A Novel Hybrid Network Architecture to Increase DG Insertion in Electrical Distribution Systems

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***Abstract*—Distribution networks will experience a deep mutation concerning their planning and operation rules due to the expected increase of distributed generation (DG) interconnection to the grid. Indeed, the opening of the electricity market or the growing global concern for environmental issues will lead to a massive development of DGs. Yet, a too large amount of DGs could raise technical problems on distribution networks which have not been planned to operate with bi-directional power flow. The existing solutions to solve marginal DG connections could be no longer relevant. The distribution network definitely has to evolve towards a smarter and more flexible network. Two possible ways to reach this goal are through new architectures and developing intelligent systems. This paper focuses on new architectures and operating modes. The traditional radial distribution network could accept more DGs by introducing appropriately specific loops. A new hybrid structure enabling the coexistence of the radial and meshed operation is proposed. It is equipped with autonomous circuit-breakers and automated switches that improve its reliability. A heuristic algorithm is also proposed to build this new architecture while ensuring the equality of consumers with respect to the continuity of service and while minimizing the global cost.**

***Index Terms*—Distributed generation, distribution network, optimization, planning, Traveling Salesman Problem.**

I. INTRODUCTION

THE distributed generators (DGs) are small production units based either on renewable energy sources (such as wind and solar photovoltaic) or conventional energy (such as small gas engines or diesel generators) that are connected to the distribution network. Their installed capacity reaches 10 MW in the USA and 12 MW in France [1], [2].

In the near future, the growing concern for environmental issues as well as for the security of supply is expected to lead to the development of local renewable DGs. These power sources will be connected to the distribution network which had been designed to see only unidirectional power flows, from upstream to load. Nevertheless, concerning consumption and production conditions, DGs have been reported to have considerable impacts on the distribution network [3]. First, DGs can modify the electrical values such as voltages, currents, and power flow. The voltage profile in the distribution network depends on both the injected active and reactive power by DGs and the loads. It is presently well known that the interconnection of DGs can lead to the violation of voltage limits, to the dysfunction, and even the deterioration of the network components. In addition, power flows that were unidirectional, coming from the transmission network to the end users, can be modified by the injected power of DGs. Consequently, in some circumstances, the maximum allowed current of a conductor can be exceeded. If the production of DGs is greater than the global consumption, the distribution network could export power. The short-circuit currents can be modified and lead to undesired behaviors of the protection scheme (e.g., protective relay blindness or inopportune trips). Furthermore, DGs supply the short-circuit current that may exceed the operating limits of the network elements [4]. The quality of the voltage can also be reduced [3].

In many countries, in order to face these problems, the reinforcement of the network or the dedicated feeders is used. The first solution consists in detecting the part of the network where constraints are violated. In case of current (or voltage) violation, the gauge mutation of conductors can annihilate the problem. The second solution consists in connecting the DG with a dedicated feeder directly to the HV/MV substation. By doing so, the power flow becomes unidirectional in normal operation mode.

Although connecting marginal quantities of DGs in the distribution network is currently well managed using "business as usual" techniques (reinforcement and dedicated feeder), the systematic use of dedicated feeders could become a very expensive solution to manage while considering a significant development of DGs.

New solutions must, thus, be found to assist the introduction of a large amount of DG in the distribution network. Some studies proposed to change the operation mode of the distribution network, inspired by the transmission network, which uses a meshed operation. This solution has been considered as inapplicable for many years due to the parallel operation of transmission network and distribution network. Such a solution could prove to be dangerous without implementing an appropriate protection scheme since loops currents are created. Recent studies have proposed to use current limiters or D-FACTS [5] that limit loop and short-circuit currents [6]. Further studies report that meshing could be a competitive way to increase the connection of DGs in the distribution network [7]–[13].

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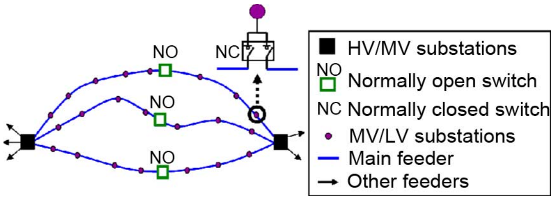


Fig. 1. Secured feeder.

This paper proposes a new architecture called hybrid structure which can increase DG connection to the network. This architecture is an evolution of an existing architecture which is radially operated which introduces partially meshed sub-feeders. Beginning from the location of HV/MV and MV/LV substations, an algorithm that builds the hybrid structure ensuring the equality of consumers regarding the energy supplied while minimizing the total length of conductors is proposed. This algorithm has been applied on an existing urban network and the capacity of the hybrid structure to accommodate DGs is highlighted.

II. NEW ARCHITECTURE TO INCREASE DGS INSERTION: THE HYBRID STRUCTURE

A. *Current French Network Architecture*

The main challenge of distribution long-term planning was to find the best architecture ensuring a good service quality while minimizing the global cost. This challenge has lead to the secured feeder structure [14] which is the most encountered architecture in France and many countries, as depicted in Fig. 1. Each consumer is supplied by several main feeders that link two HV/MV substations. The radial operation is ensured by using normally open switches in every main feeder. A main feeder consists of two radial feeders usually limited to 6 MW.

The desired service quality leads to a given number of main feeders and the choice of the consumers connected to them. The usual service quality notions include:

- System Average Interruption Duration Index (SAIDI) expressed in minutes per year;
- System Average Interruption Frequency Index (SAIFI) expressed per year;
- expected energy not supplied (EENS) expressed in kWh per year;
- equality of the consumers regarding the EENS. This index is ensured by creating areas with equivalent product PL.

For a given area, the product PL is the product of the total power demand (in MVA) and the total length of conductors connecting consumers to HV/MV substations (in km). If this index is balanced, areas having a small consumption will be supplied with longer conductors than areas having a higher consumption. The probability that a fault occurs on the network is proportional to the length of conductors. Thus, the statistical power cut during a fault is minimized if the PL is balanced. The service quality is improved. Consequently, the EENS of two areas with the same PL will be statistically the same. In the secured feeder, each main feeder has the same product PL.

In areas where the expected service quality is high, the secured feeder can evolve into two main structures: the grid and the loop [14], which are also radially operated. The redundant paths increase the service quality but the operation of such structures can be very complex, and can also be very expensive.

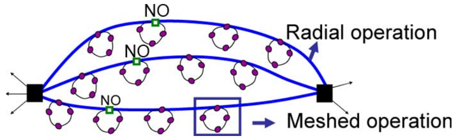


Fig. 2. Hybrid structure.

In the future, the parameter "distributed generation" should be integrated in the objectives of the long-term planning. Hybridization between the secured feeder and the permanent loops could be a novel way to increase DG connection, ensuring the service quality and minimizing the global cost.

B. *Hybrid Architecture*

The hybrid structure is illustrated on Fig. 2. As in the secured feeder, consumers are supplied by radially operated main feeders using normally open switches. But the main feeders are not directly connected to the consumers. They are connected with other consumers or producers on secondary circuit (sub-feeders) which are looped.

In case of a fault on the main feeder and after the trip of a circuit breaker within the HV/MV substation, the network is rearranged by changing the state of the normally opened and closed switches. In case of a fault inside a loop, a "distributed" circuit-breaker disconnects only the loop so that the main feeder and the other loops are not affected by the fault. Each MV/LV substations in the loop can be equipped with automated switches that can quickly locate and isolate the fault. The loop can be, then, reconnected to the main feeder in order to reenergize the healthy parts [14].

The procedure to reenergize consumers in case of a fault is faster than that of the secured feeder. Therefore, the SAIDI and the EENS decrease. The partially meshed operation will increase DG connection. Finally, supply and consumption balance can be ensured by defining PL equivalent areas. As in the secured feeder, each main feeder and each main feeder have equivalent PL products and each loop has an equivalent PL.

C. *Definition of the Evaluation Indexes*

The building of the hybrid structure consists in linking consumers and producers respecting the balancing of PL product. This structure is expected to increase the DG connection, to ensure the quality of service (SAIDI and SAIFI) and to be competitive. In this subsection, the different indexes (balancing the PL product index, global cost, SAIDI, SAIFI, and maximal DG insertion rate) are mathematically expressed.

1) Balancing the PL Product: The PL balance is expressed by using the standard deviation E of the PL product regarding the mean of the PL product. Formula (1) gives the expression of criterion E:

$$E = \frac{\sqrt{\frac{\sum_{i=1}^{n}(PL(i)-\overline{PL})^2}{n}}}{\overline{PL}} \times 100 \tag{1}$$

where

E	standard deviation of PL regarding the mean (%);
n	number of areas;
$PL(i)$	product PL of area i (MVA.km);

$$\overline{PL} = \frac{\sum_{i=1}^{n} PL(i)}{n}. \tag{2}$$

Minimizing E ensures the balancing of PL and then the equality of consumers regarding the service continuity.

2) Various Costs of the Network: The cost of the network is calculated by using the principle of actualization. It thus takes into account the fluctuation of money on the life duration of the network through the actualization rate i. i is a fixed value expressing the fact that N euros at the year N will be equivalent to $N \times (1+i)^t$ euros at the year $N+t$. Then, if a utility decides to invest D(t) euros at the year t, this investment costs $D(t)/(1+i)^t$ euros today. The actualization cost has been fixed at 8% [15]. The different costs of the networks need to be actualized to ensure correctness. The formula (3) gives the actualized cost of an annual cost on N years:

$$C_{act} = \sum_{n=0}^{N} \frac{C(t)}{(1+i)^n}. \tag{3}$$

The actualized power losses cost represents the cost of the power losses during N years, where N is planning period:

$$C_{loss} = I + \sum_{n=0}^{N} \frac{C \times P(n)}{(1+i)^n} \tag{4}$$

where

C_{loss}	actualized power losses cost in euro;
I	investment at the year 0 in euro;
C	cost of one kW of losses at peak time in euro;
$P(n)$	power losses at peak time at the year n in kW;
i	actualization rate in $\%$.

The actualized failure cost includes the EENS cost and the outages cost. The EENS cost was chosen as high as 9.5 euro/kWh and the outages cost at 0.8 euro/kW [16]. Consequently, the actualized failure cost is given by the formula (5):

$$C_{fai} = END \times C_{END} + C_{outages} \times N \times \frac{H_{P\max}}{8760} \times P_{\max} \tag{5}$$

where

$EENS$	expected energy not supplied;
N	total number of outages;
$P_{\max}$	maximal consumption;
H	number of hours of maximal consumption.

3) Reliability Criteria: To evaluate the reliability of the hybrid structure, the SAIDI and SAIFI (defined in part Section II-A) are relevant and international indicators. The reliability indicators are computed by considering the location of the fault: on the main feeder or the loop. Since the operation of these two cases is different, the SAIDI and SAIFI calculation will be different.

If a fault occurs on a main feeder, the breaker located at the top of the feeder will trip and each customer depending on the feeder is disconnected. In a few minutes, remotely controlled switches isolate the fault and reenergize all the customers. The SAIDI and SAIFI due to a fault on the feeder i are explained with the formula (6):

$$\begin{aligned} SAIDI_{feeder}(i) &= \tau \times L_i \times T_d \\ SAIFI_{feeder}(i) &= \tau \times L_i \end{aligned} \tag{6}$$

where

τ	failure rate for the feeder per year per km;
L_i	length of the feeder i in km;
T_d	duration to isolate the fault with the remotely controlled switches.

If a fault occurs inside a loop, the breaker disconnects the loop from its main feeder. Therefore, the other customers are not affected by the fault. Then automated switches enable the fault to be isolated. The total SAIDI and SAIFI due to a fault inside every loop of the feeder i are presented in (7) at the bottom of the next page, where

nb_loops^i	number of loops of the feeder i;
T_m	duration of the automatisms of the MV/LV normally closed switches of substations of the loops (20 s). There are two normally closed switches per MV/LV substations. Each operation of a switch (opening or closing) takes 10 s;
$L^i_{loop}(j)$	length of the loop j of the feeder i;
$N^i_{loop}(j)$	number of customers of loop j of the feeder i;
$NT^i_{loop}(j)$	number of MV/LV substations of loop j of the feeder i;
N_{feeder}	number of customers of feeder i.

Finally, the average SAIDI and SAIFI of a feeder is presented in formula (8):

$$\begin{aligned} SAIDI &= \frac{\sum_{i=1}^{ND} SAIDI_{feeder}(i) + SAIDI_{loop}(i)}{ND} \\ SAIFI &= \frac{\sum_{i=1}^{ND} SAIFI_{feeder}(i) + SAIFI_{loop}(i)}{ND} \end{aligned} \tag{8}$$

where ND is the number of feeders of the network.

4) Maximal DG Insertion Rate: The maximum DG insertion rate of the hybrid structure is defined with formula (9):

$$Rate_{\max} = \frac{P_{DG}(MW)}{C_{tot}(MW)} \tag{9}$$

where

$Rate_{\max}$	maximal insertion rate of DGs;
P_{DG}	maximal power output of DG;
C_{tot}	total maximal consumption of the network.

The maximal insertion rate of DGs is the maximum power of DG that can be connected to the distribution network without violating technical constraints (such as voltage and current values). A Monte Carlo algorithm has been used to estimate this rate without making any hypothesis on the type, the size, and the location of DGs [17]. To satisfy these hypotheses, each simulation consists of checking the network constraints in the worse state (minimum consumption and maximal production). This situation increases bidirectional power flows in the network and thus increases the probability of technical constraints violation.

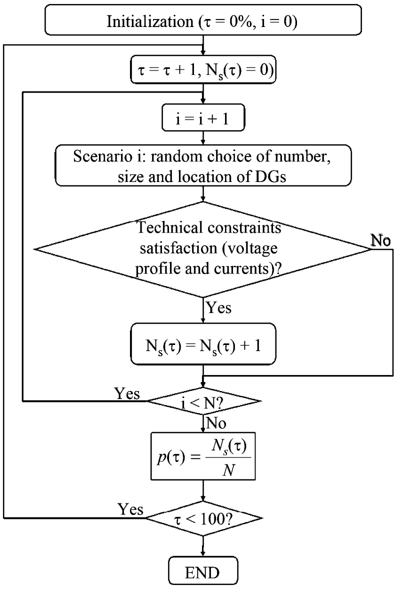
The estimation of the maximal DG insertion rate for a given network is detailed in Fig. 3. This algorithm will be illustrated with the following example:

— total consumption: 100 MW;
— number of loads: 1000.

Using the previous example for $\tau = 10\%$, it represents an introduction of 10 MW of DG in the network. One possible scenario could be 5 DGs of 2 MW, another could be 10 DGs of 1 MW, and so on. One thousand scenarios are carried out and lead to 950 successes for example. Then $\mathrm{p}(10\%) = 950/1000 = 0.95$. The probability that the technical constraints are respected introducing 10 MW of DGs in the network is 0.95.

The maximal DGs insertion rate is evaluated using the maximal rate whose probability of success is higher than a given probability. For instance, for a given risk of 3%, this probability is 0.97. This risk means that the hypothesis of minimal consumption and maximal production is unlikely. This method is well suited because it allows to evaluate if an architecture is favorable to DGs insertion without making any hypothesis on the composition of DGs (solar, wind, etc.) and the location. Indeed, these two last parameters are hardly predictable.

III. MODELING THE HYBRID STRUCTURE CONSTRUCTION



Where:
τ = DG insertion rate,
i = current scenario,
N$_S$(τ) = Number of successes for τ% of DG insertion rate = number of times that the technical constraints are respected among the N scenarios,
N = number of nodes of the studied network,
p(τ) = probability that the technical constraints of the network are respected for τ% of DG insertion rate.

Fig. 3. Monte Carlo algorithm.

The planning problem presented in this paper considers only the consumers (MV/LV substations) and the HV/MV substations locations. Then, the complete rebuilding of the grid layout is conducted (sizing and placing the different conductors to reach a hybrid structure).

A. Traveling Salesman Problem (TSP) and the Vehicle Routing Problem (VRP)

The problem of building the hybrid structure consists in connecting a group of consumers (MV/LV substations) with producers (MV/LV substations) using loops. This problem is similar to the Traveling Salesman Problem (TSP) and the vehicle routing problem (VRP) [18]. The TSP is a classical combinatorial optimization problem. For a given number of cities, the TSP consists in finding the cheapest tour that visits every city exactly once. The cost of each edge is a value associated to this

$$\left(SAIDI\_loop(i) = \frac{\sum_{j=1}^{nb\_loops^i} \tau \times T_m \times L^i_{loop}(j) \times N\_loop^i(j) \times NT^i_{loop}(j)}{N_{feeder}(i)} \right)$$
$$\left(SAIFI_{loop}(i) = \frac{\sum_{j=1}^{nb\_loops^i} \tau \times L^i_{loop}(j) \times N^i_{loop}(j)}{N_{feeder}(i)} \right) \quad (7)$$

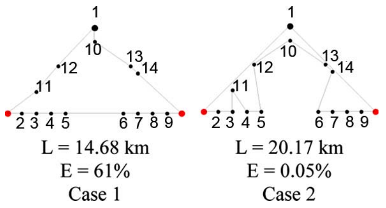


Fig. 4. Contradiction between the criteria L and PL.

path (for instance, the length of the edge). A notion of limited capacity can be added to each edge. Also, several tours are necessary to visit each city. This is the Vehicle Routing Problem (VRP). A classic example of the VRP is the dustman problem whose packer body is limited [18].

Both in the TSP and VRP, the objective function (the total cost of the tour) is linear. In the hybrid structure problem, the standard deviation E of product PL regarding the mean and the total length L of the conductors are to be minimized. But, the criteria E is nonlinear and E and L are contradictory criteria. This phenomenon can be illustrated with a simple example of a network with two HV/MV substations and 14 MV/LV substations. The load number 1 consumes 100 MVA and the other loads 5.58 MVA. The objective is to build two main feeders. In case 1, the aim is to minimize the total length of conductors and in case 2, the aim is to balance PL products. Fig. 4 shows that balancing the PL product leads to a solution with a total length of conductors approximately 6 km higher.

The hybrid structure problem seems to be more complex than the TSP or VRP. The recognition version of the TSP and the VRP are NP-complete problems [19]. In other words, there is not any algorithm that can find the optimal solution in a polynomial time. Only good local sub-optimums can be obtained using smart heuristics. The building of the hybrid structure is a derivative of the TSP and the VRP so it is also NP-complete. An overview of existing methods to solve the VRP and TSP is necessary to find an appropriate heuristic algorithm to build the hybrid structure.

B. Comparison of the Existing Algorithms

1) VRP: Two main classes of heuristics attempt to solve the VRP: classical heuristics (mainly developed between 1960 and 1990) and metaheuristics developed during the last two decades. More information on those methods can be found in [18]. Classical heuristics are local search methods that do not explore all the space solutions. They enable to get acceptable solutions in a reasonable time and can be easily adapted to many problems of daily life. Three categories of heuristics are used to solve the VRP [18]. First, the *constructive methods* (for instance Clark and Wright [20], Christofides, Mingozzi, and Toth [21]) built a feasible solution while keeping an eye on the cost of the solution. Then, *two-phase methods* (for example, the sweep algorithm [22], Fisher and Jaikumar [23]) divide the problem into two phases. First, each vertex is allocated to a vehicle. Then, several routes are built. The reverse method is also possible [24]. Finally, improvement methods try to improve any possible solution making exchanges of vertices or edges (cross, exchange, or relocation [18]). Metaheuristics consist in exploring the solutions space in order to identify the best sub-location to search. Those methods allow the deterioration of the solution and even solutions very far from the optimum in order to prevent the algorithm from converging into a local minimum. Several metaheuristics can be applied to solve TSP [18]: simulated annealing [25], deterministic annealing [26], tabu search [27], genetic algorithms [28], ant algorithms [29], and neural networks [30]. The solutions are more accurate than those of the heuristics methods, but the computation time is longer. Reference [18] tests and sorts the different algorithms on different examples. In addition, the parameters of those methods need thin adjustments that depend on the studied problem.

2) TSP: All the above heuristic and metaheuristic methods can be applied and also greedy algorithms to solve the TSP. Solutions and computation time differ from the chosen algorithm. A well-known algorithm is the Christofides one [19]. It is faster than many existing methods, and it is the only one that guarantees that the solution is far from the optimal one from 50% [19]. Indeed the other algorithms give a solution without any accuracy on its reliability. Then, the given solution can be very far from the optimal one.

3) Hybrid Structure Problem: The difference between our problem and the TSP and VRP is that the objective function is multicriteria and nonlinear. Indeed, the PL product (nonlinear criterion) has to be balanced while minimizing the total length of conductors. Constructive heuristics or two-phase heuristics previously described are not suitable because it is impossible to attribute a cost to an edge that takes into account the nonlinear criterion PL. Metaheuristic algorithms would need to be adjusted for each case because of the distribution diversity of the loads. Nevertheless, the improvement method seems to be appropriated. First, in stage 1, the loops will be built with Christofides version of the TSP [19]. The improvement algorithm will balance the PL product of those loops. Then, in stage 2, the loops will be connected with a nonlooped version of the TSP [31]. The same improvement algorithm will balance the PL product of the main feeders.

IV. PROPOSED ALGORITHM TO BUILD THE HYBRID STRUCTURE

A. Objectives

Considering only the data on HV/MV and MV/LV substation locations, the objective is to automatically generate the conductor gauges and paths to supply the consumers (MV/LV substations) following the hybrid structure. The location of the conductors will be created by minimizing the criterion E detailed in (1). Minimization of the total length of conductors will be ensured by the TSP. This will lead to minimize the investment cost of the network. Considering the reliability, the number of loops will directly impact the failure cost. Then the final number of loops of the structure will be a compromise between the investment costs and the quality of service desired.

The technical constraints (current and voltage) will be satisfied by choosing the gauges of the cables following normalized values. Choosing high gauges will decrease power losses. So, even if the initial investment is higher, the global actualized cost of the network could be cheaper. A load flow is then used to verify the technical constraints of the studied network.

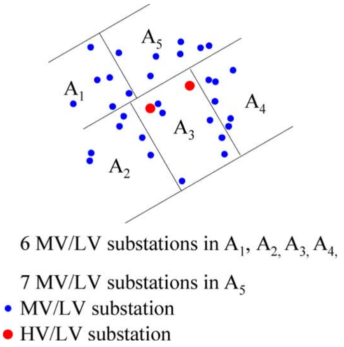


Fig. 5. Example of an inclined checkerboard.

B. Description of the Proposed Algorithm

The proposed algorithm used both in stages 1 and 2 consists in building an initial solution and then, using an improvement method, minimizing the criterion E. The only difference between stage 1 and stage 2 is the TSP algorithm used, as described in the following subsections.

1) Initial Solution Generation: A uniform partitioning is automatically generated following an inclined checkerboard. Fig. 5 shows an inclined checkerboard on a network of 31 MV/LV substations. This partitioning has been chosen first for its simplicity and also because no assumptions have to be made about power density of loads. The inclination of the checkerboard is given by the line joining the two HV/MV substations.

2) Improvement Algorithm: The improvement algorithm used to achieve local exchange between loops is summarized in Fig. 6.

The parameters used in this diagram are as follows.

- $d(M^j(i), L_S)$ is the Euclidian distance of the load $M^j(i)$ of the loop j to the selected loop L_S.
- Value^j is a two-column matrix. For each nonselected loop j, the first column gives the minimum distance between the given (or receiving) loop j with the receiving (or giving) loop L_S.

  The second column gives the corresponding load that can be exchanged between the loops.
- $M_{\rm sel}(j)$ is a vector compound with one load per loop j selected in the second column of each matrix Value^j with the first biased wheel.
- $M_{\rm sel}$ is the final load selected in the matrix $M_{\rm sel}$ with the second biased wheel.

Considering the initial solution, the criterion E and the deviation of the product PL of each loop with respect to the mean are computed. This deviation (EC) is defined with the formula (10):

$$EC\,(i) = \frac{PL(i) - PL_{mean}}{PL_{mean}} \times 100, \quad i = 1, \ldots, n \qquad (10)$$

where

$PL(i)$	product PL of the loop $N°i$ (MVA.km);
PL_{mean}	mean of product PL of all the loops;
n	number of loops.

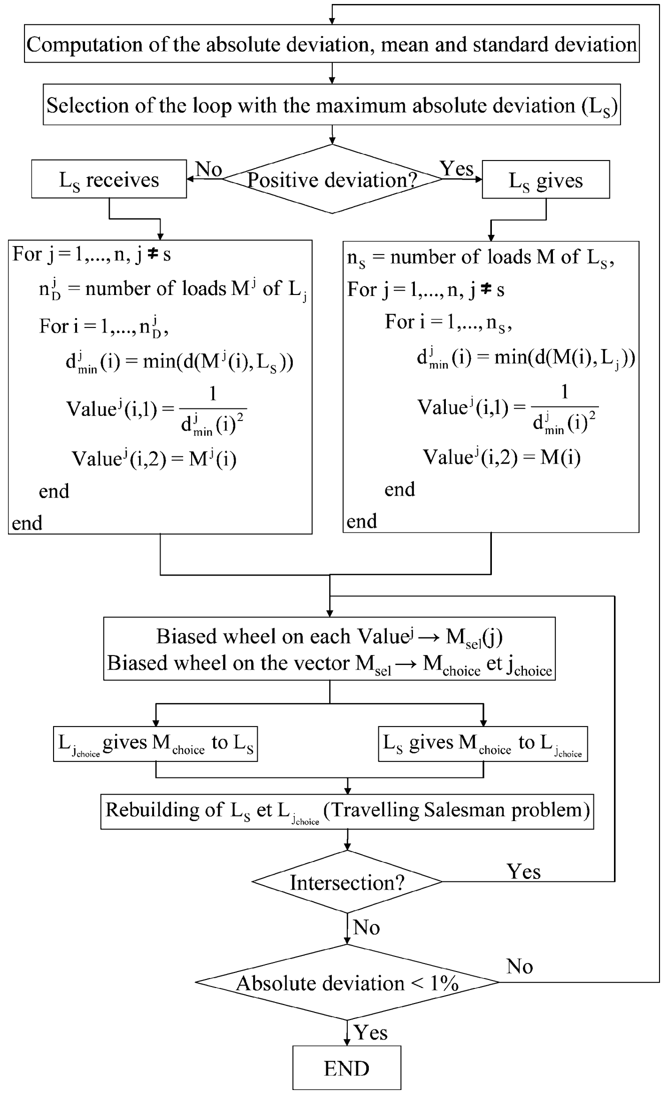


Fig. 6. Improvement algorithm.

Step 1) Selection of the loop: The selected loop has the highest absolute deviation. If this deviation is negative, then the loop should be expanded to include more loads. If it is positive, some loads should be moved to other loops. The selected loop is named LS.

Step 2) Biased wheel: If the load exchanged was only the nearest to the selected loop, then the algorithm could fall in a local minima. No other exchanges could be possible. The algorithm will be stopped, but the final solution would not be satisfactory. Therefore, two biased wheels are set to choose which loop will be selected and whose loads will be selected. Probabilities have to be biased to favor loads that are the nearest from L_S.

- If L_S has to be expanded, then for each neighboring loop j and for each load $M^j(i)$ of loop j, the minimal distance $d^j_{\rm min}(i)$ between $M^j(i)$ and the loop L_S is computed. Then, the matrix Value^j

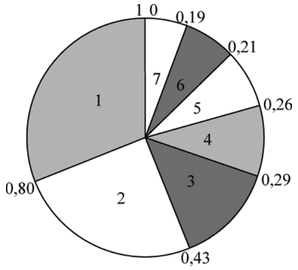


Fig. 7. Example of a biased wheel.

is created. Its first column is $1/d^{j}_{\min}(i)^2$, and in the second one, the corresponding load is $M^j(i)$.

— If some loads of L_S has to be transferred from a feeder to another one, then for each neighboring loop j and for each load M(i) of the loop L_S, the minimal distance $d^{j}_{\min}(i)$ between M(i) and the loop L_j is computed. Then, the matrix $\mathrm{Value}^{\mathrm{j}}$ is created. Its first column is $1/d^{j}_{\min}(i)^2$, and in the second one, the corresponding load is M(i). The matrix $\mathrm{Value}^{\mathrm{j}}$ gives the parameter to build the biased wheel.

To build the biased wheel, the probability that a load is first selected is computed with the formula (11) at the bottom of the page.

Results are illustrated with pie charts. A number can be randomly chosen following a uniform law on the interval $[0, 1]$. The number chosen gives the load of the loop that will be exchanged. For example in Fig. 7, if the number chosen is 0.23, then the selected load is the load number 5. There are as many biased wheels as the number of loops minus one.

Step 3) Rebuilding of loops and noncrossing checking (planar graph).

The final selected load is exchanged. The Christofides algorithm enables to rebuild the two updated loops minimizing the total length of conductors. A "not crossing test" is also applied to check that the new loops do not generate crossing. The rule used is based on the fact that loops consist of several segments connecting two consumers. In the case of crossing, another load is selected with the biased wheel. The criterion E (standard deviation E of the product PL regarding the mean of the product PL) and EC (deviation of the product PL of each loop regarding the mean) are computed again. While EC is higher than a given value fixed by the planning operator, loops keep on making exchanges.

3) Building of the Main Feeders: Once the loops are generated and their product PL is balanced, the main feeders have to be built to supply the loops. For each loop, the loads that are the closest to one of the two substations are selected. Each main feeder will pass by the two substations and some of the loads selected. The same heuristic method is applied to build the main feeders. The planning operator gives the number of main feeders that are desired. Then an initial solution is generated, and then the improvement method previously described is applied. This final part is extremely fast because there are very few loads to supply (the number of loops) and because, for a selected feeder, it has, at the worst case, only two neighboring feeders. The only difference is the way to build the initial solution. Here, the goal is to link the two given HV/MV substations passing by some other points. A simple algorithm based on an angular criterion is better adapted to minimize the conductor length while avoiding crossing cases. The line joining the two HV/MV substations separates the space into the superior part and the inferior part. For the superior part, starting for left HV/MV substation, the first feeder is built stepwise taking the point that has the maximal angle until the other HV/MV substation is reached. Then other feeders are created until all the points of the superior part are supplied. For the inferior part, the method is the same. The only difference is that the criterion to select loads is not the maximum angle but the minimum one.

V. APPLICATION ON A REAL URBAN NETWORK

The hybrid structure is built for several numbers of loops. The criterion E representing the standard deviation of the product PL regarding the mean is a free parameter. The presented results have been carried out for a fixed standard deviation of 10%. The impact of the number of loops will be studied regarding several costs of the network, reliability criteria, and maximal DG insertion rate. The studied network, depicted in Fig. 8, is extracted from a real French urban network. It consists of two MV/LV substations that supply 984 MV/LV substations and 85 239 MV and LV customers consuming a peak power of 151.4 MW.

The hybrid structure is built with the algorithm explained in part IV. To compare the impact of the meshing level on the costs, reliability, and maximal DG insertion rate, the hybrid structure has been built for several loops. The number of loops that can be

$$
\begin{array}{ll}
\text{If } L_s \text{ has to be expanded} & \text{If some loads of } L_S \text{ has to be moved} \\
\text{For } j = 1, \ldots, n \;\; j \neq s & \text{For } j = 1, \ldots, n \;\; j \neq s \\
\quad \text{For } i = 1, \ldots, n_D^j & \quad \text{For } i = 1, \ldots, n_S \\
\qquad \mathrm{Proba}(i) = \frac{\mathrm{Valeur}^j(i)}{\mathrm{sum}(\mathrm{Valeur}^j)} & \qquad \mathrm{Proba}(i) = \frac{\mathrm{Valeur}^j(i)}{\mathrm{sum}(\mathrm{Valeur}^j)} \\
\qquad \mathrm{Proba}(i) = \frac{\frac{1}{d^j_{\min}(i)^2}}{\mathrm{sum}\left(\frac{1}{d^j_{\min}(i)^2}\right)} & \qquad \mathrm{Proba}(i) = \frac{\frac{1}{d^j_{\min}(i)^2}}{\mathrm{sum}\left(\frac{1}{d^j_{\min}(i)^2}\right)} \\
\quad \text{end} & \quad \text{end} \\
\text{end} & \text{end}
\end{array}
\tag{11}
$$

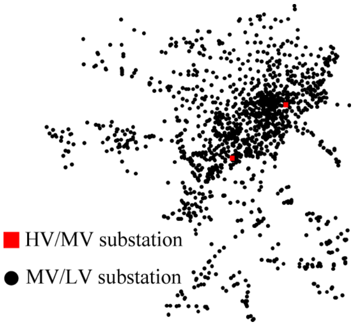


Fig. 8. Studied network.

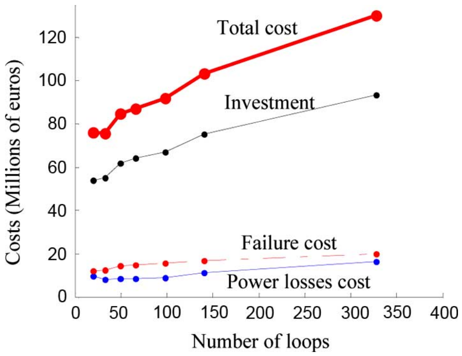


Fig. 9. Evolution of the costs of the network regarding the number of loops.

built is included in the interval $[20; 328]$. The lower limit is due to maximal allowable current constraints. The possible conductors are chosen in a list of normalized conductor currently used in France. The upper limit is due to the fact that a loop must contain at least three nodes. The hybrid structure has been built for the same number of main feeders in order to compare the impact of the number of loops.

A. *Different Costs of the Network*

Fig. 9 gives the different costs previously described in part II for a 40-year planning period. The conductors have been chosen in [15]. The choice of conductors is made using the actualized power losses cost. The investment presents a local minimum for 30 loops and then increases with the number of loops. If the number of loops increases, then the total length of conductors required also increases, as does the investment. The discontinuity of the investment comes from the discrete choice of the conductor whose cost is nonlinear. The actualized failure cost increases with the number of loops because the rate of failure depends only on the length of conductor and not on the gauge. The actualized power losses cost is not monotonous. This is also due to the discrete choice of conductors. A local minimum seems to be obtained for a number of loops between 30 and 100.

B. *Reliability Criteria*

Fig. 10 presents the evolution of the SAIDI and SAIFI when the number of loops increases. Both SAIDI and SAIFI have a local minimum for 100 loops. Between 60 and 150 loops, the SAIDI is very good (lower than 3 min). The current SAIDI in France is in the mean of 15 min per year for urban feeder [15].

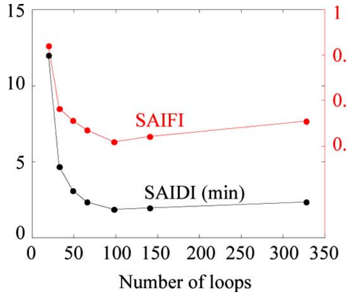


Fig. 10. Reliability indexes regarding the number of loops.

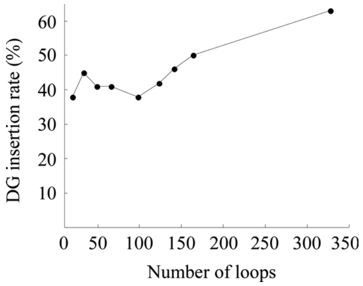


Fig. 11. Maximal DGs insertion rate regarding the number of loops.

TABLE I
COMPARISON BETWEEN THE SECURED FEEDER AND THE HYBRID STRUCTURE

	Secured feeder (from 20 to 328 loops)	Hybrid structure (from 15 to 51 feeders)
SAIDI (min)	[12.8 - 6.7]	[12 - 1.93]
SAIFI	[0.17 - 0.08]	[0.8 - 0.44]
EENS (kWh)	[846 - 111.53]	[223 - 90]
Maximal DG insertion rate (%)	[14 - 47]	[38 - 62]
Global cost (M€)	[78.8- 127.7]	[75.4 - 130]
Investment(M€)	[54 – 93.5]	[52.8 – 98.09]
Power losses cost (M€)	[7.9 – 16.5]	[4.13 - 11.6]
Failure cost (M€)	[12.1 – 20.1]	[14.3 – 25.4]
Conductors length(km)	[399.6 - 839.2]	[423 - 585]
Conductors volume (m^3)	[102.8 - 110]	[85.4 - 98.6]

The protection scheme and associated automatisms of the hybrid loops enable to increase the SAIDI.

C. *Maximal DG Insertion Rate*

Fig. 11 gives the maximum DG insertion rate obtained with the Monte Carlo algorithm [17].

It varies from 38% to 67%. Other tests on real urban networks layout show that the current architecture cannot accept more than 25% of DG [32]. Building the secured feeder (c.f. Section II-A) on the same network enables hardly to reach 47%. This curve is also nonmonotonous due to the same explanations as for the costs and the reliability criteria.

D. *Comparison Between the Hybrid Structure and the Secured Feeder*

Table I summarizes the results for the secured feeder and the hybrid structure.

The SAIDI and the EENS are much higher for the secured feeder than for the hybrid structure. The main reason is that the hybrid structure enables protecting each loop, and automatic switches increase the time of reenergizing consumers. Then the reliability indexes are improved. Nevertheless, all the real investment costs have not been taken into account. Protective relays cost and the one related to the automation of switches have been approximated using the cost of a remotely controlled switch.

Concerning the different costs, the hybrid networks roughly reduce the global cost by reducing power losses costs and investment costs. But as the real costs of protective relays have not been taken into account, the global price is more or less equivalent.

To highlight this, if we take the example of the maximal reachable DG insertion rate for the secured feeder (47%), the hybrid structure has a much better SAIDI of 4 min (against 12.8 min for the secured feeder). Moreover, the global cost is about 38 M euro (against 43 M euro for the secured feeder). Finally, if the DG scenario evolves, the DG insertion rate can be increased until 67% for the hybrid structure, whereas the secured feeder is limited or would required expensive investment.

VI. CONCLUSION

The connection of distributed generation in the distribution network may have considerable impacts. They can be beneficial but also prejudicial (increasing of voltages, disturbance of protection apparatus, etc.). Modern methods of planning could raise their limits if the connection of DGs becomes massive. Then, it is mandatory to include the DG parameters in long-term planning studies.

For this purpose, a novel architecture has been proposed as a result of hybridization between the secured feeder and the loop. The hybrid structure, robust to DGs interconnection, has main feeders radially operated but enables a meshed operation of its loops. Autonomous breakers in each loop enable consumers to be rapidly reenergized in case of a fault.

A heuristic algorithm to build the hybrid structure has been proposed. The objective was to build equivalent PL product areas minimizing the total length of conductors in order to guaranty the equality of customers with respect to the service continuity. The DG parameter was insured by the loops of the hybrid structure. The results obtained on real data show that the hybrid structure increases DGs connection and reliability. The presence of local minima gives the required number of loops regarding the privileged index.

In this paper, the main purpose after increasing the DG interconnection was to guaranty the equality of customers regarding the service continuity. Other parameters can also be taken into account. If the planning operator prefers only minimizing the total length of conductors, optimization methods exist to solve this problem that turns out to be the Vehicle Routing Problem. Multiobjective functions could be used to consider several parameters such as the risk of blindness or inopportune trips due to the insertion of DGs in the distribution network. Furthermore, some improvements can be added such as finding automatically the number of loops and feeder required for a DG insertion rate given target.

Medium-term planning has to be studied to determine if the current architectures are mutable towards the hybrid structure. The optimal investment planning could also be evaluated.

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