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# Innovative planning method for the construction of electrical distribution network master plans

V. Gouin, *Student Member, IEEE*, M.-C. Alvarez-Herault, *Member, IEEE*, B. Raison, *Member, IEEE*

**Abstract**—This paper proposes a method to optimize the feeders routes for medium-voltage distribution grids. The study aims to provide a static model for the construction of master plans and can also be applied to expansion planning. The optimization of the network is performed by a three-stage methodology. The first stage minimizes the total length of the conductors with an adapted simulated annealing algorithm. The secured feeder architecture is directly modelled in the structure of the solution. The second stage performs the balancing of the loads between the feeders in order to respect the different technical constraints. The last stage is the allocation of remote-controlled switches according to the objectives of supply quality. The methodology is applied to a real distribution network of 136 nodes. The complexity of the example is significant because there are no preselected possible routes. Instead of that, all the connections are considered, taking into account the geographical topology of urban areas.

**Index Terms**—Distribution Networks, New Expansion Planning, Optimization, Simulated Annealing.

## NOMENCLATURE

### A. Indexes

$i$	Index of loads (MV/LV substations)
$j$	Index of branches
$k$	Index of areas between two switches
$m$	Index of power lines
$t$	Index of planning years
$w$	Index of feeders

### B. Sets

$\Omega^n$	Nodes of the network
$\Omega^b$	Branches of the network
$\Omega^a$	Areas of the network
$\Omega_j^{lf}$	Loads fed by the branch $j$
$\Omega_k^{la}$	Loads in the area $k$

$\Omega_k^{lf}$	Loads in the same feeder that supplies area $k$
$\Omega_k^{ba}$	Branches in the area $k$
$\Omega_m^{al}$	Areas of the power lines $m$
$\Omega_w^{af}$	Areas in the feeder $w$

### C. Variables

$l_j$	Length of branch $j$
$R_j$	Resistance of conductor of branch $j$ (ohms/km)
$I_j$	Current through branch $j$
$I_j^{max}$	Maximal admissible current through branch $j$
$V_i$	Voltage at load $i$
$n_{rcs}$	Number of remote-controlled switches
$P_{j,t}^{loss}$	Losses of branch $j$ in year $t$
$E_{k,t}^{eens}$	Expected energy not served in area $k$ in year $t$
$P_{k,t}^{epc}$	Expected power cut of area $k$ in year $t$
$SAIDI_k$	System Average Interruption Duration Index of area $k$ (minutes/year/customer)
$SAIFI_k$	System Average Interruption Frequency Index of area $k$ (failures/year/customer)

### D. Parameters

$N$	Number of loads
$N_i^{LV}$	Number of low-voltage customers for load $i$
$M$	Number of power lines
$U$	Nominal voltage level of the network (volts)
$\cos(\varphi)$	Power factor of loads
$P_i$	Maximal active demand of load $i$ (MW)
$P_i^{mean}$	Average active demand of load $i$ (MW)
$P_{max}$	Maximal authorized power per power line (MW)
$V_i^{min}$	Minimal admissible voltage at load $i$
$V_i^{max}$	Maximal admissible voltage at load $i$
$SAIDI^{max}$	Maximal admissible SAIDI
$SAIFI^{max}$	Maximal admissible SAIFI

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$d$	Discount rate (%)
$r$	Increasing rate of consumption (%)
$\tau$	Failure rate of the conductors (failures/km/year)
$T$	Lifetime of the project (years)
$T_{iso}$	Time to isolate a failure (hours)
$T_{fix}$	Time to fix a failure (hours)
$C_j^{cdt}$	Cost of conductor of branch $j$ (€/km)
$C_j^{trc}$	Cost of the trench of branch $j$ (€/km)
$C^{swd}$	Cost of remote-controlled switch (€/unit)
$C^{loss}$	Cost of losses (€/kW during the peak period)
$C^{eens}$	Cost of expected energy not served (€/kWh)
$C^{epc}$	Cost of expected power cut (€/kW)

## I. INTRODUCTION

The current paper broaches the problem of planning for medium-voltage distribution networks. According to [1]–[4], the objective of planning is to locate and size the substations that feed the end users and the feeders circuit that connect the substations to the transmission network and the protection devices. Three categories of planning are identified in [4]: new expansion as in [5]–[13], the growth of an existing system as in [14]–[26], or operational planning as in [27]–[29]. References [1] and [2] classify two models for planning: a static system in which the state of the network remains unchanged as in [5],[7]–[10],[12]–[19],[22],[23] or a dynamic system in which the state of the network evolves over the years as in [11],[20],[21],[24]–[26]. This paper deals with the new expansion planning and focuses on the routing of the feeders. Thus the location and electric characteristics of the substations are already determined thanks to a preliminary study. A static model is used based on the maximal consumption at the end of the study period, with the assumption that no new loads appear.

The distribution network planning is a mixed integer nonlinear programming problem. The objective is to minimize the total costs of the system, including the fixed costs of investments and the variable costs of losses, maintenance of equipment, and failures. The problem is subject to a large set of constraints: electric, topologic, environmental, aesthetic, social, and so on. Commonly they are the contingency of the devices, the voltage profiles, and the radiality of the structure. The solution vector consists of discrete variables that correspond to logical decisions and sets of elements like the types of conductors. This discrete nature combined with the non-linearity of some of the objectives and constraints, as well as the great number of elements in the networks, leads to problems that are difficult to solve with the traditional techniques of discrete and continuous analysis.

A first method for the problem of planning is the Branch-and-Bound technique as in [24] and [26]. It is a systematic estimation of each solution by exploring branches of the

solutions tree while adequately cutting some branches. However this technique remains difficult to apply for large-scale problems. Thus a consequent range of heuristic methods are studied. They make it possible to find a solution that is not the optimum but is a “good” solution for the user, within a correct computation time. The Branch Exchange technique was one of the first widely used, as in [8],[9],[13],[15],[20],[23],[25]. The principle is to start with a feasible configuration, add a route to form a loop, and remove a route in order to improve the network while always ensuring the constraints are met. This is repeated iteratively until the objective function cannot be improved any further. Tabu search, used in [14]–[16], is a procedure that explores the space of solutions with a local search that consists of analysing the immediate neighbours of the current solution. The use of memory structures and adapted selection rules prevents the search from becoming stuck in a local optimum. Evolutionary algorithms, used in [5],[11],[14],[15],[18], are inspired by the process of natural evolution. They perform inheritance, mutation, and crossover operations on generations of solutions until the best solution cannot be improved. Simulated annealing, used in [5],[14],[15], mimics annealing in metallurgy and is well adapted for discrete and large search spaces. Thus there are many heuristics and combinations of them, as in [5] and [14]. Their performances depend on the way in which the problem is formulated and the empirical rules brought by the user’s experience. The other way to handle the complexity of the problem is to decompose it or to employ multi-objective optimization. Reference [15] decomposes the problem into a master problem for the topology and a slave problem for the feasibility of the solution. Reference [18] runs an evolutionary algorithm and then analyses the results according to two objective functions.

The current paper proposes a three-stage solution. The first stage is an adapted simulated annealing algorithm. It aims to provide the initial architecture of the network that minimizes the total length of conductors. The topology is the secured feeder architecture also studied in [5],[6],[12]. Most of the previous papers include the radiality of the network in the constraints, but a few aim to directly build the connections between the feeders in order to guarantee the reliability of the network. The current paper directly includes the secured feeder architecture in the structure of the solution. The second stage is the balance of the maximal consumption between the feeders in order to respect the constraints of contingency. The balance is performed by successive exchanges of substations between the feeders. The last constraint that has to be met is the quality of supply. Only [7],[11],[15],[18],[21] include protections against failures and costs of failures directly in the objective function. The current paper studies them in a third stage consisting of the allocation of remote-controlled switches along the feeders in order to obtain an open-loop architecture and to respect the objectives of supply quality. Case studies are generally provided with a set of proposed routes. The current paper considers all possible routes between nodes, taking into account the topology of the areas. Design of candidate routes is a time consuming and costly component of

the planning, and is frequently omitted in the majority of researches. The topology can be modelled by a cell map through the process of rasterization, as in [30] and [31], which solve the problem of feeder routing by using a mixed integer linear programming model and dynamic programming, respectively. These methods allow fine modelling of reality but are applied to transmission networks and are adapted to rural areas and overhead conductors. In [32] a dynamic programming method is described in order to build a radial topology considering the environment. Reference [33] suggests heuristics based on simple mathematics to allocate the substations and the feeders of a distribution network. Nevertheless the methods proposed in [32],[33] are not adapted for secured feeder architecture. The current paper proposes to focus on urban areas and to model the vector map on a graph. Dijkstra's algorithm [34] is run to obtain a complete graph that is used for the planning.

The paper is organized as follows: Section II introduces the secured feeder architecture, the costs of the network, and the different constraints used in the model. Section III describes the different stages of the planning methodology subdivided into three steps: an adapted simulated annealing for routing the feeders, a post-optimization based on the exchange of substations between the feeders, and the allocation of the remote controlled switches. Section IV applies the methodology to a part of a real distribution network with 136 nodes. Conclusions and perspectives are presented in Section V.

## II. PROBLEM FORMULATION

### A. Architecture of the Network

The studied networks are located in an urban area in France. The reference architecture for these networks is the secured feeder architecture, which is extensively used by the French distribution system operator (DSO). It is illustrated in Fig. 1.

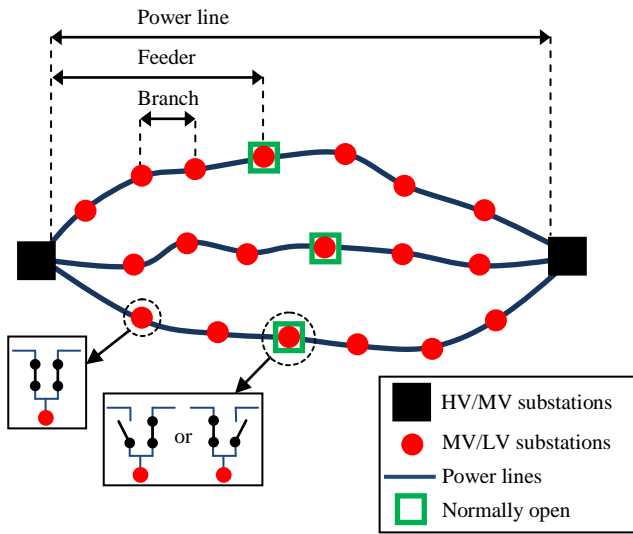


Figure 1. Description of the secured feeder architecture

Each power line goes from an HV/MV (high voltage / middle voltage) substation, supplies different MV/LV (middle

voltage / low voltage) substations, and then joins another HV/MV substation. For each load, the cable passes through two switches. All the switches of the line are normally closed except for one, which is open. Each power line consists of two feeders separated by the open switches. A branch is considered as a conductor that directly connects two loads. As several switches are remotely controlled, this structure guarantees a good quality of supply. When a fault occurs, the breaker of the HV/MV substation switches off for a few seconds. Then the remotely controlled switches are operated in order to isolate the fault within a period  $T_{iso}$ . Finally, the switches that are not remotely controlled are operated in order to isolate the fault more precisely and to proceed to repair within a duration  $T_{fix}$ .

### B. Economic Objectives

The objective is to minimize the total costs (C) of the network, which are divided into the CAPital EXpenditures (CAPEX) and OPERational EXpenditures (OPEX).

$$C = CAPEX + OPEX \quad (1)$$

The CAPEX (2) are expenditures that create future benefits and are used by a company to acquire or upgrade physical assets such as equipment, property, or industrial buildings. The CAPEX for the DSO are the investments in the power lines. They include the costs of conductors, trenches, and remotely controlled switches.

$$CAPEX = \sum_{j \in \Omega^b} l_j (C_j^{cdt} + C_j^{trc}) + n_{rcs} C^{swd} \quad (2)$$

The OPEX (3) are the ongoing costs of operating the system. For the DSO, they comprise the costs of technical losses (4) and the costs of the quality of energy (5) and (6).

$$OPEX = \sum_{t=1}^T \frac{1}{(1+d)^t} \left[ \sum_{j \in \Omega^b} C^{loss} P_{j,t}^{loss} + \sum_{k \in \Omega^a} (C^{eens} E_{k,t}^{eens} + C^{epc} P_{k,t}^{epc}) \right] \quad (3)$$

$$P_{j,t}^{loss} = 3R_j l_j \left[ \frac{(1+r)^t}{U\sqrt{3}\cos(\varphi)} \sum_{i \in \Omega_j^f} P_i \right]^2 \quad (4)$$

$$E_{k,t}^{eens} = (1+r)^{t\tau} \sum_{j \in \Omega_k^{ba}} l_j \left( T_{iso} \sum_{i \in \Omega_k^{lf}} P_i^{mean} + T_{fix} \sum_{i \in \Omega_k^{la}} P_i^{mean} \right) \quad (5)$$

$$P_{k,t}^{epc} = (1+r)^t \tau \sum_{j \in \Omega_k^{ba}} l_j \sum_{i \in \Omega_k^{lf}} P_i^{mean} \quad (6)$$

### C. Constraints

The electrical constraints are the maximal admissible current for each branch (7) and the maximal and minimal admissible voltages (8). The first depends on the type of conductor and the second is fixed by the French law.

$$0 \leq I_j \leq I_j^{max} \quad \forall j \in \Omega^b \quad (7)$$

$$V_i^{min} \leq V_i \leq V_i^{max} \quad \forall i \in \Omega^n \quad (8)$$

The criteria for quality are the SAIFI and the SAIDI, which are calculated by (9) and (10) for each branch according to the strategy described in Section II.A.

$$SAIFI_k = \tau \sum_{j \in \Omega_k^{ba}} l_j \frac{\sum_{i \in \Omega_k^{la}} N_i^{LV}}{\sum_{i \in \Omega_k^{lf}} N_i^{LV}} \quad (9)$$

$$SAIDI_k = \tau \sum_{j \in \Omega_k^{ba}} l_j \left( T_{iso} + T_{fix} \frac{\sum_{i \in \Omega_k^{la}} N_i^{LV}}{\sum_{i \in \Omega_k^{lf}} N_i^{LV}} \right) \quad (10)$$

The indexes of quality are calculated for each feeder by summing the indexes of their branches in (11) and (12). The objectives of quality for the DSO in France are regulated by the Commission of Regulation of Energy.

$$\sum_{k \in \Omega_w^{af}} SAIFI_k \leq SAIFI^{max} \quad \forall w \in 1 \dots 2.M \quad (11)$$

$$\sum_{k \in \Omega_w^{af}} SAIDI_k \leq SAIDI^{max} \quad \forall w \in 1 \dots 2.M \quad (12)$$

The last constraint is the topology of the area. It is represented by a non-oriented graph  $G = (V, E)$ .  $V$  is the set of geographic vertexes that represent the streets, the loads (MV/LV substations), the HV/MV substations, and the points that connect loads and HV/MV substations to the streets. Each load or HV/MV substation is connected to the closest street by an orthogonal projection.  $E$  is the set of edges that connect the vertexes of  $V$ . Each edge of  $E$  is weighted by the geographic distance between the two corresponding vertexes. The graph  $G$  is reduced to a new graph  $G' = (V', E')$ . 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 running the Dijkstra algorithm [34] between each pair of vertexes of  $V' \subset V$  in the graph  $G = (V, E)$ . The methodology is described more precisely in [39].

## III. PLANNING METHODOLOGY

### A. Construction of the Architecture

The first stage of the methodology is the building of the architecture. It consists in defining the configuration of the power lines and then allocating the MV/LV substations to the different lines. The configuration of the power lines is defined by their number and their distribution between the HV/MV substations. The number of power lines depends on the total maximal power consumed by the network and the maximal authorized consumption per power line. It is calculated in (13), where  $\lceil \cdot \rceil$  is the ceiling operator that maps a real number to the smallest following integer. It guarantees an integer number of power lines while respecting the maximal authorized consumption per line.

$$M = \left\lceil \frac{\sum_{i=0}^N P_i}{P_{max}} \right\rceil \quad (13)$$

$P_{max}$  is calculated in (14). This formula is based on the case of a fault that would occur at the end of the projected lifetime, in other words for the maximal possible consumption during the study period. This fault leads to the reconfiguration of a power line such that all loads will be powered by a single substation. In this situation, the power flow that goes from the substation is maximal and has to be inferior to the thermic limit of the conductor. Furthermore, a unique type of conductors is used for all the power. This choice is made by some of the French DSOs in order to build a network that is more robust against future developments and uncertainties compared to a decreasing section of conductors along the feeders that optimizes the balance between the investment in conductors and the cost of losses. Furthermore, storing only one type of conductor facilitates the management of logistics. In this way,  $I^{max}$  has the same value for all the conductors.

$$P_{max} = I^{max} U \sqrt{3} \cos(\varphi) \frac{1}{(1+r)^T} \quad (14)$$

The distribution of the power lines between the different HV/MV substations consists in the number of lines for each pair of substations. It depends on the number of lines and substations, the location of the loads, the topology of the area, and the capacity of each HV/MV substation. It also influences the good balancing of power between substations and the possibility of reconfigurations, which contribute to the reliability of the system. In the study case, the same layout of the original solution is kept in order to facilitate the comparison.

Once the configuration of the power lines is defined, the loads are attributed to them. Each power line is represented by its set of connected loads and its pair of HV/MV substations. They are modelled with the solution vector  $X$ . Each element of  $X$  corresponds to the affiliation of each load.

$$X(i) = j \text{ if the load } i \text{ belongs to the power line } j \quad (15)$$

$$\forall i \in \{1 \dots N\}, \forall j \in \{1 \dots M\}$$

The arrangement of loads along each power line is like the Travelling Salesman Problem (TSP). The objective is to connect all the loads of each line at minimal cost. The start and goal nodes of the TSP are the HV/MV substations of the lines 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 solution of the TSP for each power line provides the total length of conductors in the network. Several methods can be used to solve the TSP: exhaustive searches, heuristic algorithms, or approximation algorithms. The Christofides algorithm [35] is used. It offers the rapidity of the approximation algorithm and always guarantees the best known approximation equal to 1.5 of the optimum [36].

The construction of the architecture consists in determining the solution vector  $X$ . The description of the problem in Section II brought the evidence that the length of the power lines is closely linked to the total cost of the network, which is particularly evidenced by the investment in conductors and trenches. Furthermore, the length of conductors has a slight impact on the technical losses, the expected energy not served, and power cuts. Thus the objective function  $f_{obj}$  chosen to evaluate the solution vector  $X$  is the total length of power lines in the network.  $f_{obj}$  is evaluated by running the Christofides algorithm for each TSP corresponding to the groups of loads of each power line.

$$f_{obj}(X) = \sum_{j \in \Omega^b} l_j(X) \quad (16)$$

The determination of  $X$  is performed with a simulated annealing algorithm. This algorithm is generally used to provide a good approximation of the global optimum of a problem with discrete variables and a large search space, according to the literature [37]. The current paper proposes an adapted version of the simulated annealing for the grid optimization problem. The procedure of the algorithm is described in Fig. 2. First, an initial temperature representing the excitation state of our system is defined. For each iteration, an elementary modification is performed according to (17): a load is moved from one power line to another.

$$X(i) = j \text{ with } \begin{cases} i \in \{1 \dots N\} \\ j \in \{1 \dots M\} \setminus \{X(i)\} \end{cases} \quad (17)$$

The new length of the network is evaluated by performing the corresponding TSP with the Christofides algorithm. If the total length of the network decreases, the modification is accepted. Otherwise the modification is accepted only if the generated random  $r$  number between 0 and 1 is inferior to the probability (18).

$$p = \exp(-\Delta L/T) \quad (18)$$

$\Delta L$  is the difference between the new and former lengths of the network and  $T$  is the current temperature. The modifications that increase the length are more easily accepted when the network is in an unstable state. At the beginning of the simulation, many modifications are accepted. Gradually, 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 convergence near to the global optimum. When enough modifications have been accepted (12 times the number of loads, according to [37]), the temperature is decreased according to a geometric law. The geometric factor  $\alpha$  is inferior to 1 and is generally set as 0.9, the usual value according to [37]. The convergence of the algorithm is evaluated with the evolution of the sliding average value of the total length. The simulation is ended when the gradient of the moving average is close to zero. The initial temperature  $T_0$  is evaluated in (19) after a number  $N_0$  of elementary modifications of the initial solution have been performed and the average value of  $\Delta L$  has been calculated  $\langle \Delta L \rangle$ .

$$T_0 = -\langle \Delta L \rangle / \ln(\tau_0) \quad (19)$$

$\tau_0$  is the initial rate of acceptance of the modifications. In order to correctly explore the search space, values of  $\tau_0$  equal to 50% and  $N_0$  equal to 100 are chosen, according to [37]. Furthermore, the initial solution is randomly generated.

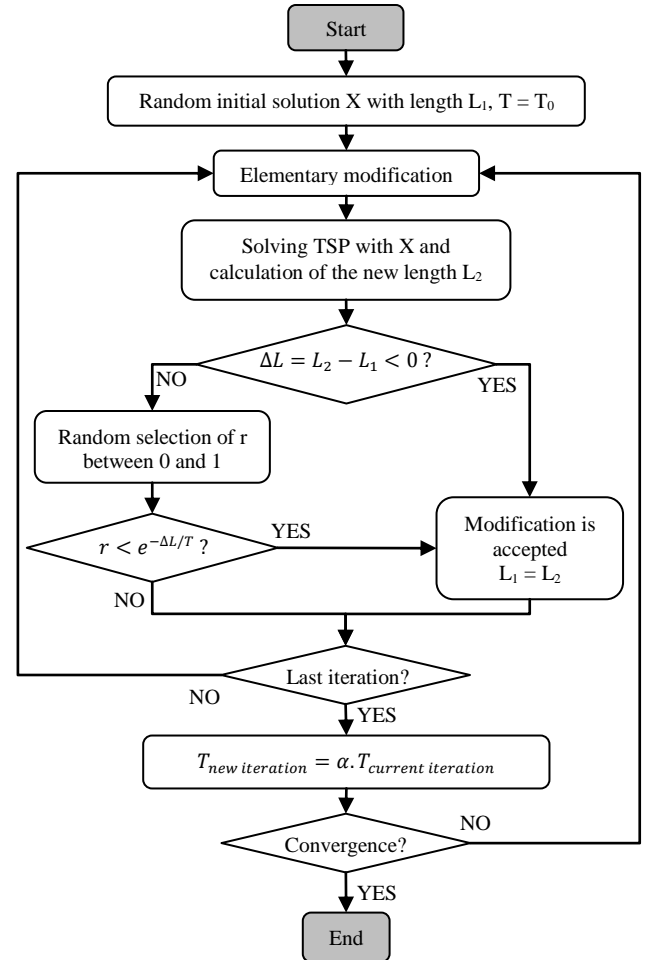


Figure 2. Simulated annealing adapted to distribution grid planning

### B. Post-optimization of the Solution

The second stage of the methodology consists of post-optimization of the solution provided by the simulated annealing. Indeed, the obtained architecture offers a well

minimized length but does not respect all the technical constraints linked to planning purposes. The most important constraint is the maximal admissible power per power line, evaluated by (14). It limits the maximal current in the conductor, the losses, the energy not served, and the voltage drops at the end of each feeder. The proposed method of respecting  $P_{max}$  is described in Fig. 3. The principle is to make exchanges of loads between the power lines in order to balance their power. The first step is to identify the most loaded power line. For each load of this line, the migration to the non-overloaded power lines is considered. A migration is rejected if it makes the line that accepts the load overloaded too. The distance between each candidate load and each power line is evaluated with the graph  $G'$ . The exchange that minimizes the distance is realized, and the operation is repeated until all the power lines respect the maximal power constraint. The interest of considering the topology of the streets is that the exchange of loads is made between neighbouring power lines that share the same street or use close streets. Thus the exchange is realized with a minimized increase of the total length of the network.

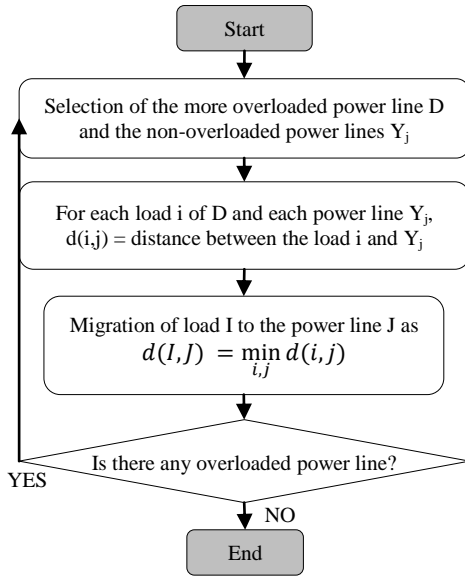


Figure 3. Post-optimization of the solution

### C. Allocation of Remote-Controlled Switches

The final stage of the methodology is the choice of the number and location of the remote-controlled switches, according to the methodology described in Fig. 4. The allocation is performed according to two parameters. The first one is the objective of supply quality of the network. The second one is the criterion of the product  $PL$ .  $PL$  is a quality criterion commonly used in French planning studies. The product  $PL$  of an area of the network is the product of the total maximum demand and the total length of conductors.

$$PL_k = \sum_{i \in \Omega_k^{la}} P_i \sum_{j \in \Omega_k^{ba}} l_j \quad (20)$$

$PL$  is representative of the supply quality. The total length of conductors is proportional to the probability of a failure and

the total demand is proportional to the expected energy not served. Equilibrating the  $PL$  between customers guarantees a balance of power quality between them. For each power line, the normally open remotely controlled switch is allocated in order to balance the product  $PL$  between the two feeders. Then new switches are added step by step until the quality objectives are respected.

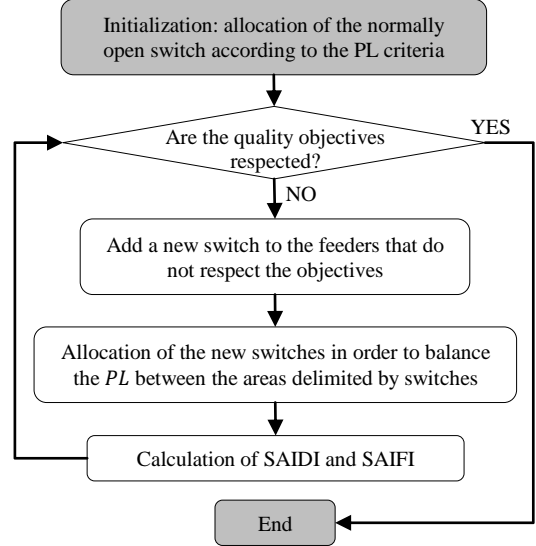


Figure 4. Allocation of the remote-controlled switches

## IV. CASE STUDY

### A. Description of the Network

The study case is a part of the distribution network of the city of Grenoble in France, with 136 loads for a total power of 61.19 MW. The topology of the area is modelled by a graph  $G$  of 758 vertexes and 911 edges. The existing network consists of six main power lines connecting three substations with the secured feeder architecture, comprising a total length of 38.70 km. The original configuration is kept during the optimization for the purpose of comparison, that is to say, one line between substations S1 and S2, two between S1 and S3, and three between S2 and S3. Table I presents the values of the technical and economical parameters used to compare the real network and the results of the optimization. Their values are based on [38].

TABLE I. TECHNICAL AND ECONOMIC PARAMETERS

Project lifetime (year)	30
Discount rate (%)	8
Load increase (%)	0.5
Cos( $\phi$ )	0.92
Conductor cost: 240 mm <sup>2</sup> Alu (k€/km)	20.1
Resistance: 240 mm <sup>2</sup> Alu ( $\Omega$ /km)	0.125
Reactance: 240 mm <sup>2</sup> Alu ( $\Omega$ /km)	0.1
Maximal admissible current: 240 mm <sup>2</sup> Alu (A)	419
Trench cost with one feeder (k€/km)	100
two feeders (k€/km)	140
three feeders (k€/km)	165
four feeders (k€/km)	185
Cost of technical losses (k€/kW during peak period)	0.181
Cost of expected energy not served (€/kWh)	9.2
Cost of expected power cuts (€/kW)	0.8
Cost of remotely controlled switch (k€)	8

Failure rate (%/km/year)	5
Isolation time in case of a fault (minutes)	5
Repair time in case of a fault (minutes)	40
Admissible voltage limits (%)	5

According to the characteristics of the network and the numerical values of the parameters in Table I, the maximal power for each power line is calculated with (14) and is equal to 11.497 MW. The power factor  $\cos(\varphi)$  is taken to be equal to 0.92, which is the minimal value imposed by French law. The objectives of quality are to not exceed the maximal values of SAIFI and SAIDI of the feeders in the original network.

### B. Simulation Results

Fig. 5 shows the network obtained after performing the planning methodology. Table II compares the lengths and the costs of the different networks.

TABLE II. COMPARISON WITH THE REAL NETWORK

		Simulated annealing		
		Real network	Before post-optimization	After post-optimization
Length (km)	Feeders	38.70	31.62	32.59
	Trenches	22.69	22.36	22.02
Maximal voltage drop		3.39%	4.10%	3.60%
SAIFI	Minimum	0.015	0.096	0.100
	Maximum	0.320	0.172	0.188
SAIDI	Minimum	1.033	4.359	4.485
	Maximum	13.352	7.760	8.438
Final cost of the network (k€)	Conductors	745.34	632.38	651.82
	Trenches	2672.69	2381.00	2400.00
	Losses	551.72	340.36	326.29
	EENS	46.89	32.90	33.61
	EPC	48.68	34.07	34.81
	Switches	120.00	48.00	48.00
	Total	4185.35	3468.71	3494.53

The total length of the final solution is 32.59 km, which is 6.11 km (15.79%) less than that of the real network. The reduction of the total cost of the network is 690.82 k€ (16.51%). Costs are reduced by 12.55% for conductors and 10.20% for trenches. The saving for trenches is lower because their cost is also reduced if more conductors use the same streets, which is the case for the real network. The average number of cables per trench is 1.47 for the real network and 1.24 for the final solution of the simulation. The impact on the supply quality is more significant. Costs are reduced by 28.32% for Expected Energy Not Supplied (EENS), 28.49% for Expected Power Cuts (EPC), and 60% for remote-controlled switches. The cost of technical losses is reduced by 40.86%, which represents 225.43 k€, which is 32.63% of the total savings. This saving is due to the reduction of the length but also due to the balance of consumption between the power lines. This impact is highlighted by the post-optimization.

After the simulated annealing has been performed, the optimized network shows two feeders whose power is too high: 14 and 14.415 MW, respectively. After the post-optimization the increase in length is equal to 0.97 km, which is an increase of 3.07%. However the increase of the costs is equal to only 25.82 k€, which is 0.74%. Even if the length of the power lines is increased, the technical losses are still reduced. The maximal voltage drop of the networks is evaluated at the end of the study period with the highest consumption. The three networks respect the limits.

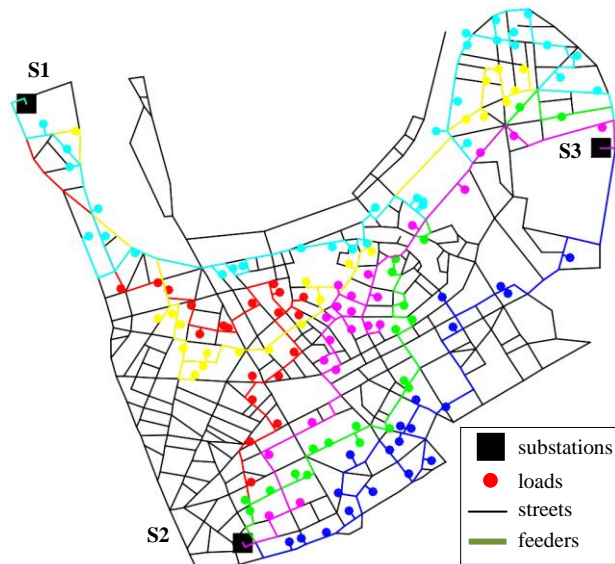


Figure 5. Result of the simulated annealing

The convergence performance and robustness of the simulated annealing have been analysed. For this purpose, the simulation is performed 100 times with a random initial solution on a Core2 machine with a 2.40-GHz CPU and 4 GB of RAM. For each simulation, the evolution of the objective function is recorded. The average computation time for each simulation is 2 hours and 23 minutes. The final value of the objective function varies between 31.62 and 35.25 km with an average of 32.80 km and a standard deviation of 0.64 km.

### V. CONCLUSION

This paper proposed a three-stage methodology for the static model of new expansion planning of middle voltage distribution networks. The first stage is the construction of the architecture thanks to adapted simulated annealing combined with the resolution of TSP. Unlike most of the previous works dealing with radial topologies, the present methodology models the solution directly as a secured feeder architecture, which is economic, reliable, and easy to operate. Furthermore the routes of the power lines take into account the topology of urban areas thanks to the use of algorithms from graph theory. The procedure is simple to implement and only requires the coordinates of the substations and the streets. Moreover, application of the corrective coefficient to the cost of the streets allows the existing system to be taken into account. The

methodology and a case study from a real industrial network are addressed in [39]. The industrial application is the expansion of an existing system, due to the connection of new customers, the need to bury overhead cables, or the modification of the voltage level, for example. The second stage is a heuristic method based on the balance of the loads between the power lines. It makes it possible to respect the technical constraints and decrease the technical losses. Taking the topology into account improves the efficiency of this stage by reducing the increase in the total length. The last stage is the location of the remote-controlled switches in order to reach the objectives of supply quality. This stage is done by respecting the French quality criterion PL, which distributes the supply quality evenly between customers. The methodology has been proved on a real case study and the results showed reduced costs and a higher supply quality. The next improvement of the methodology will be to also determine the optimal distribution of the power lines between the HV/MV substations in order to further minimize the costs of the network.

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