



Smart Cities - The Optimization of their Development

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Smart Cities – The Optimization of their Development

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Abstract—The ongoing development and extensions of cities, as well as the requirement for large scale deployment of renewable energy sources and electro-mobility determine the transformation of current electrical grids towards smart grids. The increasing demand and the requirement for its reliable supply is imposing new planning challenges for the development of electrical networks. The present paper describes a method of optimizing the development of urban electricity networks, by selecting from a set of available locations, the positions and the size of new power sources, using a multistage model. Results can be useful to plan the installation of new power sources in an existing network (distributed sources, renewable sources for powering electric vehicles).

Index Terms-- distribution network, multistage model, optimization method, smart city.

I. INTRODUCTION

In agreement with current European Union framework plans for the development of exiting cities, the current electrical networks should evolve towards smart grids [1]. In addition, the requirement of pollutant reduction emissions within the cities is leading to a diversification of energy mix within city boundaries by large-scale integration of renewable energy sources. Also, the transportation sector is evolving and electro-mobility and storage systems large scale deployment is envisaged by 2030 and 2050. All this is requiring advanced information and telecommunication technologies with large data volumes to be managed and used [2].

The current operation of the electrical urban networks is done in a radial configuration. As nowadays the cities are evolving, with new residential districts being built new electrical networks configuration can be proposed [3-6]. The integration of electrical vehicle charging stations (slow/fast/ultrafast) and distributed storage systems impose further constraints in the design of future electrical networks. In addition, power quality and continuity of supply requirements are more and more restrictive for increasing the residents level of wellbeing satisfaction [7-10].

This paper proposes a model considering the existing and future potential power sources within the network. Hence, for an existing source, the unitary cost of energy supplied and the capacity of the source are known. For the new power sources, we will know the unitary cost of supplied energy, their capacities and a fixed cost needed for construction and procurement works. If a potential power source is out of operation, it cannot provide electricity and its fixed cost is no further considered.

The remainder of the paper is organized as follows: the methodology with the optimization mathematical model (the objective functions and the constraints) is presented in section II. Section III reports the analyzed case study and the obtained results, while the conclusions are discussed in section IV.

II. METHODOLOGY

The assumptions envisaged are as follows:

- a) the maximum power that can circulate on each of the power lines of the network is known;
- b) the cost of transporting electricity on a line is approximated by a linear function;

The studied electrical network is represented by a non-oriented connection graph with the source nodes (existing and potential) as well as the nodes corresponding to the consumers. The edges of the graph are determined by the power lines of the network. A fictive source vertex is introduced into the graph, which is considered a power supply for the entire power consumed in the network. Each vertex corresponding to an existing or potential source is connected by an edge to the fictitious point. Fig. 1 presents the modeled network with his main elements.

The following notations will be used:

s = fictitious source;

$I = \{1, \dots, m\} \cup \{s\}$ = set of source points;

$J = \{1, \dots, n\}$ = the set of the corresponding network consumer points;

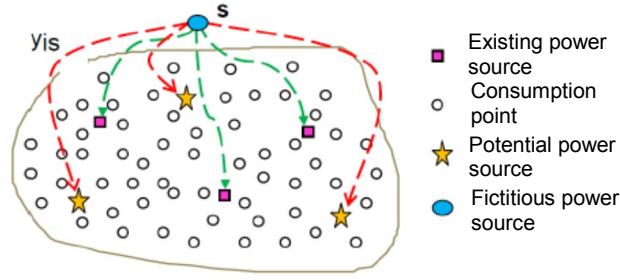


Figure 1. Modeling of the studied network elements

$N = I \cup J$ = the set of graph's vertices;

a_i = the available power at the source i , $i \in N$;

b_j = power consumption at the consumer j , $j \in N$;

c_{ij} = cost of one kW transported from the source i to the consumer j , $i \in N, j \in N$;

- $c_{ii} = 0, \forall i \in N$;
- $c_{ij} = \infty$ if the vertices i and j are not connected by an edge;

P_{ij} = power absorbed from the source i by the consumer j , $i \in N, j \in N$;

D_{ij} = the maximum permissible power that can be carried on the line section $i-j$;

F_{is} = fixed cost associated with source operation at vertex i ($F_{is} \neq 0$ only for new sources);

$$y_{is} = \begin{cases} 0, & \text{if the source situated in the vertex } i \\ & \text{is not in operation;} \\ 1, & \text{if the source situated in the vertex } i \\ & \text{is in operation.} \end{cases}$$

Using the above notations, the following mathematical model is written:

$$\text{MIN} \left(\sum_{i \in N} \sum_{j \in N} c_{ij} P_{ij} + \sum_{i \in I} y_{is} F_{is} \right) \quad (1)$$

$$\sum_{j \in N} P_{ij} \leq a_i, \quad i \in N \quad (2)$$

$$\sum_{i \in N} P_{ij} = b_j, \quad j \in N \quad (3)$$

$$0 \leq P_{ij} \leq D_{ij}, \quad i \in N, j \in N, j \neq s \quad (4)$$

$$0 \leq P_{is} \leq y_{is} D_{is}, \quad i \in I \quad (5)$$

$$y_{is} = 0 \text{ or } 1, \quad i \in I \quad (6)$$

The equation (1) represent the objective function of the mathematical model, minimizing the total cost of the network development. The constraint (2) represents the condition that the sum of the power flows from source i to all the consumers must be inferior or equal to the power available at source i . The constraint (3) represents the condition that the sum of the power flows from all the sources to the consumer j must be equal to the power needed by the consumer j . The constraint (4) represents the condition that on each line section $i-j$, the power flow P_{ij} must be inferior to the maximum permissible power on that line, D_{ij} . The constraint (5) is similar to the constraint (4), but applicable only to the fictitious lines is . The constraint (6) reflects the binary character of the y_{is} variables.

The problem defined by the equations (1)–(6) has two types of variables, P_{ij} and y_{is} , which represents the optimization variables. For this reason, the problem is a mixed linear programming problem, having real continuous variables (P_{ij}) as well as binary variables (y_{is}).

If each of the y_{is} variables is set to either 0 or 1, the problem given by the equations (1)–(4) is a transport problem with limited capacities.

By enumerating all the situations in which the m binary variables y_{is} can be found, a finite number of 2^m transport problems will result, by solving which can be determined the optimal solution of the problem (1)–(6).

This type of problem presented above was solved in [11] using the "branch and bound" method. But, starting from the fact that of the m variables y_{is} only the ones corresponding to the potential sources can be interesting (by the fixed costs involved in commissioning) and considering the variables $y_{is} = 1$ for all the existing sources in the network, another solution will be proposed in this paper for the problem (1)–(6) using the "backtracking" method.

We will use the notations:

$$I' = \text{the set of potential source vertices,} \quad (7)$$

$$I' \subseteq I, \text{ card } I' = m' \leq m;$$

$$Y' = \text{vector containing the } m' \text{ variables } y_{is}, i \in I'. \quad (8)$$

Under these circumstances, from the 2^m distinct problems in which the problem (1)–(6) can be decomposed, we will only be interested by $2^{m'}$ problems. In addition, by applying the backtracking method, it will not be necessary to research all of the $2^{m'}$ possible solutions.

Thus, elements of the vector Y' are assigned values one by one. For the variable y_{is_k} is given a value of 0 or 1 only if values

for the variables $y_{is_1}, \dots, y_{is_{k-1}}$, have already been assigned. After setting a value for the variable y_{is_k} , the algorithm does not go directly to the assignment of values to $y_{is_{k+1}}$, but verify first a continuity condition for $y_{is_1}, \dots, y_{is_k}$. This condition determines the situations in which it makes sense to pass to the calculation of $y_{is_{k+1}}$, failure to do so by expressing the fact that if we choose $y_{is_{k+1}}, \dots, y_{is_m}$, anyway, we cannot reach a possible solution to the problem (1)–(6). If the continuation condition is not met, another choice will be made for y_{is_k} or, if this is not possible, k is reduced by one unit and a new value for the current y_{is_k} variable is attempted.

If we denote with PT the total power demanded by the consumers in the grid, with the PE power provided by the existing sources and with PP the proposed power to be installed in the new sources, we will have:

$$PP \geq PT - PE \quad (9)$$

Thus, we can consider as continuation condition for the backtracking algorithm to solve the problem (1)–(6) reduced according to the notations (7) and (8), the requirement that the sum of the available power in the potential sources for which the corresponding y_s variables do not have yet the value 0 (these sources can still be put into operation) be at least equal to the PP value. By denoting with I'' the subset of I formed from potential sources for which the variables y_{is} were given the value 0, the continuation condition can be written as:

$$\sum_{i \in I' \setminus I''} a_i \geq PP \quad (10)$$

The condition (10) assure us that it is still possible to obtain a possible solution for the problem (1)–(6), considering all the values granted so far for the variables y_{is} .

For each of the final vectors $\mathbf{Y}'$ obtained by respecting condition (10), the condition (10) for validation of the value of the last variable is checked again, after which a transport problem (1)–(5) with fixed y_{is} values is solved. Among the solutions to these problems will finally be selected the optimal solution or, in other words, the sites in which new power supplies will be put into operation.

III. CASE STUDY

Let us consider a network having 20 consumption points, from which 3 power supplies (1, 2 and 3) already exist and 3 locations are proposed to install new sources (4, 5 and 6). The values PT = 2100 kVA, PE = 1200 kVA, PP = 900 kVA are known. Table I reports the capacities and fixed costs for each of the $m = 6$ power supplies.

For this example, we will have thus:

- $m = 6$ and $m' = 3$;
- $I = \{1, 2, 3, 4, 5, 6\}$ and $I' = \{4, 5, 6\}$;

$$\bullet (\mathbf{Y}')^t = (y_{4s}, y_{5s}, y_{6s}).$$

In Table I are presented the capacities of existing power sources (1, 2 and 3), the capacities that can be installed in the new potential power sources (4, 5 and 6), as well as the fix costs (given in monetary units, only for the new power sources).

TABLE I. INSTALLED POWER AND FIXED COSTS ASSOCIATED WITH SOURCES

Source no.	S_n (kVA)	Fixed Cost (m.u.)
1	400	0
2	400	0
3	400	0
4	250	4000
5	650	4500
6	400	3500

There are therefore $2^{m'} = 2^3 = 8$ possibilities of operation for the new 3 potential sources. The mode of determination, according to the backtracking method, of the $2^{m'}$ vectors $\mathbf{Y}'$ is illustrated in Fig. 2, where the solution space was represented for the studied example.

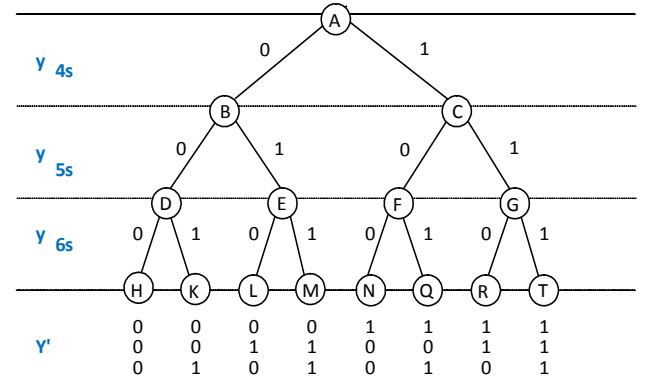


Figure 2. Solution space

The search of the solutions starts from the vertex A. By giving to the binary variable y_{4s} the value 0 (the first possible value) we reached the vertex B of the binary tree which describes the generation process of all eight vectors $\mathbf{Y}'$. Being in B, we verify the fulfillment of the continuation condition (10):

$$I_B'' = \{4\}; \sum_{i \in I' \setminus I''} a_i = a_5 + a_6 = 650 + 400 = 1050 \text{ kVA} > PP = 900 \text{ kVA};$$

$$(\mathbf{Y}'_B)^t = (0, y_{5s}, y_{6s}).$$

The value 0 is then assigned to the variable y_{5s} , reaching the D vertex. From verification of the continuation condition, it follows that a possible solution cannot be obtained if y_{4s} and y_{5s} are equal to zero:

$$I_D'' = \{4; 5\}; \sum_{i \in I' \setminus I''} a_i = a_6 = 400 = 400 \text{ kVA} < PP = 900 \text{ kVA};$$

$$(Y_D')^t = (0, 0, y_{6s}).$$

Therefore, it is not necessary to examine the vertices H and K, but returns to the vertex B, giving to the binary variable y_{5s} the other remaining available value, the value 1, thus reaching the vertex E. The continuation condition is also checked here:

$$I_E'' = \{4\}; \sum_{i \in I' \setminus I''} a_i = a_5 + a_6 = 650 + 400 = 1050 \text{ kVA} > PP = 900 \text{ kVA};$$

$$(Y_E')^t = (0, 1, y_{6s}).$$

Next, we assign a value to the variable y_{6s} . Fixing $y_{6s} = 0$, we reached the vertex L. The solution obtained cannot be accepted because it does not fulfill the condition (10):

$$I_L'' = \{4; 6\}; \sum_{i \in I' \setminus I''} a_i = a_5 = 650 = 650 \text{ kVA} < PP = 900 \text{ kVA};$$

$$(Y_L')^t = (0, 1, 0).$$

Consequently, we return to the vertex E and we assign the next available value to the binary variable y_{6s} , that is, the value 1, thus arriving to the vertex M. The new solution corresponding to the vertex M fulfills the condition (10):

$$I_M'' = \{4\}; \sum_{i \in I' \setminus I''} a_i = a_5 + a_6 = 650 + 400 = 1050 \text{ kVA} > PP = 900 \text{ kVA};$$

$$(Y_M')^t = (0, 1, 1).$$

Y_M is the first possible solution obtained until now. For the determination of other solutions, since the variables y_{6s} and y_{5s} have taken all their possible values, we return to the vertex A and we assign to the binary variable y_{4s} the next available value (that is 1), thus moving to the vertex C. We must verify here also the condition of continuation:

$$I_C'' = \{0\}; \sum_{i \in I' \setminus I''} a_i = a_4 + a_5 + a_6 = 250 + 650 + 400 = 1300 \text{ kVA} > PP = 900 \text{ kVA};$$

$$(Y_C')^t = (0, y_{5s}, y_{6s}).$$

We continue the displacement in the solution space, and we assign then the value 0 to the binary variable y_{5s} , reaching so the vertex F. The continuation condition is not met at the vertex F:

$$I_F'' = \{5\}; \sum_{i \in I' \setminus I''} a_i = a_4 + a_6 = 250 + 400 = 650 \text{ kVA} < PP = 900 \text{ kVA};$$

$$(Y_F')^t = (1, 0, y_{6s}).$$

By not respecting the continuity condition at the vertex F, the final solutions corresponding to the N and Q vertices will not be further investigated. Returning to the vertex C, we will assign the next available value to the binary variable y_{5s} , that is the value 1. At the vertex G, the continuation condition is met:

$$I_G'' = \{\emptyset\}; \sum_{i \in I' \setminus I''} a_i = a_4 + a_5 + a_6 = 250 + 650 + 400 = 1300 \text{ kVA} > PP = 900 \text{ kVA};$$

$$(Y_G')^t = (1, 1, y_{6s}).$$

If the variable y_{6s} is then assigned to 0, the final solution at the vertex R will satisfy the condition (10) and therefore R will represent another possible solution, the second one:

$$I_R'' = \{6\}; \sum_{i \in I' \setminus I''} a_i = a_4 + a_5 = 250 + 650 = 900 \text{ kVA} = PP = 900 \text{ kVA};$$

$$(Y_R')^t = (0, 1, 1).$$

The last solution is obtained by returning to the vertex G and fixing the variable y_{6s} to the value 1. The final solution, corresponding to the vertex T, met the condition (10):

$$I_T'' = \{\emptyset\}; \sum_{i \in I' \setminus I''} a_i = a_4 + a_5 + a_6 = 250 + 650 + 400 = 1300 \text{ kVA} > PP = 900 \text{ kVA};$$

$$(Y_T')^t = (1, 1, 1).$$

Fig. 3 presents the trajectory of the algorithm through the solution space. Green lines represent movements in the depth of the solution space, red lines represent returns due to non-fulfillment of condition (10), while blue lines represent returns to the next possible value for the current binary variable.

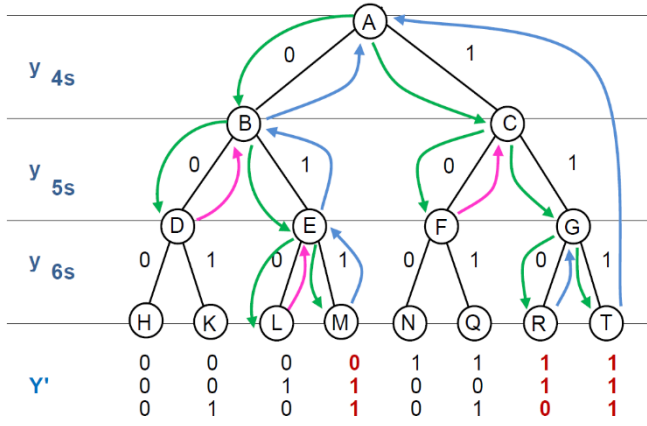


Figure 3. Trajectory of the algorithm in the solution space

Therefore, from the $2^m = 2^3 = 8$ possibilities to install the new power supplies, only 3 represents possible solutions, namely Y'_M , Y'_R and Y'_T . To further determine the locations in which new power supplies will be deployed, we will now solve 3 transportation problems with the y_{4s} , y_{5s} and y_{6s} variables fixed according to the three possible solutions above (M, R and T). From the three possible locations of the new sources, it will be chosen the one having the lowest value of the objective function (1).

The efficiency of the backtracking method presented is given by the ratio between the number of transport problems solved by its application, N_{BM} , and the number of transport problems required to be solved by the enumeration method, N_T . It must be said that the enumeration method will identify, for the analyzed example, 8 solutions, for all this, then a transport problem must be solved. This ratio (N_{BM}/N_T) will show how many of the total number of solutions has been studied to get the best solution of the problem. So,

$$\frac{N_{BM}}{N_T} \cdot 100 = \frac{3}{8} \cdot 100 = 37,50\%$$

As a result, the analysis of 62.5% of the solutions were avoided for the studied example. The percentage of efficiency depends on the size of the problem (the number of potential sites) and on the power to be installed in the network and on the power installed at each site.

If $a_i \geq PP$, $\forall i \in I$, so if the power available in each potential new site is at least equal to the total power required to be installed in the grid, $2^m - 1$ possibilities of operation of the new sources will have to be investigated. The amount of power available in each potential site is not determined in this method.

If the variables y_{is} are also left free for the existing sources in the network and if the available power of the new potential sources is large enough, solutions can be found where some of the existing sources are closed (due to the losses of energy they generate through the electrical lines of the grid), their consumers being supplied more economically by the rest of existing sources along with new ones.

By solving transport problems, the topology of the electrical network's operation schemes will be mixed, with both dual-source and radial-fed consumers.

The constraint (4) corresponds to the requirement to limit the power flow through the network lines to the maximum allowable values D_{ij} . For the optimal solution, however, the level of voltages in the nodes of the network must be checked, as there is no such verification in the method presented.

IV. CONCLUSIONS

The present paper describes a method of optimizing the development of urban electricity networks, by selecting from a set of available locations, the positions and the size of new power sources, using a multistage model. As results, we obtain the optimum number of sources and their size, as well as the topology of the new electrical lines. The optimization model assures also the minimization of the operation costs of the network (mainly the cost losses of energy in the electrical lines), including the costs for the new sources.

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