OPTIMAL PLANNING OF URBAN DISTRIBUTION NETWORK CONSIDERING ITS TOPOLOGY

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ABSTRACT

The current paper deals with the optimal planning for the expansion of urban distribution network. It aims to minimize the necessary workings taking into account the infrastructures of the existing network. In urban areas it depends a lot on the topology of the streets. This paper proposes a methodology that takes into account the topology of the streets as well as the existing networks. Their modeling is made by the use of tools from the graph theory like Dijsktra and the resolution of the Traveling Salesman Problem (TSP). The routing of the power lines among the streets is calculated by an adapted simulated annealing. Then the minimization of the workings for the expansion plan is made by a methodology that attributes corrective coefficients to the costs of the streets. The procedure is experimented on a part of the distribution network of the city of Grenoble in France. The loads of a 5.5 kV networks have to be connected to a neighboring 20 kV network in order to harmonize the voltage levels.

INTRODUCTION

The subject broached is the construction of the long-term target taking into account the existing network. The applications can be the connection of substations from new buildings or districts, the necessity to burry overhead cables for improving the reliability, or the modification of the voltage level for example. The construction of the new target has to minimize the investment costs and on-going expenditures of the network while respecting a set of economical, technical, environmental and sociological constraints. Ours studies focus on the topology of urban areas that strongly influences the decisions of planning. In urban areas the topology is mainly constituted by the streets that impose the path of the power lines and also the number of cables allowed in each street. Taking into account the streets during planning allows considering the real length of the lines which has a strong impact on the investment costs. This also has a slightly impact on technical losses and energy not served. This also allows knowing exactly the number of conductors in each trench which will influence their cost. The topology can be modeled by cells map with the process of rasterization, as in [1] and [2] that solve the problem of feeders routing respectively by using a MILP model or the dynamic programming. These methods allow to model finely the reality but are more adapted to rural areas and overhead conductors, and are applied on transmission networks. In [3] a dynamic programming method is described in order to build a radial topology considering the environment. [4] suggests heuristics based on simple mathematics to allocate the substations and the feeders of a distribution network. Nevertheless [3] and [4] are not adapted for secured feeder architecture.

The current paper focuses on urban areas and models the vector map into a graph. The topology of the street is taken into account by compiling the coordinates of the streets and the loads into a unique none-oriented graph. The Dijkstra algorithm is performed on this graph. It provides the paths between each load and their associated costs. This methodology is described in Section I. Routing of power line is performed by resolving the corresponding TSP. The algorithm proposed to build the architecture is a meta-heuristic based on simulated annealing presented in Section II. As burying a conductor has not the same price regarding the type of street, coefficients can be attributed to each street in order to be closest to real costs. Furthermore, those coefficients can be used to represent the existing network. By decreasing the cost of the street already used by existing power lines, the new architecture will be incited to reuse the existing lines. Thanks to an adapted methodology presented in Section II, the optimal coefficient is found in order to minimize the length of the new lines, and maximize the length of the unchanged lines. In Section III, the methodology is used on a part of the distribution network of Grenoble wherein some loads have to be transferred from 5.5 kV to 20 kV. A conclusion is drawn in Section IV.

I. CONSIDERATION OF THE TOPOLOGY

The topology of the area consists of the geographic location of the electric elements and the configuration of the streets. The electric elements are the loads (MV/LV substations or MV customers), and the HV/MV substations. Each element is attributed to a geographic point. Streets are represented by several segments, depending on the number of times each street is crossed by other streets, and their shape. Thus a straight street is represented by one segment whereas a curved street is represented by several segments depending on the geometric precision. Each electric element is connected to the closest street by an orthographic projection. This connection creates an additional street and splits the connection segment into two new segments.

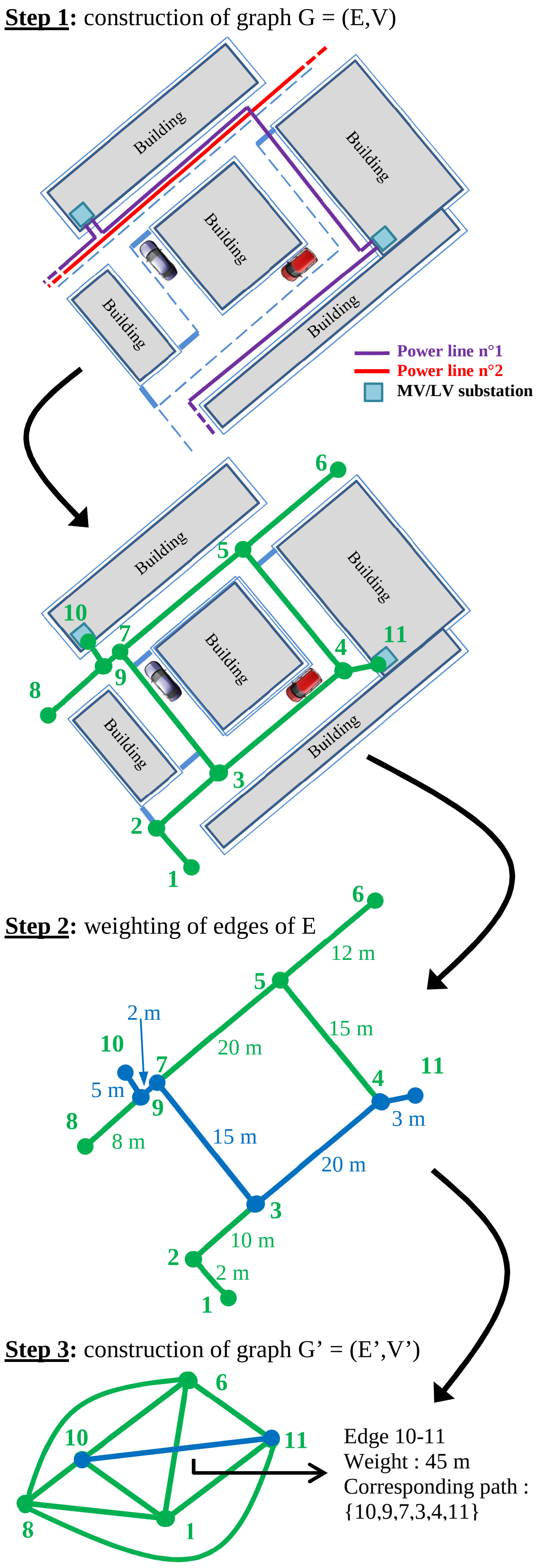

Figure 1: Steps for integrating topologic data

Mathematically the topology of the area is represented by a none-oriented graph $G = (V, E)$ where E is the set of edges of the vertexes of the set V. V is the set of geographic vertexes that represent the streets, the loads, the HV/MV substations, and the points that connect load and HV/MV substations to the streets. The set of edges E represents the segments of the streets and the connections between the streets and the element of the network. Each edge of E is weighted by the geographic distance between the two corresponding vertexes. This information allows the calculation of the paths for power lines according to the shortest distance. The geographic distance is representative of the future cost if all the streets have the same investment cost. As it is not the case for real studies, the weight of each edge can be modified by a corrective coefficient that represents that fact that a street is more or less expensive. It can be due to the nature of the street (concrete, cobblestones …), to the importance of the traffic that has to be interrupted, or to the opportunities for workings thanks to other interventions (water, gas, communication networks). The graph G is reduced to a new graph $G' = (V', E')$. The aim is to reduce the computation time during the building of the architecture. This new graph contains only the set of all loads and HV/MV substations V'. G' is a complete graph which means that E' is the set of all possible edges between the vertexes of V'. The length of each edge of E' is the real distance between the two corresponding vertexes considering the streets. This distance is obtained by performing the Dijkstra algorithm [5] between each couple of vertexes of $V' \subset V$ in the graph $G = (V, E)$. The Dijkstra algorithm also provides the set of streets that are to be crossed to connect each couple of load with a minimal cost. It is highlighted in Fig.1 for the path between the vertexes 10 and 11 that represent two MV/LV substations.

II. APPLICATION FOR OPTIMAL NETWORK EXPANSION PLANNING

A. Routing of the architecture

The architecture used for the study is the secured feeder architecture. Each line can be represented by a couple of HV/MV substations and a set of loads. The architecture of the network is modeled with the vector X. Each element of X represents the affiliation of each load to the corresponding line.

$$X(i) = j \text{ if the load n°i belongs to the line n°j} \quad \forall i \in \{1 \dots N\}, \forall j \in \{1 \dots M\} \qquad (1)$$

N is the number of loads and M is the number of power lines. The elements of X corresponding to the load of the existing network are fixed whereas the elements corresponding to the new loads have to be determined. The arrangement of loads along each line is a TSP. The objective is to connect all the loads of each line with a minimal cost. The start and goal nodes of the TSP are the

HV/MV substations and the intermediary nodes are the loads of the line. The graph used to solve the TSP is the graph G' evaluated in the previous section. The resolution of the TSP is performed by the Christofides algorithm [6] which offers the rapidity of the approximation algorithms and guarantees the best known approximation equal to 1.5 of the optimum [7]. The construction of the architecture consists in determining the solution vector X. As the objective of the expansion planning is to reduce the cost of the workings, the objective chosen is the total length of conductors in the network. It is evaluated by solving each TSP corresponding to each power line.

X is determined with an adapted simulated annealing algorithm which is generally used to provide a good approximation of the global optimum of a problem with discrete variables and a large search space [8]. Fig. 2 describes the proceeding of the simulated annealing in the grid optimization problem. The principle of the simulated annealing is to define an initial temperature which will define the excitation state of our system. At each iteration, an elementary modification is performed: a load is moved from a power line to another one. The new length of the network is evaluated by solving the corresponding TSP. If the total length of the network decreases, the modification is accepted. Otherwise the modification is accepted according to the probability:

$$p = \exp(-\Delta L/T) \quad (2)$$

ΔL is the difference between the new and the former lengths of the network and T the current temperature. The modifications that increase the total length are be accepted more easily when the network is in an unstable state. At the beginning the network is in a unstable state and a lot of modifications are accepted. As the temperature decreases the number of accepted modifications decreases and the network starts to stabilize. This process allows a good exploration in the search space and a final solution near to the global optimum. When enough acceptances of modification are done – 12 times the number of loads according to literature [8] – the temperature is decreased according to a geometric law with a geometric factor α. The geometric factor α is inferior to 1 and is generally set to 0.9 [8]. The convergence of the algorithm is evaluated with the evolution of the sliding average value of the total length. The simulation ends when the gradient of the sliding average is close to zero. The initial temperature T_0 is evaluated in (3) according to literature [4]. N_0 elementary modifications are performed on the initial solution and $\langle\Delta L\rangle$ – which is the average value of ΔL after modification – is calculated. τ_0 is the initial rate of acceptance of modifications. In order to explore correctly the search space, a τ_0 equal of 50% and a N_0 equal of 100 are chosen, according to [8].

$$T_0 = -\langle\Delta L\rangle/\ln(\tau_0) \quad (3)$$

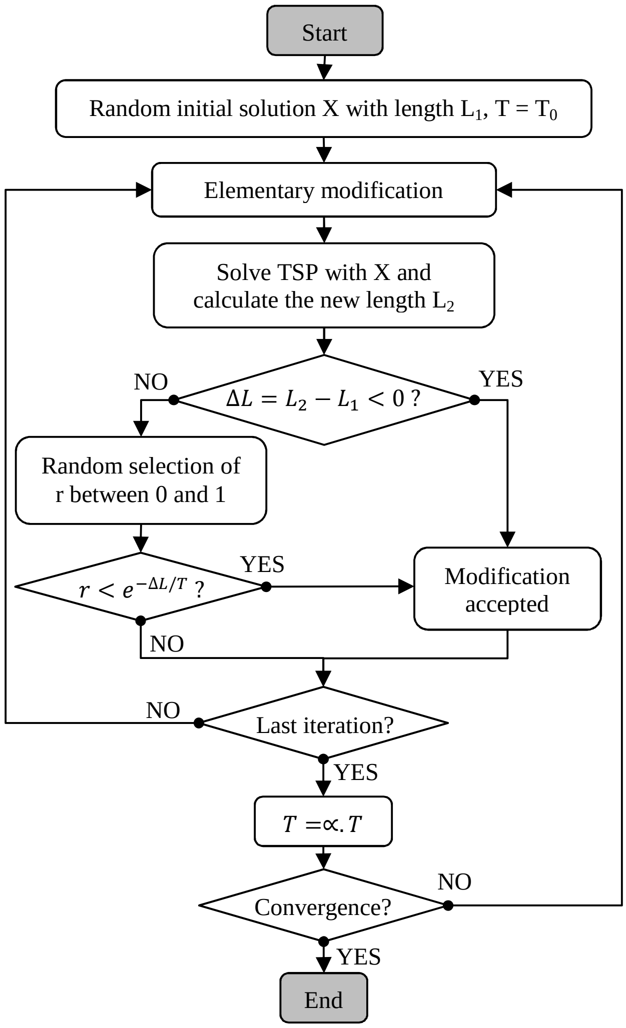

Figure 2 : Adapted simulated annealing

B. Minimization of workings

The objective is to determine the route of the power lines of the new architecture that minimizes the cost of workings. This is a compromise between a good reuse of the existing lines and a minimization of the new created lines. In order to incite the power lines to take into account the existing network, the streets that are already crossed by existing power lines are identified. Then in the graph $G = (V, E)$ described in Section I a corrective coefficient β is attributed to the segments of the corresponding streets. The choice of β is crucial. A β equal to 100% means that the existing network is not taken into account. It could lead to a network with a minimized total length but at the cost of an important yielding up of existing lines. A β equal to 0% means than the streets already used by the existing network do not cost anything. In this case the routing of the architecture could lead to incoherent choices with a very long and costly final network. Thus different values of β are studied in order to determine its optimal value. Furthermore, as the simulated annealing is an heuristic with random processes, several optimizations are performed for each value of β in order to take into account the variance of the results. The methodology is described in Fig. 3. At the end the best solution is kept for each tested value of β.

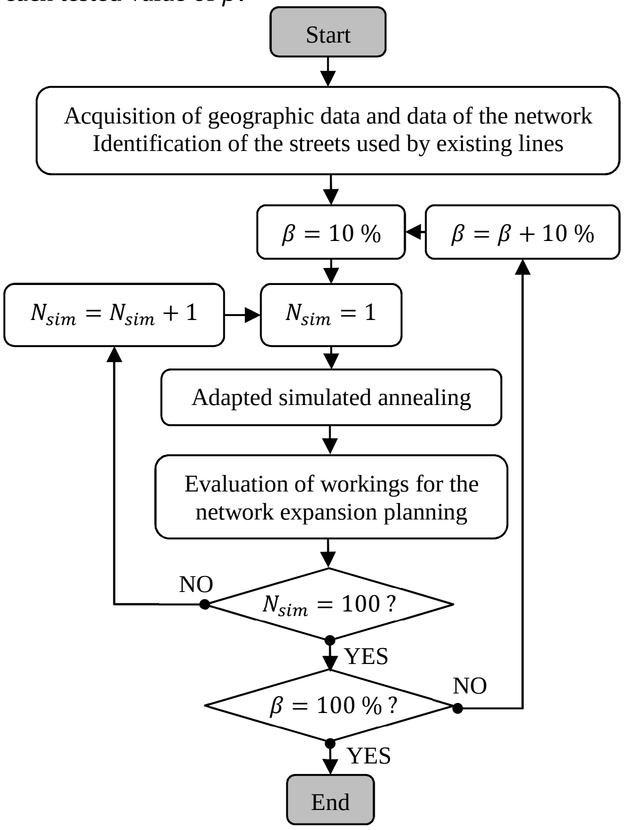

Figure 3 : Determination of the corrective coefficient

III. STUDY CASE

A. Description of the network

The study case is a French distribution network. It is located in the center of the city of Grenoble. The existing network has 136 loads connected by six 20 kV power lines with a secured feeder structure, represented in Fig. 4. Three HV/MV substations feed the area. The total consumption is equal to 61.19 MW. The total length of underground cables is equal to 37.16 km buried in 22.69 km of trenches. 46 loads that represent 5.69 MW are feed by a 5.5 kV network that has to be removed. These loads are represented on Fig. 5. They have to be connected to the 20 kV network with minimizing the costs of the workings. Several solutions are contemplated for the connection. It could be done at the low voltage level with connecting directly the end-customers to the existing 20 kV MV/LV substations with low voltage underground cables. Other solutions are to convert the 5.5 kV MV/LV substations to 20 kV MV/LV substations and then create new 20 kV power lines or connect them to the power lines of the existing network. This last solution is studied. In order to make the connection, the number of power lines and their configuration between the HV/MV substations remain the same, that is to say three lines between substation 1 and 3, two between substations 2 and 3 and one between substations 1 and 2. Furthermore, as the most loaded power line feeds 13.34 MW, this value is chosen as limit for the power lines of the new configuration. The solutions that do not respect this limit are eliminated. The streets of the area of the 5.5 and 20 kV networks are modeled by 480 geographic points connected by 772 segments of streets.

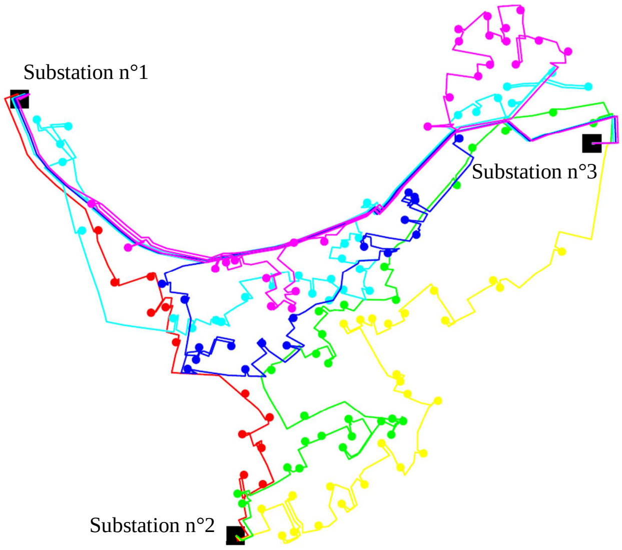

Figure 4: Existing network of the study case

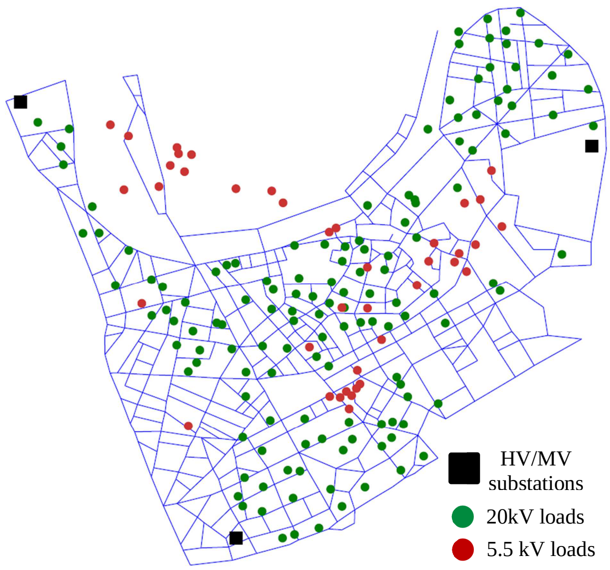

Figure 5: Loads and map of the study case

B. Simulation results

The methodology to find an optimal β is applied for the study case. Three types of workings are studied: the parts of the network that have to be created, removed or transferred. A section of a line that is transferred means that it is no longer used by a line and use by another one. Table 1. shows the results of the optimization.

	Created (km)		Removed (km)		Transferred (km)	
β (%)	Cables	Trenches	Cables	Trenches	Cables	Trenches
10	19.78	11.91	3.82	3.22	0.88	0.88
20	16.55	11.13	3.95	3.46	1.21	1.12
30	11.50	9.25	4.09	3.53	1.08	1.08
40	14.86	9.34	4.36	3.73	0.38	0.38
50	15.17	10.45	4.92	4.92	0.69	0.69
60	13.57	10.67	7.83	7.12	0.67	0.67
70	13.61	10.31	6.28	5.64	1.20	1.20
80	14.80	10.49	6.47	5.56	1.13	1.13
90	14.31	11.39	7.32	5.56	1.27	1.27
100	16.02	12.66	9.15	6.69	0.67	0.67

Table 1: Results of the optimization

In order to minimize the costs of the expansion, the chosen solution is the one that minimize the total length of underground cables. It corresponds to a value of β equal to 30%: 11.50 km of underground have to be buried in 4.09 km of trenches. It can be noticed that the total length of removed cables decreases progressively as β decreases. Logically it would be expected that the optimal solution would be a β equal to zero. But for β lower than 30%, the gain on removed cables becomes too low in comparison to the increased cost due to the created cables. From a β of 30% to a β of 10% the gain of removed cables is 0.27 km whereas the augmentation of created cables is 8.28 km. It can also be highlighted that the length of transferred cables does not depend on the value of β and thus does not take part in the decision. The conclusions are the same concerning the lengths of the trenches. Thus the final value of 30% for the β is kept. Fig. 3 shows the final expansion network planning corresponding to this value.

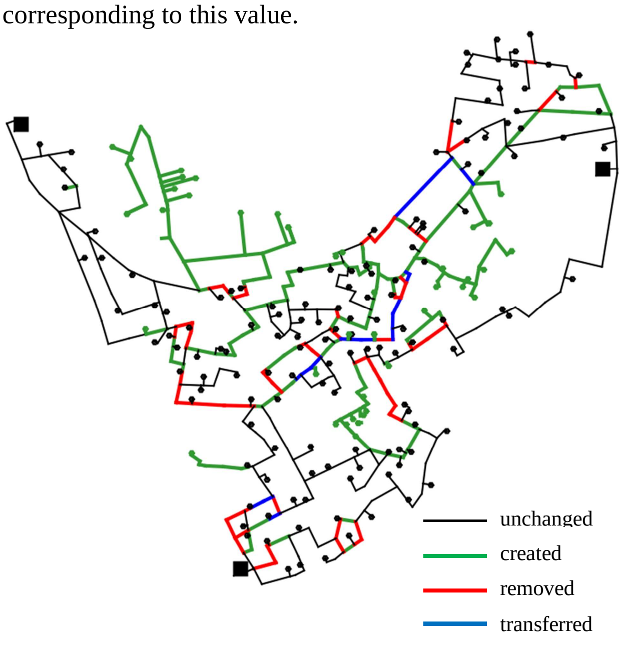

Figure 3: Result of the optimization of expansion planning

IV. CONCLUSION

A methodology has been developed that model the topology of the streets in urban areas thanks to classical tools from the graph theory. It is easily possible to change the costs of the streets in order to take into account the characteristics of the streets as well as the existing network. The adapted simulated annealing proposed minimizes the length of the power lines of the new network. By an adapted methodology that deals with the corrective coefficients attributed to the streets, the total lengths of created and removed cables are minimized. The next step of this methodology is to exploit the information of the number of underground cables per trench. It will allow evaluating precisely the costs of the workings according to the number of cables already present, cables that have to be buried or cables that have to be removed, for each trench. In order to be closer to reality the coefficients costs can also take into account the nature of the streets and the workings due to the other networks (communication, gas …).

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