2 Output: $\text{Transf}; \text{Subest}; \text{PuntSal}; \text{CostoO}$

Step 3 Initialize: $\text{CostoINF}; \text{CostoTINF}$

Step 4 $\text{CostoOP} = \text{distPuntSal} \times \text{CostoXuS};$

Step 5 $\text{for } k \in \{1, \ldots, \text{Subest}\}$

Step 8 $\text{for } i \in \{1, \ldots, |x|\}$

$\text{Actualizar (cola, } < j, \text{ dist}[j] >)$
\( V = S \cup MSP \cup Subest; \)

**Algorithm 2.** Optimal deployment of the grid

\[
V = S \cup MSP \cup Subest; \\
\text{Step 6 for all } i \in \{1, \ldots, |V|\} \\
\begin{align*}
\text{dis}[i] &= \infty; \quad \text{padre}[i] = \text{null}; \\
\text{add} (\text{cola} < i, \text{dis}[i] >) &; \quad \text{dis}[s] = 0; \\
\text{while } \text{cola} \neq 0 \\
\quad i &= \text{cola} \cap \min (\text{cola}) \\
\quad \text{for } j \text{ adjacent } \text{ a } i \\
\quad \quad \text{if } (j \in \text{cola}) \text{ and } (\text{dis}[j] > \text{peso}(i, j)) \\
\quad \quad \quad \text{padre}[j] = i; \quad \text{dis}[j] = \text{peso}(i, j); \\
\end{align*}
\]

**Algorithm 2 (Cont).** Optimal deployment of the grid

\[
\text{end if} \\
\text{if } sTransf \neq \text{Sub} \\
\quad \text{col}a_k (\text{col}a_k == \text{transf}_k) = [ ]; \\
\quad \text{Transf}_k = \text{tr}ay2ordk (., b + 1); \\
\quad \text{dis}k = \text{dis}k - 1; \\
\text{end if} \\
\text{end for} \\
\text{Step 9 Return} : \text{CostoOP } ; \text{ Transf } ; \text{Subest} ; \text{PuntSal} ; \Delta P
\]

The proposed algorithm describes a heuristic based on an intelligent search of feasible solutions, in which this case are defined candidate sites and that meet the characteristics for the location of a transformer center or a trace of the air line of either distribution or transmission. The algorithm also calls for other algorithms for calculating distances and location of reference clusters.

**4. Case studies and results analysis**

**Figure 2.** Optimal deployment of six transformers, substation and transmission. Rural areas with equal residential loads were considered, with average current values of \( I \) equal to 3.62 A, gauge power cables 2 P/u and distribution 1/u, for 40 houses located randomly between 900 sites that define the territory, and a capacity constraint that selects only 6 transformers for power supply. The cost between the distribution grid and transmission grid is 0.5/u to 1/u.

**Figure 3.** Comparison of cost metrics for different scenarios. The optimization model was evaluated under three different simulated scenarios, in which metrics are obtained and define cost function and loss for each one, as shown in figure.

The scenarios are described for different capacity allocations that define the amount of subtransmission transformers located at distribution, different cost ratios between electric conductor that describe the distribution and transmission, and losses in distribution circuits. It is necessary to point out that for each case study, the rural residential areas are considered with equal loads, with the average current \( I \) is 3.62A, gauge of transmission cables 2 P/u and distribution 1/u. By changing the amount of selected transformers in distribution according to the defined capacity, different costs are acquired that would be dependent on the nominal power to meet demands. The heuristic algorithm described in Matlab generates Figure 2 and figure 3, which shows the path of optimal deployment for
grids and optimal location of the transformation centers for this scenario. Centers and high capacity lines show the results obtained from k-means.

5. Conclusions and future works

This strategy is justified by ‘sacrificing’ the accuracy of the solution by seeking lower computational costs of data processing and reducing the mathematical effort, under the criterion that, it is not always convenient to describe a problem with all its information assuming a high computational time. By establishing a trade-off between accuracy and effort, the uncertainty is managed more efficiently and vigorously.

For future developments concerning this study, in addition to the orientation and development of the algorithm towards urban or underground electrification, other algorithms and heuristic optimization would be developed in order to calculate costs for Microgrid designs with Distributed Generation. This algorithm would help implement a decision between electrification with the national system, implementing a network with only micro distributed generation, or determine the level of penetration of clean energy to the distribution system of the national network in certain areas.

In future studies, a georeferenced algorithm may be used that recognizes images by sectors that allow the identification and location of candidate sites.

6. References

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