# Planning of Large Rural Low-Voltage Networks Using Evolution Strategies

Eloy Díaz-Dorado, José Cidrás Pidre, *Member, IEEE*, and Edelmiro Míguez García, *Associate Member, IEEE*

***Abstract*—This paper presents a method based on evolution strategies for designing large rural low-voltage (lv) distribution networks. Planning rural lv distribution networks involves radial configuration design, location of medium-voltage/low-voltage substations, and minimum cost. In this work, these goals are considered by taking into account different conductors, voltage drop and conductor capacity constraints, power losses in lines, and deterministic loads. The algorithms developed in this paper are based on evolution strategies (ES) and were implemented on large-scale rural lv distribution networks, but they could also be used in general network optimization.**

***Index Terms*—Evolutionary computation, evolution strategies (ES), low-voltage (lv) network planning, network design.**

## I. Introduction

DIFFERENT planning practices and processes are needed for urban and rural networks. Rural networks, as distinct from urban networks, are characterized by: low load densities, small equipment ratings, and frequent use of overhead lines.

The basic problem in the planning of low-voltage (lv) distribution networks is essentially to search for a radial network with lowest overall cost by taking into account size and locations of medium-voltage/low-voltage substations (mv/lv substations), routes, and capacities of lv lines to supply a given spatial distribution of forecast loads, thermal limits (lines and substations), and voltage level.

In general, the methods proposed by several authors assume known mv/lv substation location [1] or consider only some possible location for mv/lv substation to optimize lines and substations simultaneously [2]–[7]. A method using branch exchange procedures is presented in [8], which considers the complete lv network and substation design, over a specific graph and considering only investment cost. However, error in the optimization process can appear due to neglect power losses (high impedance conductors and long distances).

In [9] and [10], an algorithm to design lv distribution networks by using dynamic optimization is presented. In this algorithm, mv/lv substation location and size with voltage drop constraints and power losses are considered, but its use is limited to areas with a small ratio defined as: number of loads/number of mv/lv substations.

This paper presents a new method based on evolution strategies (ES) which does not have this limitation.

The difficulty in planning lv distribution networks can be solved by using heuristic methods where evolution strategies yield good results. The ES can solve large-scale networks without simplifying the cost function and without fixing or restricting mv/lv substation locations, as in mathematic programming methods [7], widely used for planning medium-voltage (mv) distribution networks.

In recent years, methods have been developed for network planning based on metaheuristic models: simulating annealing [11], [12], genetic algorithms [13], [14], evolution strategies [10], [15]–[19] and evolutionary programming [20]. In general, these works present applications for mv distributions networks, but they do not consider the simultaneous optimization of hv/mv substation locations and mv networks.

The method proposed in this paper is essentially a heuristic process to search for the optimal solution of a large-scale radial lv distribution network. The method is based on application of the metaheuristic evolution strategies [21] over a specific tree. The algorithm begins with a specific distribution network tree, where loads are considered on nodes. The typical initial tree is defined by the minimum distance algorithm (minimum Euclidean spanning tree) but other trees can be considered. Over an initial tree, using a random process, several forests are defined. Each forest (set of subtrees) is called a population. Using the crossover and mutation operators of evolution strategies, other populations (forests) are produced. Each subtree is optimized considering mv/lv substation, type of line, and voltage constraints, by using mathematical programming [9]. The set of subtree costs (population cost) is used by the selection operator. Thus, the proposed iterative method for optimal design of a lv network can be divided into three processes:

1) to obtain forest-populations with crossover and mutation operators;
2) to evaluate the cost of each population using [9];
3) to apply the operator selection to populations, and to get the best populations.

The processes are repeated until a set of the best populations is stable.

The following section describes the forest codification, crossover and mutation operators, selection operator, and cost function.

Manuscript received February 19, 2003. This work was supported by the Dirección General de Investigación of the Ministerio de Ciencia y Tecnología of Spain under Contract DPI2002-02566.

The authors are with the Departamento de Enxeñeria Electrica, Universidade de Vigo, Vigo 36210, Spain (e-mail: ediaz@uvigo.es; jcidras@uvigo.es; edelmiro@uvigo.es).

Digital Object Identifier 10.1109/TPWRS.2003.818741

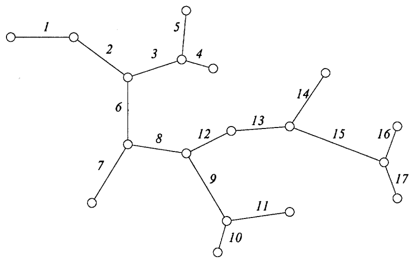


Fig. 1. Initial tree.

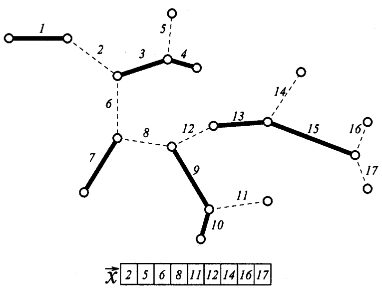


Fig. 2. Member codification.

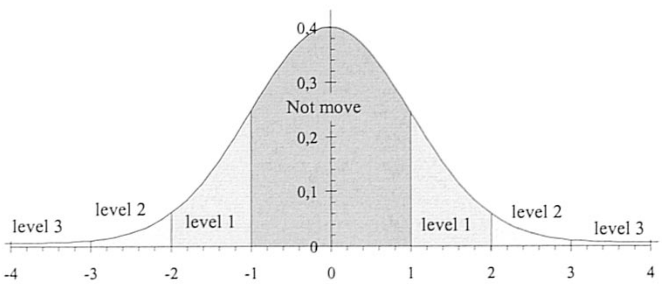


Fig. 3. Normal distribution and interval levels.

## II. Population Codification

A population-member is a forest defined over the initial tree, formed by branches named *chords*. For the forest codification, we used the other branches named *links* $(\text{link} = \text{no chord})$. Thus, over the initial tree in Fig. 1, the member P can be built (Fig. 2) defined by chords: 1, 3, 4, 7, 9, 10, 13, 15, and codified by links: 2, 5, 6, 8, 11, 12 14, 16, 17.

The initial tree branches that are chords represent the lv network trajectory, and they form a forest of subtrees. Each subtree of a member will be fed by one mv/lv substation, and will be evaluated by the cost function expressed in Section V (cost function of population member).

## III. Mutation and Crossover Operators

The mutation and crossover operators are the mechanisms to modify the population members in the evolution strategies [21]. The mutation operator applies to one member, and produces a new member. The crossover of two members (*parents*) creates two new members (*children*) with combined parent characteristics. The general conditions for mutation operator are random, high frequency, and with few variations from the original member. The crossover operator is also random, with low frequency and produces new members with combined characteristics. These mechanisms guarantee iterative populations with new characteristics (mutation operator) and combined characteristics (crossover operator).

### A. Mutation Operator

In evolution strategies, the mutation operator is built using a Normal distribution $\mathrm{N}(0, \sigma)$, associated to each link of the member selected. In the proposed algorithm, the mutation operator consists, basically, of changing the links from their position to another.

For each link of the member, a random variable $v$ is obtained with the Normal distribution function associated to it. The new position of the link is obtained using the value of variable $v$, taking into account the different intervals in Normal distribution (see Fig. 3). (Please see the equation at the bottom of the page.)

When the initial tree has various branches in the selected level, one will be selected at random (e.g., link 12 on Fig. 4 can be moved with level 1 to the positions of the branches 8, 9, or 13 of the initial tree). The figure shows the result when it is moved to branch 13. Fig. 5 shows link 12 moved to branch 3 (possible positions with level 3: branches 2, 3, 16, or 17).

The members of the population have a vector associated with the different standard deviation of each link. Each link $k$ has a standard deviation $\sigma_\mathrm{k}$ associated that defines its Normal distribution. The standard deviation values are modified in each iteration and they are defined by the expression

$$\sigma_\mathrm{k}^{(\mathrm{t}} = \sigma_\mathrm{k}^{(\mathrm{t}-1} \cdot \mathrm{e}^{(\mathrm{z}_0 + \mathrm{z}_i)} \tag{1}$$

where

- t number of the iteration;
- $\mathrm{z}_0$ random Normal variable with null mean and $\tau_0$ standard deviation;
- $\mathrm{z}_\mathrm{i}$ random Normal variable with null mean and $\tau_\mathrm{i}$ standard deviation.

$$\mathrm{z}_0 \sim \mathrm{N}\left(0, \tau_0^2\right) \quad \mathrm{z}_\mathrm{i} \sim \mathrm{N}\left(0, \tau_\mathrm{i}^2\right) \tag{2}$$

$$v \in \begin{cases} (-1,1) & \text{link is not moved} \\ (-2,-1) \cup (1,2) & \text{link is moved to an adjacent branch} \\ (-3,-2) \cup (2,3) & \text{link is moved to a branch in level 2} \\ \vdots & \vdots \\ (-\mathrm{k}-1,-\mathrm{k}) \cup (\mathrm{k},\mathrm{k}+1) & \text{link is moved to a branch in level k} \end{cases}$$

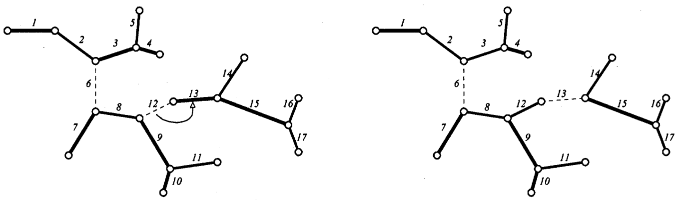

Fig. 4. Link mutation moved to level 1.

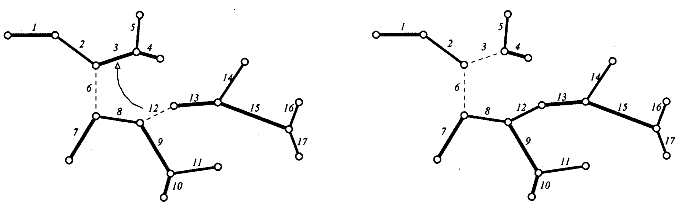

Fig. 5. Link mutation moved to level 3.

Values $\tau_0$ and $\tau_i$ are always constants; $z_0$ is different for each member, and $z_i$ is different for each link of a member.

### *B. Crossover Operator*

The crossover operator belongs to the designated group "bisexual," because it is applied to two chromosomes (parents), obtaining two new chromosomes (children), with mixed characteristics of both parents (Fig. 6). The steps are

1) to select by random, two members i and j of population t, named parent 1 and parent 2;
2) to select by random, a set $S$ of branches of the initial tree (dark color);
3) child 1 is created with the links of parent 1 belonging to set $S$, and the links of parent 2 not belonging to set $S$;
4) child 2 is created with the links of parent 2 belonging to set $S$, and the links of parent 1 not belonging to set $S$.

## IV. Selection Operator

When the mutation and crossover operators are finished, the population t, of size $\mu$, will be of size $\mu + \lambda$, where $\lambda$ is the number of new members corresponding to operators (see Fig. 7). After building the new population t, with $\mu + \lambda$ dimension, a selection operator is needed to return population $t + 1$ to size $\mu$. The selection operator criterion is: To choose from among the $\mu + \lambda$ population, the best $\mu$ members according to cost function (survival function). This cost function is described in the next section, and it is defined taking into account the complete optimization problem: objective function and constraints.

## V. Cost Function

Each member of population t is formed by several subtrees. These subtrees are produced by taking off branches (named links).

The objective function to minimize is the sum of the total costs for the mv network, mv/lv substations, and lv networks, and a penalty function for unfeasible lv networks.

In order to determine the cost of a member, the following hypotheses are considered.

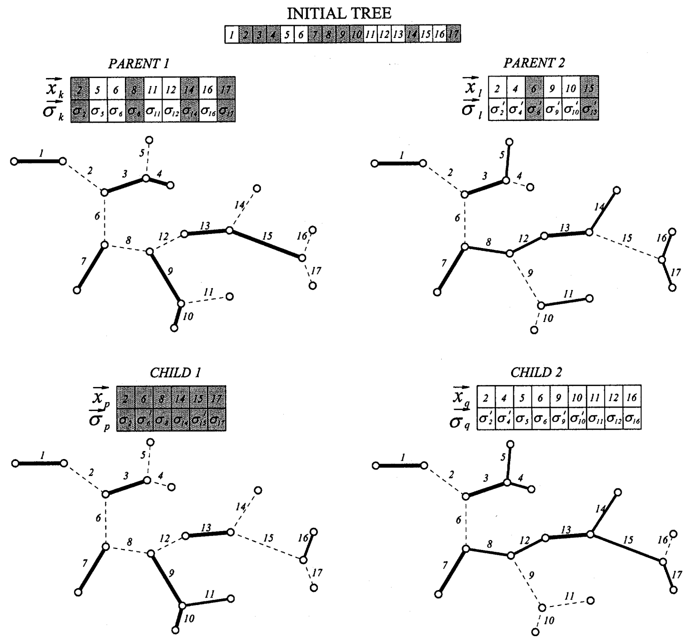


Fig. 6. Crossover operator.

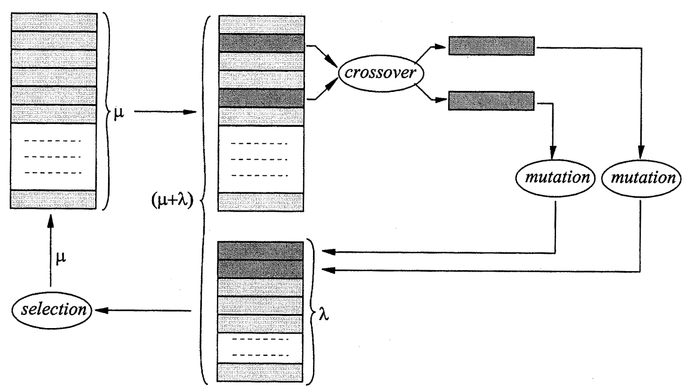


Fig. 7. Operators implementation.

1) Each subtree will be one mv/lv substation.
2) The mv network is defined taking into account the minimum distance tree between mv/lv substations.
3) The lv network, defined by subtree topologies, one mv/lv substation, and nodal loads is optimized considering investment, power losses, line maintenance, and voltage drop and capacity constraints.

Thus, the cost function of a member is the addition of subtree costs and can be mathematically defined by

$$\Psi = C_{MV} + C_{LV} + C_{Sub} \tag{3}$$

with

$$\begin{aligned} C_{MV} &= K_{i_{MT}} \cdot \sum_{(j,k)\in A_{min}} L_{j,k} \\ C_{LV} &= \sum_{(j,k)\in LV} \left(K_{i_{j,k}} + K_{m_{j,k}} + K_{p_{j,k}} \cdot I_{j,k}^2\right) \cdot L_{j,k} \\ C_{Sub} &= \sum_{j\in Sub} \left(K_{i_j} + K_{m_j} + K_{Fe_j} + K_{Cu_j} \cdot P_j^2\right) \end{aligned} \tag{4}$$

where

- $C_{MV}$ total cost of the mv network;
- $K_{iMT}$ investment cost of mv network, per unit of length;
- $L_{j,k}$ length of line $(j, k)$;
- $A_{min}$ minimal spanning tree;
- $C_{LV}$ total cost of the lv network;
- $Ki_{j,k}$ investment cost of the line $(j, k)$, per unit of length;
- $Km_{j,k}$ maintenance cost of the line $(j, k)$, per unit of length;
- $Kp_{j,k}$ electrical losses cost of the line $(j, k)$, per unit of length;
- $I_{j,k}$ intensity of line $(j, k)$;
- $C_{Sub}$ cost of the mv/lv substations;
- $Ki_j$ investment cost of the mv/lv substation in node j;
- $Km_j$ maintenance cost of the mv/lv substation in node j;
- $Kfe_j$ iron losses cost of the mv/lv substation in node j;
- $Kcu_{j,k}$ electrical losses cost of the mv/lv substation in node j, per unit of power;
- $P_j$ real power that flows through the mv/lv substation in node j.

The optimal cost of each subtree is obtained by using the dynamic programming optimization presented in [9]. This optimization algorithm is described in Appendix A, and is an improvement on the method developed by Tram and Wall [22]. When any subtree is an unfeasible network due to the voltage drop or conductor capacities constraints, the penalty cost of the network will be defined by the proposition "the cost of the optimal network without constraints multiplied by the number of parallel conductors (for the complete subtree) needed to make the network feasible."

## VI. Results

Fig. 8 shows the results of the algorithm applied in a typical rural area with 1 530 lv customers. The example represents real position of customers, obtained with a global positioning system (GPS). The value of the parameters employed was $\mu = 200, \lambda = 300$ and the initial value of the variance was $\sigma = 0.8$. The optimal solution has 68 mv/lv substations, with sizes from 25 to 630 kVA, and the lv network is 71.9 km long with conductor types from 30 to 150 $mm^2$. The total cost, including lv network, and mv/lv substations is 2.082 M€. Fig. 9 shows a enlargement of the shaded area, with the highest concentration of customers.

Fig. 10 shows cost evolution, the number of mv/lv substations, and the mean variance of the evolutionary algorithm. The first curves represent the best, the mean, and the worst cost of the population for each iteration. The mean of the variance curve represents the population convergence to the optimal solution.

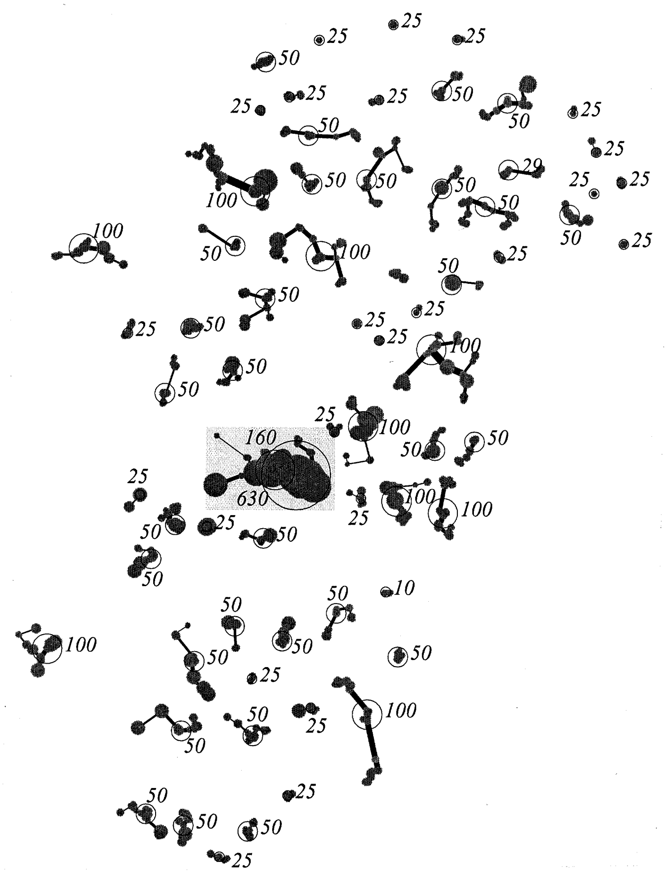


Fig. 8. lv network and mv/lv substations.

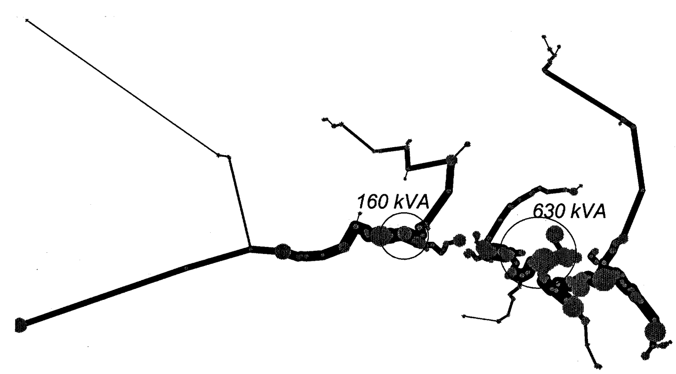


Fig. 9. Enlargement of the shaded area in Fig. 8.

## VII. Conclusion

A method for planning low-voltage radial distribution networks was developed. The proposed method is based on an implementation of an evolution strategy over a specific tree. The member costs (cost function) were optimized by dynamic programming and took into account several conductors, load losses, line maintenance, voltage drops, and exact cost function of lv lines and mv/lv substations. Several improvements were developed so as to make the proposed method applicable to large-scale rural lv network planning.

This method considers the planning problem as a whole. While the mathematic programming methods simplify the cost function (linealization) and fix or restrict mv/lv substation locations, the proposed method uses the real cost function and the mv/lv substation location is optimized simultaneously with the lv network.

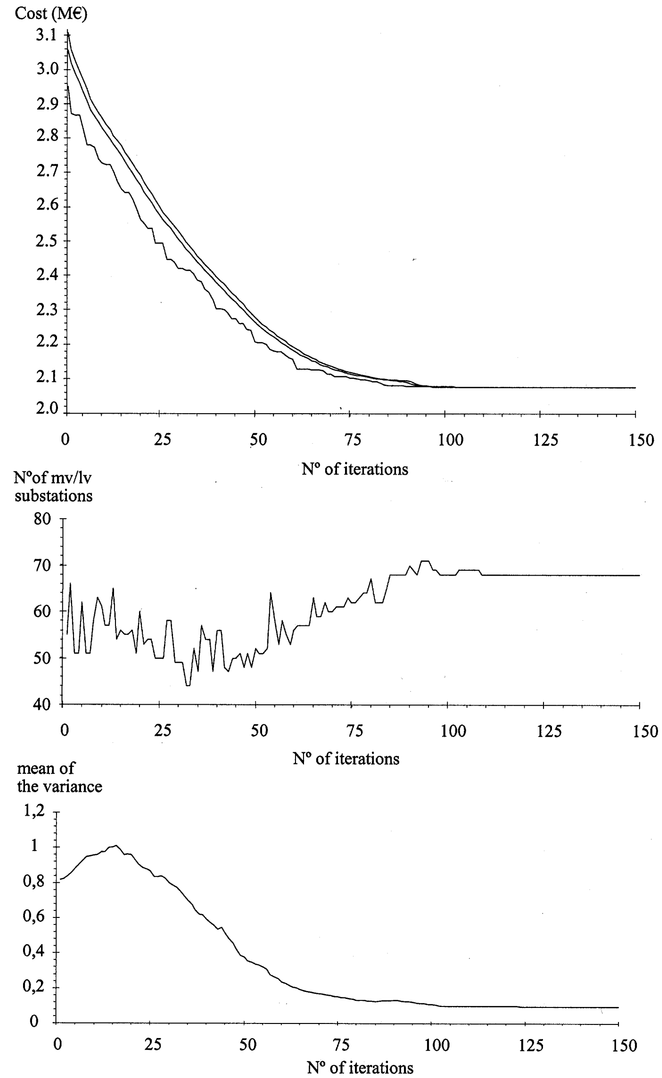


Fig. 10. Curves for cost evolution, number of mv/lv substations, and mean value of the variance.

## APPENDIX

### A. Evaluation of a Tree [9]

This section describes the algorithm, based on dynamic programming, to evaluate the cost of a generic tree. It is considered that the tree is fed by only one mv/lv substation, and when this is not possible, the cost value is infinite. The proposed algorithm considers mv/lv substation location as not fixed, so it is an improvement of Tram and Wall's [22] method where mv/lv substation locations are considered fixed.

Fig. 11 presents an example. From a generic tree T, the subtrees are defined $A^i_{(i,j)}$ and $A^j_{(i,j)}$; as a result of taking off the branch $(i, j)$. The $A^i_{(i,j)}$ subtree includes the node i, and $A^j_{(i,j)}$ the node j. The current $I^i_{(i,j)}$, that will be named subtree current, is defined by the addition of all loads into the subtree $A^i_{(i,j)}$, and that will feed $A^i_{(i,j)}$ if the mv/lv substation is in subtree $A^j_{(i,j)}$. Similarly, for current $I^j_{(i,j)}$ of subtree $A^j_{(i,j)}$.

By using subtree $A^i_{(i,j)}$, costs can be represented as a function of voltage drop for the various types of conductors employed

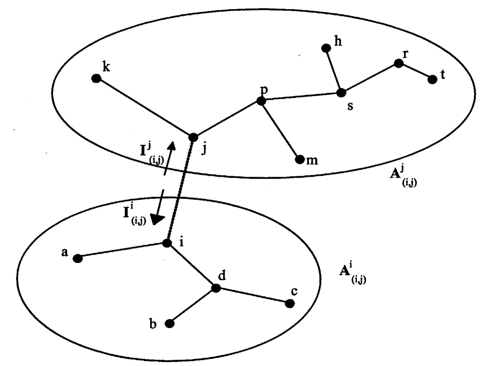


Fig. 11. Generic tree and subtrees.

along each branch. According to the dynamic programming process, the cost function is associated with maximum voltage-drop in the subtree.

So mathematically, the cost function of subtree $A^i_{(i,j)}$ can be noted by $D^i_{(i,j)}[\Delta u^i]$, where $\Delta u^i$ is the maximum voltage-drop in subtree $A^i_{(i,j)}$. Recursively, the expression is

$$D^i_{(i,j)}\left[\Delta u^i\right] = \sum_{\substack{x=adj(i)\\ x\neq j}} \min_{t_k\in Y}\left\{D^x_{(x,i)}\left[\Delta u^x_s\right] + C_{(x,i),t_k}\right\} \Big/ \quad \Delta u^i = \max\left\{\Delta u^x_s + \Delta u_{(x,i),t_k}\right\} \quad (5)$$

where

| | |
|---|---|
| $adj(i)$ | adjacent nodes to i; |
| $t_k$ | k-type conductor; |
| $C_{(x,i),t_k}$ | cost of branch $(x, i)$ with the $t_k$ type conductor defined by expression (7); |
| Y | set of type conductors and $\Delta u^x_s$ represents the "s" different voltage-drop values in subtree $A^x_{(x,i)}$. |

The process starts in leaf nodes, f, where $A^f_{(f,.)}[0] = 0$ and $\Delta u^f_0 = 0$ are considered. When the recursive process ends, each node has an associated table: DV-table. The DV-table is defined by cost and voltage-drop. So each node i has $\delta$ tables, where $\delta$ is the degree of node i (number of branches which have i as terminal endpoint). These DV-tables have a dimension according to level in the tree and number of types of lines used.

The operation process to calculate the cost of T tree can be defined by the following algorithm.

1) Select one branch $(m, s)$ where it is supposed the mv/lv substation exists.
2) Select DV-tables corresponding to $A^m_{(m,s)}$ and $A^s_{(s,m)}$ subtrees $D^m_{(m,s)}$ and $D^s_{(s,m)}$.
3) The cost $S_{(m,0,s)}$ of T, considering the substation in fictitious node "0" (see Fig. 12), is determined as: (Please see the equation at the bottom of the next page.) where

| | |
|---|---|
| "0" | fictitious node (between m and s) where the mv/lv substation is located; |
| $\Delta u_{max}$ | maximum voltage-drop submitted. |

To search for the node "0," where the mv/lv substation is located, a discretization of branch $(m, s)$ is needed.

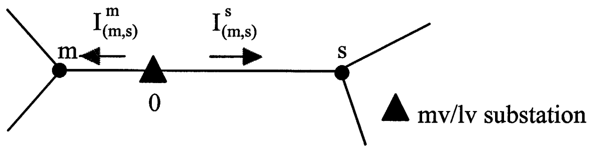


Fig. 12. mv/lv substation location.

So the length of branch $(m, s)$ is discretized in N intervals: $(m, 1), (1, 2), \ldots (N-1, s)$; and each new node $(1, 2, \ldots N-1)$ is a new location of the mv/lv substation (node "0") to evaluate.

### *B. Costs of Investment and Electrical Losses by the lv Lines and mv/lv Substations*

*1) Line cost:* The line cost (branch cost) of the branch $(i, j)$ is defined by the expression

$$C_{(i,j),t_k} = \left(c_{t_k} + c'_{t_k} \cdot I^2_{(i,j)}\right) \cdot d_{(i,j)} \tag{7}$$

where

$I_{(i,j)}$ current that flows in branch $(i, j)$, from i node to j node;

$d_{(i,j)}$ distance of branch $(i, j)$;

$c_{tk}$ cost of the k-type line, per unit of length;

$c'_{tk}$ cost of electrical losses in type k lines, per unit of length;

$I^{max}_t$ limit of current of the k-type conductor

If $I_{(i,j)} > I^{max}_t$, the cost of the line $(i, j)$ with conductor type $k$ is considered infinite. The conductor costs are represented by Fig. 13.

*2) mv/lv Substation Cost:* The cost of the different substations considered in the algorithm are obtained by the following expression:

$$C_{s_k} = c_{s_k} + c'_{s_k} \cdot P^2_k \tag{8}$$

where

$c_{s_k}$ investment cost and cost of iron losses in the type k substation;

$c'_{s_k}$ cost of electrical losses in the type k substation;

$P_k$ real power that flows through the type k substation;

$P^{max}_k$ limit of power of the type k substation.

If $P_k > P^{max}_k$, the cost of the substation type $k$ is considered infinite. The mv/lv substation costs are shown in Table I.

The economic parameters are: 0.04 €/kW-losses, 25-year planning, 5% overload factor, 1% annual inflation, and 5% annual interest. The annual loss load factor employed was [23]: $lsf = 0.16 * lf + 0.84 * lf^2$, with the load factor $lf = 0.25$.

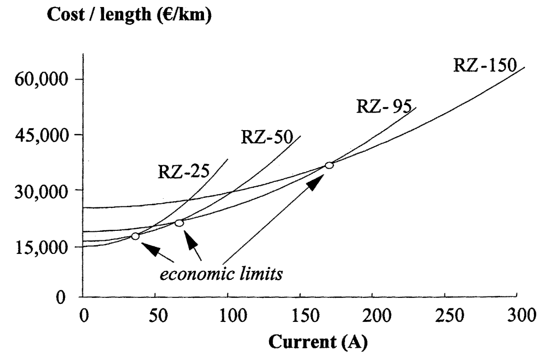


Fig. 13. Cost for typical Spanish commercial lv lines.

TABLE I
COSTS FOR COMMERCIAL mv/lv SUBSTATIONS

| mv/lv type Rating transformer (kVA) | Fixed costs (€) | Variable costs (€/kVA$^2$) |
|---|---|---|
| 25 | 8,920 | 0.984 |
| 50 | 9,450 | 0.386 |
| 100 | 10,940 | 0.154 |
| 160 | 13,685 | 0.080 |
| 250 | 23,260 | 0.045 |
| 400 | 26,650 | 0.025 |
| 630 | 30,470 | 0.014 |
| 1000 | 34,635 | 0.009 |

## REFERENCES

[1] T. L. Grimsdale and P. H. Sinclare, "The design of the housing estate distribution system using a digital computer," *Proc. Inst. Elect. Eng.*, vol. 107A, pp. 295–305, 1960.

[2] Y. Backlund and J. A. Bubenko, "Computer aided distribution system planning," *Electric Power Energy Syst.*, vol. 1, no. 1, pp. 35–45, 1979.

[3] ——, "Computer aided distribution system planning: Part 2. Primary and secondary circuits modeling," in *Proc. 6th Power Syst. Comput. Conf.*, 1978, pp. 166–175.

[4] M. J. Carson and G. Cornfield, "Design of low-voltage distribution networks. Interactive computer method based on the calculus of variations," *Proc. Inst. Elect. Eng.*, vol. 120, no. 5, pp. 585–592, May 1973.

[5] Z. Sumic, S. S. Venkata, and T. Pistorese, "Automated underground residential distribution design. Part 1: Conceptual design," *IEEE Trans. Power Delivery*, vol. 8, pp. 637–643, Apr. 1993.

[6] Z. Sumic, S. S. Venkata, and T. Pistorese, "Automated underground residential distribution design. Part 2: Prototype implementation and results," *IEEE Trans. Power Delivery*, vol. 8, pp. 644–650, Apr. 1993.

[7] K. S. Hindi and A. Brameller, "Design of low-voltage distribution networks: A mathematical programming method," *Proc. Inst. Elect. Eng.*, vol. 124, no. 1, pp. 54–58, 1977.

[8] G. Ahlbom, B. Axelsson, Y. Backlund, J. Bubenko, and G. Toraeng, "Practical application of computer-aided planning of public distribution system," in *Proc. 8th Int. Conf. Electricity Dist.*, 1985, pp. 424–428.

[9] E. Díaz-Dorado, E. Míguez, and J. Cidrás, "Design of large rural low-voltage networks using dynamic programming optimization," *IEEE Trans. Power Syst.*, vol. 16, pp. 898–903, Nov. 2001.

[10] E. Díaz-Dorado, "Herramientas para la planificacion de redes de baja tensión y media tension urbanas," Ph.D. dissertation (in Spanish), Univ. Vigo, Vigo, Spain, 1999.

$$S_{(m,0,s)} = C_{\text{subst}} + \min \left\{ \begin{array}{l} D^m_{(m,s)}[p] + D^s_{(s,m)}[q] + C_{(m,0),t_k} + C_{(0,s),t_{k'}} / \\ \max\{p \cdot \Delta u + \Delta u_{(m,0),t_k}, q \cdot \Delta u + \Delta u_{(0,s),t_{k'}}\} \le \Delta u_{\max} \\ p, q = 0, \ldots, M \end{array} \right\} \tag{6}$$

[11] C. W. Hasselfield, P. Wilson, L. Penner, M. Lau, and A. M. Gole, "An automated method for least cost distribution planning," *IEEE Trans. Power Delivery*, vol. 5, pp. 1188–1194, Apr. 1990.

[12] S. Jonnavithula and R. Billinton, "Minimum Cost Analysis of Feeder Routing in Distribution System Planning Rep.," IEEE, 96 WM 113-1 PWRD, 1996.

[13] I. J. Ramírez-Rosado and J. L. Bernal-Agustín, "Genetic algorithms applied to the design of large power distribution systems," *IEEE Trans. Power Syst.*, vol. 13, pp. 696–703, May 1998.

[14] V. Miranda, J. V. Ranito, and L. M. Proença, "Genetic algorithms in optimal multistage distribution network planning," *IEEE Trans. Power Syst.*, vol. 9, pp. 1927–1933, Nov. 1994.

[15] D. E. Bouchard and M. M. A. Salama, "Optimal distribution feeder routing and optimal substation sizing and placement using evolutionary strategies," in *Proc. Canadian Conf. Elect. Comput. Eng.*, vol. 2, Halifax, NS, Canada, 1994, pp. 661–664.

[16] P. M. S. Carvalho, L. A. F. M. Ferreira, F. G. Lobo, and L. M. F. Barruncho, "Optimal distribution network expansion planning under uncertainty by evolutionary decision convergence," *Int. J. Electrical Power Energy Syst.*, vol. 20, no. 2, pp. 125–129, 1998.

[17] E. Míguez, E. Díaz-Dorado, and J. Cidrás, "An application of an evolution strategy in power distribution system planning," *Proc. IEEE Int. Conf. Evol. Comput.*, pp. 241–246, May 1998.

[18] E. Míguez, "Herramientas para la planificación de redes de distribución en áreas de población dispersa," Ph.D. dissertation, Universidade de Vigo, Spain, 1999. Spanish.

[19] E. Díaz-Dorado, J. Cidrás, and E. Míguez, "Application of evolutionary algorithms for the planning of urban distribution networks of medium voltage," *IEEE Trans. Power Syst.*, vol. 17, pp. 879–884, Aug. 2002.

[20] V. Miranda, D. Srinivasan, and L. M. Proença, "Evolutionary computation in power systems," *Electrical Power Energy Syst.*, vol. 20, no. 2, pp. 89–98, 1998.

[21] G. Winter, J. Périaux, M. Galan, and P. Cuesta, *Genetic Algorithms in Engineering and Computer Science*. New York: Wiley, 1996.

[22] H. N. Tram and D. L. Wall, "Optimal conductor selection in planning radial distribution systems," *IEEE Trans. Power Syst.*, vol. 3, pp. 200–206, May 1988.

[23] G. J. Salis and A. S. Safigianni, "Optimum long-term planning of a radial primary distribution network. Part I: Data description and first proposed network form," *Int. J. Electrical Power Energy Syst.*, vol. 20, no. 1, pp. 35–41, 1998.

**Eloy Díaz-Dorado** received the Ph.D. degree in electrical engineering from the Universidade de Vigo, Vigo, Spain, in 1999.

Currently, he is a Professor of the Departamento de Enxeñeria Eléctrica Universidade de Vigo. His research interests include estimation and planning of power systems.

**José Cidrás Pidre** (M'92) received the Ph.D. degree in electrical engineering from the Universidade de Santiago de Compostela, Spain, in 1987.

Currently, he is Professor of the Departamento de Enxeñeria Eléctrica, Universidade de Vigo, Spain. He leads some investigation projects into wind energy, photovoltaic energy, and planning of power systems.

**Edelmiro Míguez García** (A'98) received the Ph.D. degree in electrical engineering from the Universidade de Vigo, Vigo, Spain, in 1999.

Currently, he is Professor of the Departamento de Enxeñeria Eléctrica Universidade de Vigo. His research interests include planning and analysis of power systems.