Multistage Distribution System Expansion Planning with many Alternatives of Conductors

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***Abstract*—Distribution system expansion planning models generally do not limit the number of conductors' alternatives that can be used in planning, and Distribution Companies may be faced with a scenario of many alternatives as they expand their systems. However, Distribution Companies are interested in few stocking alternatives for the conductors that will be installed during the expansion. In this context, this paper proposed an algorithm based on Chu-Beasley's genetic operators for selecting a reduced number of conductors' alternatives and Branch & Cut to solve the distribution expansion planning problem. The algorithm uses genetic operators to create a set of conductors' alternatives that are used in the distribution system expansion planning model. The mixed-integer planning model addresses the inclusion or replacement of substation, conductors, and transformers, and the inclusion or increase of substation capacity. Conductor alternatives are generated from the alternatives found in the literature. The results show that the proposed method is promising in the search for valid conductors' alternatives to reduce the investment costs in the distribution expansion.**

***Index Terms*—Genetic algorithms, materials requirements planning, power distribution, power system planning.**

I. Introduction

The Distribution Companies need to expand their systems to serve their consumers complying with the requirements of power quality and system reliability imposed by local regulatory agencies. During the planning phase, these companies are looking for the lowest possible investment cost. This duality between quality and cost characterizes the problem of distribution system expansion planning, which aims to minimize expansion costs by making changes to the current system that respect the constraints of power quality and reliability, given the growing demand from consumers.

Relevant work in the area of distribution system expansion planning has been carried out using the multistage linear integer-mixed model. This model was initially proposed by Haffner *et al.* [1], in which he makes the planning considering investment and operating costs. In [2], the necessary and sufficient constraints to maintain radiality in distribution system problems were discussed. In [3], the allocation of both conventional and renewable distributed generators, including radiality constraints, are unified in the model. More recently, [4] included reliability indicators. Finally, [5] included in the model the demand response and allocation of energy storage using stochastic programming techniques.

During the distribution system expansion planning, there may be several alternatives available in the market for the devices that can be used. Among the expansion planning models, there is a gap over the limit of the conductor alternatives used. In these models, the distribution company needs a prior study of the conductors that can be used in the expansion plan to prevent many alternatives being kept in stock for future maintenance. However, this prior study may not select conductor alternatives that minimize investment costs.

Therefore, it would be ideal to choose the reduced set of conductors' alternatives used as a decision of the expansion planning problem, rather than deciding which conductors will be used as prior information, as this decision may increase investment costs.

On the other hand, the problem of conductor size selection has been widely investigated. This problem has a focus on minimizing: the total cost of investment in conductors or the total energy losses. Some studies used heuristics and evolutionary algorithms to solve this problem [6]–[9]. In [10], a linearization of the problem is proposed. However, most of these studies address only the reconductoring and selection of an already operated distribution system.

In this context, the main contribution presented in this paper is to incorporate the selection of many conductors' alternatives in the problem of distribution expansion planning. The distribution expansion planning was modeled as an integer-mixed linear based in the model proposed by Muñoz-Delgado *et al.* [3]. This proposal is addressed by integrating Chu-Beasley's genetic processes [11] and the Branch & Cut method.

This paper is organized as follows: This section presents a contextualization of the problem as well as an introduction to the topic. In Section II, we present the problem formulation and the objective function. In Section III, the proposed method for resolution is presented. Section IV presents the numerical results found with a proposed approach. Finally, some relevant conclusions, as well as future work, is presented in Section V.

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II. Problem Formulation

The classical distribution expansion planning problem consists of determining the location, insertion moment, new equipment such as conductors and transformers. This problem also includes the possibility of creating or increasing the capacity of new substations. The plan has to respect the operational limits of the equipment, the voltage limits, and the demand forecasts. This problem is generally characterized as an optimization problem. The costs in the objective function are related to investments and system operation. The operating limits of voltage and equipment installed in the system are considered in the constraints of the model.

A. The mathematical model of distribution planning expansion problem

In this paper, the mathematical model proposed by Muñoz-Delgado *et al.* [3] is used to represent the distribution planning expansion problem. In that model, the planning problem is represented as a mixed-integer linear programming problem. In which it considers the inclusion or replacement of substation, conductors, and transformers and the inclusion or increase of substation capacity. The present value of the total costs (c^{TPV}) include investments, technical losses, cost of electricity production, and non-supplied energy. A representation of the model used can be seen in (1).

$$\begin{aligned} \text{min. } & c^{TPV} \\ \text{s.t. } & \text{Power Balance} \\ & \text{Operational limits} \\ & \text{Radiality constraints} \\ & \text{Logical constraints} \\ & \text{Investment constraints} \end{aligned} \tag{1}$$

In this model, loads and power injections are represented as a current injection. It is recognized that this model represents an optimistic and simplified system. However, this model presents acceptable results for planning, as applied in [3]–[5].

The model constraints are made up of five groups. In the power balance, Kirchoff's law of voltage and current are described, relating the demands with the current injections of the substation transformers through the current flow and voltage drop of the branches used and with the data of the conductors. Within the operating limits, the voltage and current limits of the system and installed devices are described. Radiality constraints describe the equations that ensure that the planned system remains radial. Logical constraints describe the equations regarding device uses. Investment restrictions describe a cap on investments that can be made per stage.

B. The problem of many conductors' alternatives

As can be seen in the model [3], in the logical and investment constraints, there are no conductor choice limits. Thus, in an extreme case, if the solution found in the planning problem uses 50 conductors' alternatives, the distribution company will need to keep 50 conductors' types in stock for maintenance.

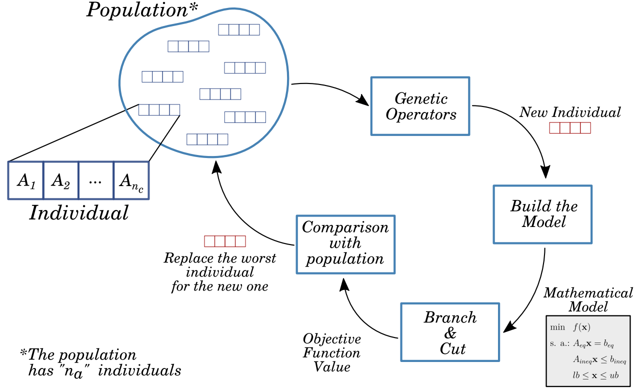

Fig. 1. The general idea of proposed method

In this example, it is noticeable that the distribution company does not intend to keep all types of conductors in stock.

To solve this problem, the distribution company may carry out a preliminary study of which conductors' types it is most interested in purchasing and from this reduced set, solve the planning problem.

Another option is to solve the planning problem for each combination of alternatives. However, this option suffers from a combinatorial explosion, significantly increasing the combinations that can be made, making the problem unfeasible. Thus, the following is the proposed method for the solution of this problem.

III. Proposed Method

This problem of many conductors' alternatives is addressed in this paper through a genetic process based on the Chu-Beasley's version [11] as can be seen in Fig. 1. This metaheuristic differs from the traditional genetic algorithm in that it only allows the replacement of one new individual from the population by generation, with the crossing of only two individuals from the population. Substitution in the population is made if the individual is better than the individual with the worst value of the evaluation function and different from everyone in the population.

In this paper, the individual is represented as a vector of size n_c. Each individual represents the set of conductors alternatives (A_{n_c}) that will be used in the mathematical model, and each position of the individual contains one alternative. Initially, the population is randomly generated, with size n_a and ensuring that the population has at least all available options. In which, n_c is the number of conductors' alternatives that the Distribution Company wants in the stock, and n_a is the number of available alternatives.

The evaluation function is the value of the objective function of the planning problem (1) solving for each individual using the Branch & Cut method. The Branch & Cut is executed with a *cut-off* mechanism with worst objective function value of the current population and a relative *gap* value. Although the proposed model by Muñoz-Delgado *et al.* [3] is used, any other mixed-integer linear model could be used. The use of *cut-off* and relative *gap* (an input parameter) in the proposed method, ensuring the strategy of substitution in the population of Chu-Beasley's genetic process.

For the initial population, the *cut-off* is not included. If, while exploring the Branch & Cut branches, the value of the objective function of the dual problem is worse than the *cut-off* value, the individual is automatically rejected and not included in the population. The selection of individuals from the population that will cross over is made by tournament, in which two individuals are randomly selected, and the one with the best evaluation function value is selected. The crossing is made by a fixed point, in the middle if n_c is even, or in the middle before it is odd.

The mutation is done in one of the randomly chosen alternatives of the individual. The mutation process randomly changes the alternative to the next or previous one. If the alternative chosen for mutation is the last one, it is always replaced by the previous one. If it is the first alternative, it is always replaced for the previous one.

A memory factor is included in the algorithm, preventing it from evaluating previously visited solutions. Every time the algorithm visits a new solution, it is included in memory in a random position. The memory also has a size that can be adjusted.

Using the *gap* makes Branch & Cut return solutions close to optimality in the first generations. However, with an increasingly better *cut-off* value, the *gap* value is no longer the main stopping criterion, forcing Branch & Cut solutions to move closer to optimality.

There are two criteria for stopping the algorithm. The first is due to reaching the maximum number of generations. The second is a stagnation criterion, which is incremented every time the algorithm looks for the same solution that has already been visited. The step-by-step algorithm is shown below.

Step 1: Start the initial population and empty memory.
Step 2: Evaluate the initial population by solving the planning problem for each individual in the population with the relative *gap*.
Step 3: Assign the *cut-off* value as the worst objective function of the population.
Step 4: Select two individuals per tournament.
Step 5: Generate a new individual by crossover and mutation, if applicable.
Step 6: If the individual is not in memory, reset the stagnation counter and go to **Step 7**, if so, increment the stagnation counter and go to **Step 10**.
Step 7: Solve the planning problem for the new individual with the relative *gap* and *cut-off*.
Step 8: If feasible, replace the worst individual in the population with the new, and add the new one to the memory.
Step 9: Increase generation counter.
Step 10: If it has reached the maximum generation or maximum stagnation generation value, stop the algorithm. The final solution is the best individual in the final population. If not, go to **Step 3**.

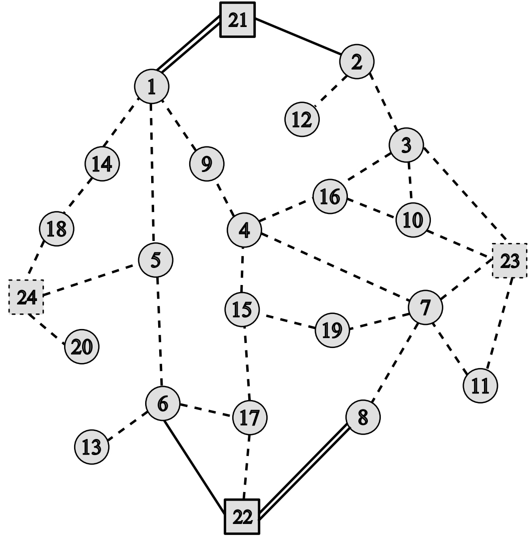

Fig. 2. Diagram of the 24-node distribution system

TABLE I
ALTERNATIVES OF CONDUCTORS BASE

Type	Alternative 1			Alternative 2		
	Amp.	Ω/km	$/km	Amp.	Ω/km	$/km
NRF	6.28	0.557	19140	9.00	0.478	29870
NAF	3.94	0.732	15020	6.28	0.557	25030

IV. Numerical Results

For illustration, the proposed method is tested in a 24-node system with three stages of planning whose input parameters and system data can be found in [3]. Fig. 2 illustrates the system to be designed, in which the dashed line indicates feeders that can be added, the solid line indicates feeders. The double solid line indicates feeders that can be replaced. The circles indicate a load node, the squares in solid lines indicate existing substations and squares in dashed lines the nodes that can receive substations. In this illustration, no distributed generator is used.

This planning case presents two conductors' alternatives that are presented in Table I. Eighty-eight other alternatives are created to represent the many conductor's case. These other alternatives are created multiplying the two original conductors' alternatives by 88 pseudorandom numbers between 0 and 2, respectively. In which, NRF is the nomenclature of the new replaceable feeder, and NAF is the nomenclature of the new added feeder.

These pseudorandom numbers are generated by a Mersenne Twister algorithm [12] with seed 1234. This pseudorandom number generator is implemented in several numeric packages of different programming languages [13], facilitating reproducibility.

In this illustration, it is considered that the Distribution Company intends to have only two conductors' alternatives in stock ($n_c = 2$). This problem constraint configures a total of 4005 different combinations of conductors' alternatives, which

TABLE II
INPUT PARAMETERS FOR THE NUMERICAL RESULTS

Description	Parameter	Value
Number of alternatives	n_a	88
Number of alternatives desired	n_c	2
Maximum number of generations	–	500
Mutation rate	–	20%
Size of population	–	90
Size of memory	–	90
Relative *gap*	–	1%
Maximum value of stagnation counter	–	50

TABLE III
SELECTED ALTERNATIVES

Type	Alternative 25			Alternative 35		
	Amp.	Ω/km	$/km	Amp.	Ω/km	$/km
NRF	5.514	0.489	16804.9	10.312	0.915	31427.9
NAF	3.459	0.643	13187.6	6.469	1.202	24662.8

makes the evaluation of each pair of alternatives unfeasible due to the complexity of the planning problem.

The planning problem model was implemented in JuMP v0.19 [14] and solved using the IBM ILOG CPLEX 12.9 solver [15]. The genetic algorithm and the solver call were implemented in Julia v1.1 language [16]. The tests were performed on an Intel i5-8400 8 GB computer with Windows 10 PRO 64 bit.

The input parameters of the proposed algorithm used in this paper can be seen in Table II. 1000 algorithm executions were performed, taking an average of 12 min. for each execution. Among the executions, the solution with options 25 and 35 (Table III) presented the lowest present value of the total costs, obtaining $c^{TPV} = \$\ 283.810 \times 10^6$. This value is close to the value reported in [3].

The planning solution for each stage can be seen in Fig. 3. It is possible to observe that all the nodes that have loads in each stage are fed and that the conductors already added in previous stages are not replaced. This is because these replacements increase the planning costs. In the presented solution, no load was without supply during the three planning stages, as well as the other two substations were used. It is also possible to observe that some nodes are connected even without a demand; this is due to other loads after they need to be supplied.

Fig. 4 shows the evolution of the objective function at each iteration of the algorithm. In this figure, it is observed that several iterations of the objective function remain constant, with some iterations of significant improvement. This behavior justifies the use of the 20% rate used due to the need to diversify the proposed method.

Fig. 5 presents the histogram of the algorithm's 1000 executions, demonstrating that it tends to find close objective function values and none higher than \$ 283.88 million. This behavior is explained by the impact that the feeder investment cost has on the planning problem of this system.

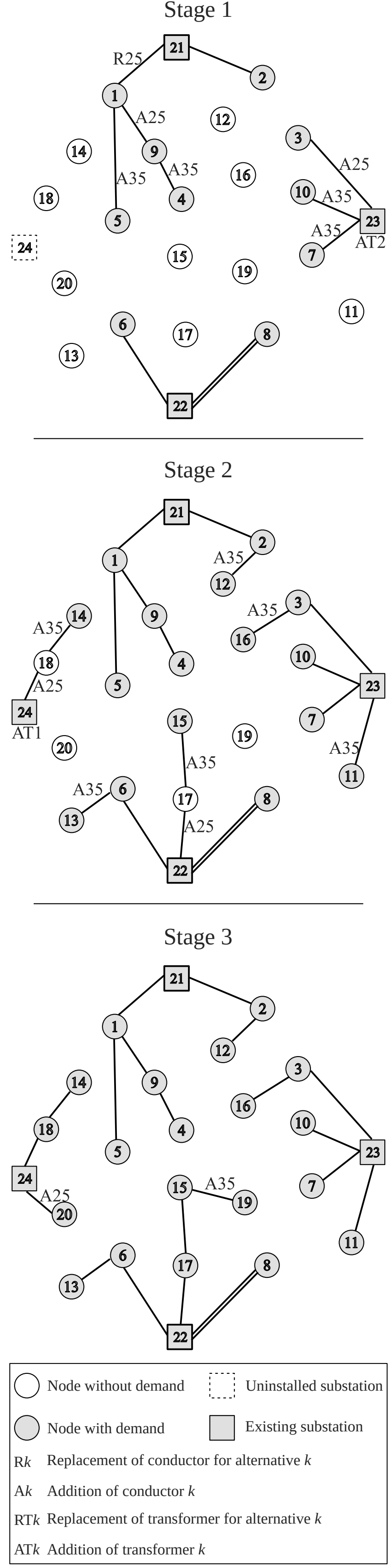

Fig. 3. Solution planning

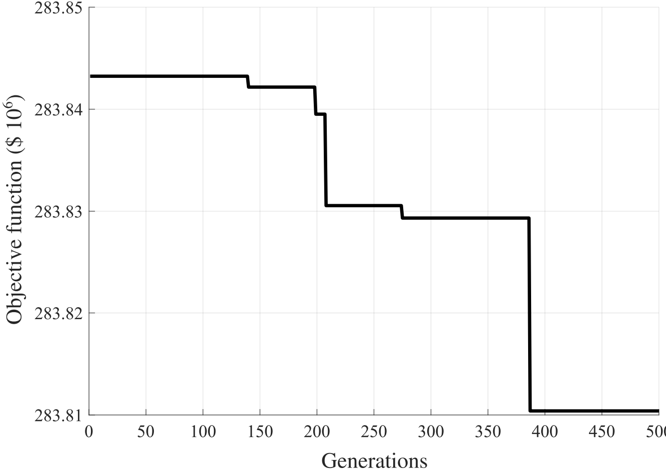

Fig. 4. Evolution of the objective function value.

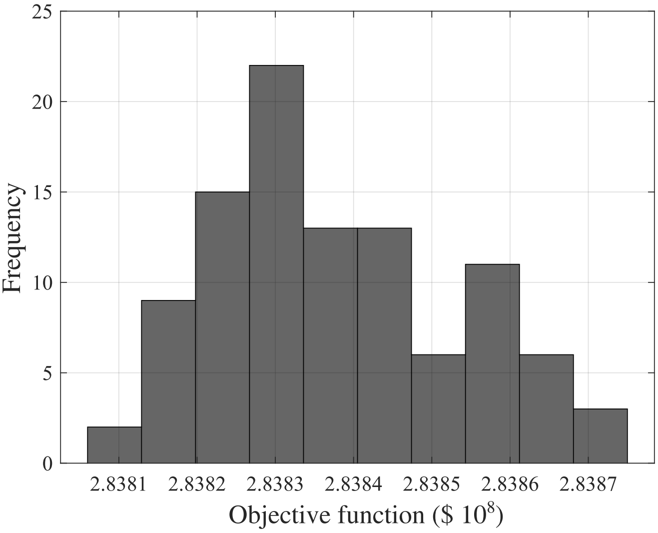

Fig. 5. Histogram of algorithm executions.

V. Conclusion

This paper proposes a conductor selection method for the distribution expansion planning problem. The method is based on Chu-Beasley's genetic algorithm and the Branch & Cut method. Genetic operators select the set of alternatives that will be used in the mathematical model solved by Branch & Cut. By way of illustration, the method was tested in a 24-node system with 88 conductors' alternatives. The results demonstrated that the algorithm could choose a reduced set of conductors that the Distribution Company will use in system planning. In the last generations of the algorithm, it was observed that the solutions came close to optimality due to the use of cut-off. In future work, the method can be improved by including new restrictions that limit options and are tested on larger systems.

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