2017 European Conference on Electrical Engineering and Computer Science

Electric Power Distribution Planning Tool Based on Geographic Information Systems and Evolutionary Algorithms

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***Abstract*— The expansion of electric distribution networks in new geographic areas is a tedious task. Once the position of the low voltage power substations has been decided, the planning engineers need to select the routes for the new power lines ensuring more efficient connections among the substations. This paper presents the methodology followed to plan the set of overhead power lines which achieves the optimal distribution network with the minimum installation and maintenance costs. The methodology is based on the use of Geographic Information Systems, which provide the needed functions to find feasible and economic routes for the new overhead power lines linking the substations, and an evolutionary algorithm which selects the optimal links. The application of the proposed methodology allows finding the optimal solution under an economic perspective in an automatic manner.**

Keywords*— *geographic information systems, power distribution planning, evolutionary algorithm, routing.

I. INTRODUCTION

Many times electric power distribution networks require to be expanded in order to feed customers' needs. Electric power distribution planners, analyzing the existing network, the spatial load forecasts, and technical, geographical and economic factors, decide about the construction, replacement o reinforcement of a new element in the network.

Optimal planning of distribution networks is a complex task due to the large number of possible solutions. Several models and optimization methods have been used to solve these problems [1] [2]. The technique of evolutionary algorithms has given good results for greenfield in planning problem of power distribution networks [3].

In the planning of distribution networks a very important task is the selection of routes for the new electric power lines, since the cost of construction of these lines is a very influential aspect in the global cost of the final solution. Traditionally in planning problems, these "optimal" routes are selected among some possible ones and only some works take into account the geographic information of the study area [4].

The use of Geographic Information Systems to solve problems of optimal routes produces good solutions [5]. This is due to the fact that the geographic characteristics can be modeled with spatial structures and used to solve these problems [6].

In this paper a new methodology, combining a meta-heuristic optimization technique with Geographic Information Systems (GIS), is described. The methodology allows studying all possible links between substations, for a new electric distribution system, with the only condition that the final solution has a radial configuration. The optimization is based on economic criteria but the presented methodology would allow us to include, with a few modifications, other criteria for the selection the optimal routes in the planning solution.

The paper is structured as follows: in section II the new methodology is described; sections III presents a case study with the results obtained using the proposed methodology; finally, the conclusions are presented in section IV.

II. METHODOLOGY

A. Planning model

Our goal in the planning problem is to obtain the optimal expansion of an electric power distribution network.

The problem of the optimal power distribution network expansion can be stated as:

$$min\,[F(x, y)] \tag{1}$$

subject to $(x, y) \in X = \{(x, y) \mid gc\,(x, y)\ \{\geq,=,\leq\}\ 0, gc \in C\}$, where $F(x, y)$ is the objective function, $gc\,(x, y)$ are the technical constraints and C is the set of constraints.

In this case, the objective function, $F(x, y)$ is an economic cost function. This function includes fixed and variables

978-1-5386-2085-4/17 $31.00 © 2017 IEEE
DOI 10.1109/EECS.2017.79

costs of the future electric power lines and power substations. It can be stated as:

$$\begin{aligned}&\sum_{i\in S_s}(FC_{is})_z+\sum_{(i,j)\in S_l}\sum_{N\in N_n}(FC_{i,j})_N(D_{i,j})_N+\\&+(VC)\sum_{(i,j)\in S_l}\sum_{N\in N_n}(3R_{i,j})_N(I_{i,j})^2(D_{i,j})_N\end{aligned}\tag{2}$$

Where:

$(FC_{is})_z$ are the investment cost associated with a future power substation in node i with a power size z. These costs depend on the number of electric power lines connected to the power substation;

$(FC_{i,j})_N$ are the investment cost associated with a future power line linking nodes i and j with conductor size N;

$(D_{i,j})_N$ is equal to 1 if a power line with conductor size N is built linking nodes i and j, otherwise this variable is equal to 0;

S_l is the set of proposed routes, linking nodes, where to build future power lines;

S_s is set of network nodes associated with future substations;

N_n is the set of different sizes for conductors of the power lines;

VC is the variable cost constant, corresponding to the cost of losing one energy unit;

$I_{i,j}$ current, in A, through a power line linking the nodes i and j;

$(R_{i,j})_N$ is the phase resistance of the power line linking node i and j with a conductor size N.

As mentioned above, the objective function is minimized subject to the following technical constraints:

- All substations must be connected to each other, and the planning solution must be associated with a radial operating state.
- The power capacity limits of the power lines must be met, as expressed in (3),

  $$(I_{i,j})\leq(I_{i,j,\max})_N \qquad \forall i,j \tag{3}$$

  where $(I_{i,j,\max})_N$ corresponds to the current capacity associated with the route linking nudes i, j for power line with conductor size N.
- The voltage drop in the distribution network must be under a limit.

The investment cost associated with a future electrical power line between nodes i and j with a feeder size N, $(FC_{i,j})_N$, is calculated taking into account the geographical characteristics of the studied area as it will be explained in the following subsection. This cost corresponds to the minimum investment cost associated with the electrical power line that links nodes i and j (two power substations).

B. *Optimal route selection*

This subsection presents the methodology followed to select the optimal route for a new high voltage overhead power line, which links two power substations.

The solution is based on the use of a (GIS), which provides the proper data structures and tools for selecting the optimal route in geographic areas without any previous facilities.

GIS manipulates geographic data basically with two types of structures: vector and raster data.

Vector data are used in network problems based on lines, edges and nodes, although actual terrain information (height, soil type, land use, obstacles, etc.) is not directly associated with lines or nodes. That information related to terrain is more easily represented by small areas, which are denoted as elementary cells, what constitutes the raster data structure.

Raster data structure divides the geographic zone under study into a regular grid of square cells with the desired resolution according to the nature of the problem to solve. Each cell is georeferenced and can contain the value of a variable of interest associated to its geographic coordinates. With raster data structure, the spatial analysis is based on matrix operations, where each element in the matrix corresponds to the value of the variable stored in a cell.

In our analysis, each GIS raster cell contains the cost associated to cross the geographic area represented by that cell with an overhead power line with the characteristics defined in the problem. This cost corresponds to the aggregation of different cost components associated to the features of the area represented by such cell.

Basically we can differentiate two types of costs: geographic cost and nongeographic cost.

The nongeographic cost is independent of the position of the cell, for example, the cost (per km.) of the conductor selected for the power line.

The geographic cost, dependent of the geographic position of the cell, can be described as:

1) Access cost: it depends on the equipment transportation, installation, and maintenance. This cost can be different for each cell (for the geographic area represented by each cell). It depends on the geographic position and it can be calculated using the distance to existing roads.

2) Local terrain characteristics cost: additional cost related to the soil type, vegetation coverage, land use or cost associated to the reduction of environmental impacts. The local characteristics of the area represented by the cell can increase the cost in aspects as the need of reinforcement in the foundation of the towers, vegetation pruning, etc.

3) Elevation cost: cost associated with altitude, which increases the probability of ice, lighting and strong winds, what imply higher cost in the equipment (surge arresters, reinforced towers, etc.).

4) Obstacles cost: Crossing some infrastructures or natural elements as roads, railways, rivers, power lines, etc., involves additional cost.

Finally, the aggregation of all different cost components in each cell allows us to obtain a map (a raster file), where each cell contains the value of cost per km for a new high voltage overhead power line (HVOPL) which crosses the geographical area represented by such cell. This map is called as the terrain cross cost map (*TCCM*). Fig. 1. represents this calculation process.

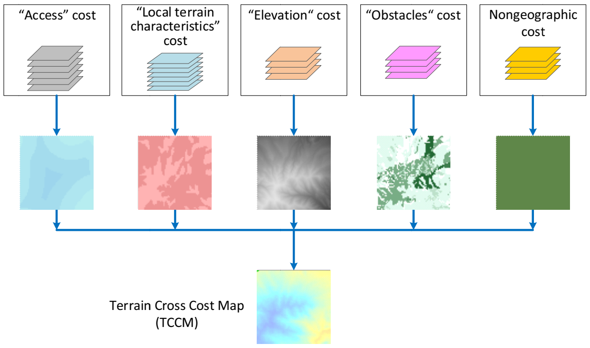

Fig. 1. Terrain Cross Cost Map calculation process.

The *TCCM* will be used to obtain the optimal economic path for the new HVOPL which links two nodes (origin and destination). The calculation process (Fig. 2.) is based on the application of the tools "Cost Distance", "Cost Back Link" and "Cost Path", implemented in the ArcMap 10.0 software of ESRI, on the *TCCM*. These functions calculate optimal routes in heterogeneous geographic spaces represented as grids or raster files.

The optimal path between two locations is the set of connected cells that links origin and destination with minimum aggregated transition cost. In our case, the elementary cost of transition between two neighbouring cells (p_k, p_{k-1}) are calculated by (4) if the link between p_k and p_{k-1} is in diagonal direction and by (5) if the link between p_k and p_{k-1} is in longitudinal or transverse directions. These costs of transition, CT_d and CT_l, depend on the resolution of the cells (r), on the value of cell p_k in the terrain cross cost map, $TCCM(p_k)$, and on the value of cell p_{k-1} in the terrain cross cost map, $TCCM(p_{k-1})$.

$$CT_d = \sqrt{2}\ r\,\frac{TCCM(p_k)+TCCM(p_{k-1})}{2} \tag{4}$$

$$CT_l = r\,\frac{TCCM(p_k)+TCCM(p_{k-1})}{2} \tag{5}$$

When the process has finished we obtain the optimal route, the length, and the minimum investment cost, $(FC_{i,j})_N$, for an HVOPL that links two nodes (origin and destination).

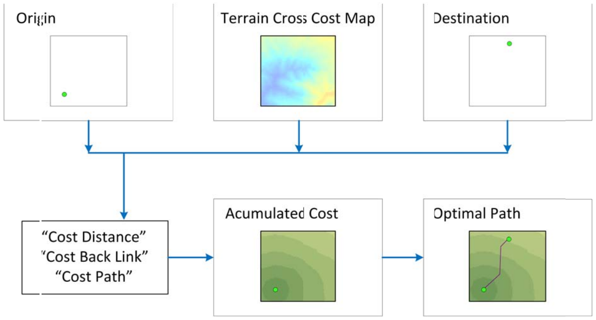

Fig. 2. Optimal path calculation process.

C. Distribution network optimization

In order to optimize the solution, an evolutionary algorithm is used. In this sense, we will work with a set of feasible solutions (population), instead of one only solution. Each feasible solution, i.e., each configuration of the distribution network, is coded into a string containing the links and the conductors linking the nodes (power substations) of the network. There is not any specific ordination for the links into the string, and all the elements are represented by integer numbers with two digits (the number of the nodes or power substations, and the number corresponding to the selected conductor size). The structure of the string is the represented in Fig. 3.

For example, a link coded as 05-09-03 corresponds to a power line connecting nodes (or substations) 5 and 9 with a conductor size 3. The total number of nodes (or power substation to connect) is *n*, so the number of links needed to obtain a radial distribution network is *n*-1.

An evolutionary algorithm is used to optimize the distribution radial network. This algorithm is based on the following steps:

1) An initial population of feasible solutions is built in a random way. Prüfer sequences [7] are used to obtain radial configurations. The size of the conductors in each link are also randomly selected.

2) Each individual in the population is evaluated: the cost associated to the solution represented by each individual is computed using (2). The individuals are ranked according this cost in an ascending order, i.e., the best individual in the population is that one with the lowest cost.

3) Genetic operators (elitism, selection, crossover and mutation) are applied to the existing population achieving a new population.

4) Steps *2* and *3* are repeated a fixed number of iterations (generations).

The crossover operator interchanges links between two selected individuals (parents) in order to achieve an offspring (an individual for the next generation). The process of crossover is structured in three steps:

1) Two individuals (parents) are selected randomly using the roulette wheel selection operator. The selection ensures that individuals who represent better solutions have more probability to be selected.

2) All the links common for both parents are included in the offspring.

3) The offspring is completed with links of both parents (not common to both of them) randomly selected, but always preserving the radiality of the solution represented by the offspring.

Fig. 4. represents an example of the crossover implemented in the evolutionary algorithm.

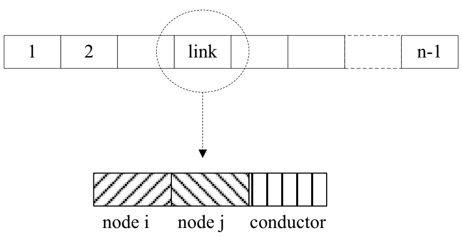

Fig. 3. Structure of the coded string.

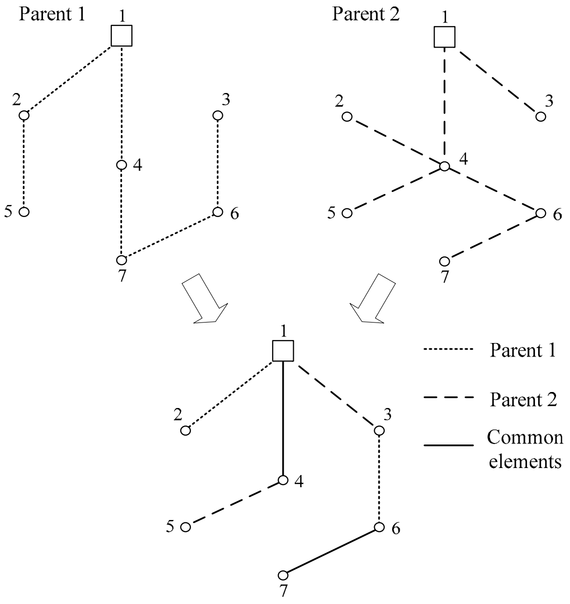

Fig. 4. Crossover operator.

The mutation operator is applied to an individual randomly selected from the population. The mutation operator erases one of the links of the selected individual and replaces it for another one selected randomly from the possible connections, that is, from the set of new links that maintains the radiality condition connecting all the nodes.

The conductor size is randomly selected form the set of available sizes. Fig. 5 represents an example of the application of the mutation operator implemented in the algorithm.

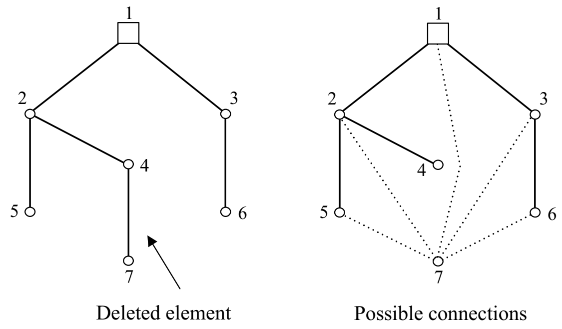

Fig. 5. Mutation operator.

When the evolutionary algorithm has finished the best individual in the population (network configuration with lowest cost according (2)) corresponds to the optimal solution of the electric power distribution network.

III. CASE STUDY

We applied the proposed methodology to the planning of a new electric power distribution network (13.2 kV) in La Rioja (Spain). This electric power distribution network starts from a power substation of 66/13.2 kV and is composed of eight new low voltage power substations (13.2/0.4 kV) with defined positions. The capacity of the planned low voltage power substations is 630 kVA and all the links are planned with the conductor ACSR size 94-AL1/22-ST1A. Fig. 6 shows the positions selected for the new low voltage power substations, ST1 to ST8.

The area represented in Fig. 6. is around 225 km^2. Near the upper-left border, it is placed the 66/13.2 kV power substation (ST Arenz.). The background map in Fig. 6 corresponds to the terrain cross cost map (*TCCM*) for the conductor ACSR size 94-AL1/22-ST1A. The resolution, *r*, of this map is 100x100 meters. The values in the areas represented for each cell ranges 15000 to 30000 €/km. Notice that blue colored cells represent areas where the installation of a kilometer of a new overhead power line, with the selected conductor, is more expensive than in areas colored in orange and yellow colours.

Fig. 7 shows, as an example, the optimal routes which connect ST2 with all the substations. These optimal routes were obtained using the methodology proposed in subsection II.*B*.

Obviously, the routes represented in Fig. 7 are only an example, because our methodology calculates the optimal solution which links all the substations with the minimal installation and maintenance costs.

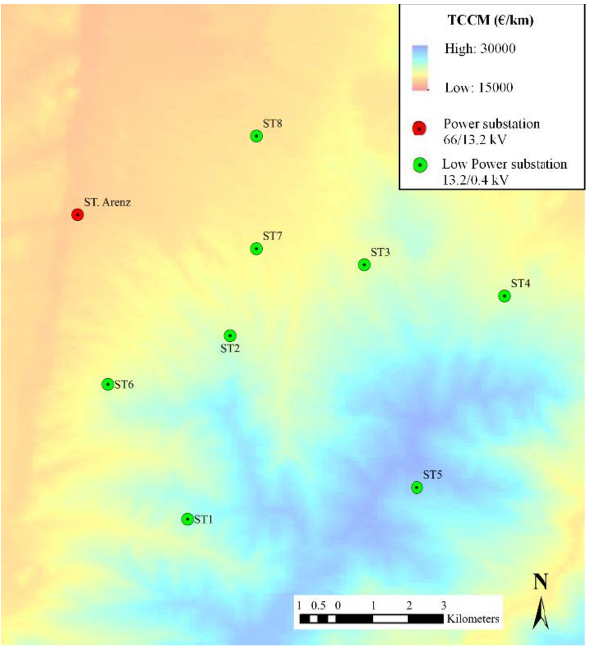

Fig. 6. Power Substations locations.

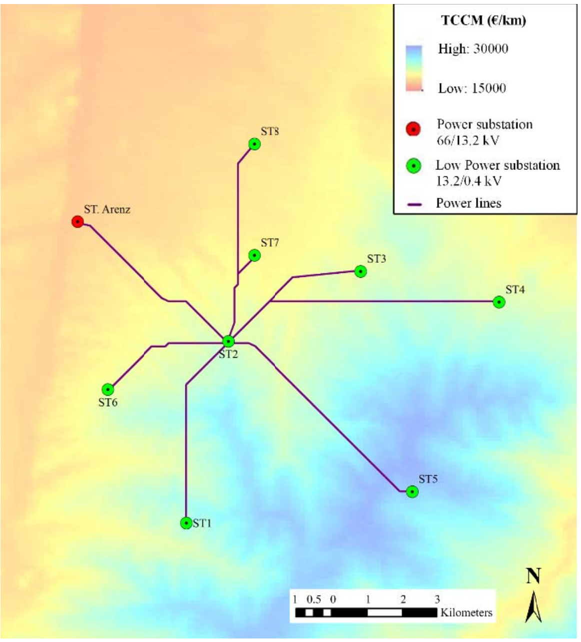

Fig. 7. Optimal routes from ST2 to each other power substations.

The lengths and costs of all the routes obtained following the proposed methodology are shown in Table I (lengths) and Table II (costs).

On the base of the information contained in Table I and Table II, we run the evolutionary algorithm described in subsection II.*C*. We used 200 generations with 100 individuals per generation. We used a 0.8 crossover rate and a 0.01 mutation rate.

Fig. 8 shows the evolutionary algorithm optimization progress. It shows the total cost of the best individual (lowest cost in the population) in each generation.

The optimal solution obtained is the represented in Fig. 9, which corresponds to a total cost of 777761 €.

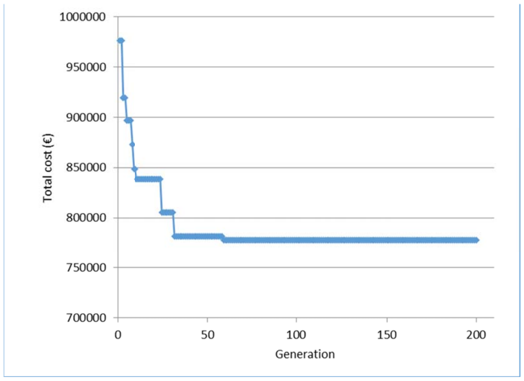

Fig.8. Evolutionary algorithm optimization progress.

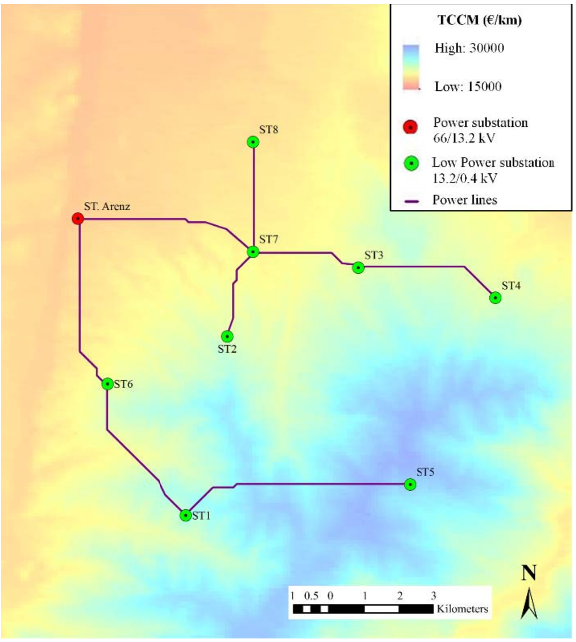

Fig. 9. Optimal planning solution.

TABLE I. LENGTH OF THE OPTIMAL ROUTES BETWEEN TWO SUBSTATIONS (METERS)

	STArenz.	ST1	ST2	ST3	ST4	ST5	ST6	ST7	ST8
STArenz.	0	10514	5645	8661	12970	12811	5181	5387	5982
ST1	10514	0	5647	9345	12170	6902	4646	8450	11778
ST2	5645	5647	0	4626	8326	7113	4030	2734	6008

ST3	8661	9345	4626	0	4323	6943	8800	3177	4887
ST4	12970	12170	8326	4323	0	6398	12933	7545	9172
ST5	12811	6902	7113	6943	6398	0	10195	8635	11881
ST6	5181	4646	4030	8800	12933	10195	0	5840	8931
ST7	5387	8450	2734	3177	7545	8635	5840	0	3250
ST8	5982	11778	6008	4887	9172	11881	8931	3250	0

TABLE II. TOTAL COSTS OF THE OPTIMAL ROUTES BETWEEN TWO SUBSTATIONS (€)

	STArenz.	**ST1**	**ST2**	**ST3**	**ST4**	**ST5**	**ST6**	**ST7**	**ST8**
STArenz.	0	179896	98747	138571	232264	285366	77668	81364	82941
ST1	179896	0	137570	220927	300985	216218	104230	187253	232090
ST2	98747	137570	0	93755	184033	195286	82368	53233	103528
ST3	138571	220927	93755	0	94512	204462	166683	59929	85099
ST4	232264	300985	184033	94512	0	195701	259580	153749	173197
ST5	285366	216218	195286	204462	195701	0	267974	219953	271825
ST6	77668	104230	82368	166683	259580	267974	0	110557	140519
ST7	81364	187253	53233	59929	153749	219953	110557	0	52403
ST8	82941	232090	103528	85099	173197	271825	140519	52403	0

IV. CONCLUSIONS

The expansion of electric power distribution networks is a tedious task, even in virgin areas. The position of low voltage power substation is selected according to urban, social or economic criteria, and the power line routes linking these substations must be chosen after evaluating multiple possible solutions.

This paper presents an original methodology, based on the use of Geographic Information Systems and an evolutionary algorithm, followed to plan the optimal distribution network with the minimum cost selecting the set of overhead power lines routes linking all the substations and satisfying all the technical restriction.

The Geographic Information System is used to select the routes between every two pair of substation, while the evolutionary algorithm selects the routes included in the optimal solution. The application of the proposed methodology allows us to find the optimal solution under an economic perspective in an automatic manner. In summary, this paper presents a useful tool for the planning of distribution networks considering economic and geographic criteria.

ACKNOWLEDGMENT

The authors would like to thank the ''Ministerio de Economia y Competitividad'' of the Spanish Goverment for supporting this research under the project ENE2013-48517-C2-2-R and the ERDF funds of the European Union.

REFERENCES

[1] P. S. Georgilakis and N. D. Hatziargyriou, “A review of power distribution planning in the modern power systems era: Models, methods and future research,” *Electr. Power Syst. Res.*, vol. 121, pp. 89–100, Apr. 2015.

[2] M. Sedghi, A. Ahmadian, and M. Aliakbar-Golkar, “Assessment of optimization algorithms capability in distribution network planning: Review, comparison and modification techniques,” *Renew. Sustain. Energy Rev.*, vol. 66, pp. 415–434, Dec. 2016.

[3] G. A. Jimenez-Estevez, L. S. Vargas, and R. Palma-Behnke, “An Evolutionary Approach for the Greenfield Planning Problem in Distribution Networks,” in *2007 International Joint Conference on Neural Networks*, 2007, pp. 1744–1749.

[4] J. Shu, L. Wu, Z. Li, M. Shahidehpour, L. Zhang, and B. Han, “A New Method for Spatial Power Network Planning in Complicated Environments,” *IEEE Trans. Power Syst.*, vol. 27, no. 1, pp. 381–389, Feb. 2012.

[5] C. Monteiro, I. J. Ramirez-Rosado, V. Miranda, P. J. Zorzano-Santamaria, E. Garcia-Garrido, and L. A. Fernandez-Jimenez, “GIS Spatial Analysis Applied to Electric Line Routing Optimization,” *IEEE Trans. Power Deliv.*, vol. 20, no. 2, pp. 934–942, Apr. 2005.

[6] W. Jewell, T. Grossardt, K. Bailey, and R. S. Gill, “A New Method for Public Involvement in Electric Transmission-Line Routing,” *IEEE Trans. Power Deliv.*, vol. 24, no. 4, pp. 2240–2247, Oct. 2009.

[7] Prüfer, H. (1918). «Neuer Beweis eines Satzes über Permutationen». Arch. Math. Phys. 27: 742-744.