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SPECIALIZED TABU SEARCH ALGORITHM APPLIED TO SECONDARY DISTRIBUTION SYSTEMS PLANNING

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ABSTRACT

To solve the problem of secondary distribution systems planning, this paper proposes a methodology using a tabu search algorithm as a solution technique. The problem is formulated as a nonlinear mixed-integer model, which takes into account the location and capacity of new elements (distribution transformers and primary-secondary distribution networks), relocation of existing distribution transformers, increasing the capacity of existing elements, secondary network reconfiguration, and phase balance. It also considers the costs associated with connections between primary and secondary networks and energy losses in distribution transformers. The methodology is applied to two test cases: in the first, a comparative analysis with the Chu-Besley genetic algorithm is made to verify the efficiency of the proposed methodology; and in the second, the results are analyzed in a Colombian distribution system. In both cases, the results are of high quality, supporting the proposed methodology.

KEYWORDS: Tabu search; Combinatorial optimization; Electrical systems planning; Secondary networks.

ALGORITMO DE BÚSQUEDA TABÚ ESPECIALIZADO APLICADO AL DISEÑO DE REDES SECUNDARIAS DE ENERGÍA ELÉCTRICA

RESUMEN

En este artículo se presenta una metodología para solucionar el problema del planeamiento de sistemas de distribución secundarios, empleando como técnica de solución el algoritmo de búsqueda tabú. El problema se formula como un modelo no lineal entero-mixto, en el cual se tienen en cuenta la ubicación y capacidad de nuevos elementos (transformadores de distribución y tramos de red primaria y secundaria), reubicación de transformadores de distribución existentes, aumento de capacidades de elementos existentes, reconfiguración de red secundaria y balance de fases. Adicionalmente considera los costos asociados a la conexión entre red primaria y secundaria y las pérdidas de energía en transformadores. Se emplean dos casos de prueba; en el primero se realizan ensayos comparativos con el algoritmo genético de Chu-Besley para verificar la eficiencia del método propuesto, y en el segundo se analizan los

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resultados obtenidos en un sistema de distribución colombiano. En ambos casos los resultados obtenidos son de gran calidad, lo que respalda lo propuesto en este trabajo.

PALABRAS CLAVE: búsqueda tabú; optimización combinatorial; planeamiento de sistemas eléctricos; redes secundarias.

ALGORITMO DE PESQUISA TABU ESPECIALIZADO APLICADO NO DESENHO DE REDES SECUNDÁRIAS DE ENERGIA ELÉTRICA

RESUMO

Neste artigo apresenta-se uma metodologia para solucionar o problema do planejamento de sistemas de distribuição secundários, empregando como técnica de solução o algoritmo de pesquisa tabu. O problema formula-se como um modelo não lineal enteiro-mixto, no qual se tem em conta a localização e capacidade de novos elementos (transformadores de distribuição e tramos de rede primária e secundária), relocalização de transformadores de distribuição existentes, aumento de capacidade de elementos existentes, reconfiguração de rede secundária e balanço de fases. Ademais consideram-se os custos associados à conexão entre rede primária e secundária e as perda de energia em transformadores. Empregam-se dois casos de prova, no primeiro realizam-se ensaios comparativos com o algoritmo genético de Chi-Besley para verificar a eficiência do método proposto, e no segundo analisam-se os resultados obtidos no sistema de distribuição colombiano. Nos ambos casos os resultados obtidos são de grande qualidade, o que apoia o que foi proposto neste trabalho.

PALAVRAS-CHAVE: pesquisa tabu; optimização combinatória; planejamento de sistemas eléctricos; redes secundárias.

1. INTRODUCTION

Proposals for secondary electrical energy distribution systems (PSEEDS) take into account the creation of expansion plans in areas that show growth in existing demand and the appearance of new loads. When these plans are designed, different alternatives appear depending on the needs of each energy provider and the conditions imposed by the governing body. The most appropriate solution for the given needs must consider a technical-economic balance that maximizes benefits for the company and minimizes project costs. Finding this solution requires modeling and solution techniques that optimize the given problem.

The related literature considers diverse methods, including the mathematical model that describes PSEEDS, the resolution technique, and the model of the system's elements. Some studies describe the problem using: a nonlinear model (Díaz-Dorado, Míguez & Cidras, 2001; Díaz-Dorado, Pidre & Míguez, 2003; Navarro & Rudnick, 2009), a nonlinear mixed-integer model (Costa & França, 2002; Cossi, Romero & Sánchez, 2005; Souza, 2006; Marroquín, 2008; González, Gallego & Hincapié, 2009; Cossi, Romero & Sánchez, 2009; Londoño, Hincapié & Gallego, 2011), and a linear mixed-integer model (García et al., 2003; Tapias, Galeano & Hincapié, 2011).

To solve the problem, some studies have proposed heuristic techniques (Da Silva, França & Da Silveira, 1996; Costa & França, 2002; Gilvanejad et al., 2007). Díaz-Dorado et al. (2001) present a methodology based on dynamic programming. Díaz-Dorado et al. (2003) & Cossi et al. (2005) present a specialized evolutionary algorithm. García et al. (2003) solves the problem using a Greedy Randomized Adaptive Search Procedures (GRASP) algorithm. Souza (2006) uses a tabu search algorithm. Marroquín (2008) chooses an ant colony optimization algorithm. Cossi et al. (2009)

solve the problem by means of a tabu search algorithm. In the same year, Navarro & Rudnick (2009) use a hybrid methodology that takes into account heuristic techniques and a tabu search algorithm. Tapias et al. (2011) use a Branch and Bound algorithm and Londoño et al. (2011) propose a genetic Chu-Beasley algorithm. In addition, the system's elements have been modeled by their monophasic equivalent (Costa & França, 2002; Tapias, Galeano & Hincapié, 2011), and others have used triphasic models (Cossi, 2003; Souza, 2006; Marroquín, 2008; González, Gallego & Hincapié, 2009; Londoño, Hincapié & Gallego, 2011).

In PSEEDS solutions, location and dimensioning of new elements, augmentation of existing elements, phase balance, and costs of energy losses in sections of the network have traditionally been considered. In addition to these aspects, this study considers the relocation of distribution transformers in operation and in storage, the costs associated with energy loss in distribution transformers, and the costs of connection between the primary and secondary networks. To solve the problem, this study presents the development and implementation of a methodology that uses a tabu search algorithm (TSA) as a solution technique. This approach makes it possible to optimally determine the elements that make up the electric energy distribution network to meet needs of demand and technical criteria. This configuration takes into account the number of circuits necessary to meet said demand, the location and necessary capacity of distribution transformers, the topology of the primary and secondary networks, the type of conductors, and connections with the network's users, complying with a set of technical, operative, and economic restrictions. The proposed method is applied in two test cases. In the first, efficiency is checked through a comparative analysis with the results obtained by solving the problem with a genetic Chu-Besley algorithm (Chu & Beasley, 1997). The second case shows the solution's application to a Colombian distribution system.

This article is organized as follows: section 2 presents the description and formulation of the problem. The following section describes the proposed method, including the solution technique, problem codification, initial configuration construction, configurations evaluation, neighborhood structure, stopping criteria, and appropriateness of the technique for solving the problem. Section 4 presents the proposed method's application to the two test cases. Finally, section 5 offers conclusions derived from this study.

2. PROBLEM DESCRIPTION AND FORMULATION

PSEEDS takes into account the creation of plans for secondary network expansion in areas with growing existing demand and the appearance of new demand. Its main goal is to find a network design that guarantees the lowest project cost while complying with technical, regulation, and operative demands.

Incorrect planning of these systems can result in secondary circuit and distribution transformer overloads, regulation problems, phase load imbalances, increased technical losses in the system, a loss of confidence, quality, and continuity, overdimensioning elements, and excessive costs in projects.

To avoid these problems, planning that involves the following aspects is undertaken: location and capacity of new secondary sections in the network and distribution transformers, redimensioning existing secondary sections of the network and distribution transformers, relocation of working and stored distribution transfers, balance of system loads and new sections of the primary network to feed the secondary network. The network has a triphasic model which can carry monophasic, biphasic and triphasic loads (Kersting, 2007).

The problem is formulated as a nonlinear mixed-integer programming model. The system's objective function considers the fixed costs associated with initial investment and the operative costs associated with energy losses along the planning horizon (**Equation 1**). The two first terms represent uninstalling costs for existing sections of the network and installation of new sections in the network, respectively. The third term is the cost of energy losses for all sections of the network. The following term corresponds to the cost of uninstalling an existing transformer plus transportation costs from the operation site to the warehouse. The fifth term is the cost of installing new transformers. The next term guarantees that the cost of a transformer that has previously been uninstalled and is currently in storage will not be considered. The seventh term shows the cost of energy losses in distribution transformers associated with vacuum and low-load losses. The next term represents the load balance operation cost. The final term considers the cost of the primary network that feeds the transformers. The nomenclature used is presented at the end of this paper.

In this equation, the term f_{act} expresses the present value of operating costs during the elements' service life and is defined in **Equation 2**. This calculation is made due to the rise in energy costs, which causes different operating values in each period. The term f_{anual} brings the cost of installation and operation to an annual period (**Equation 3**). The parameters λ^c_{ij}, λ^d_k and λb^b_k are associated with existing elements like sections of the secondary network, distribution transformers, and loads, respectively. In other words, these values are given by the existing network such that if the element exists, the parameter's value is 1; if not, the value is zero. Based on the relationship between these parameters and binary decision variables δ^c_{ij}, δ^d_k and δb^b_k, different costs can be considered for the terms involved. For example, if line *ij* contains a type 1 conductor, then $\lambda^1_{ij}=1$; if the decision variable proposes installation of a type 1 conductor ($\delta^1_{ij}=1$), then the term that corresponds to uninstalling this section of the network and to the cost of the new section is nullified in the objective function.

$$min\ Z = \left(\begin{array}{l} \sum_{ij\in\Omega_{ij}} \sum_{c\in\Omega_c} \{L_{ij} \cdot [\lambda^c_{ij} \cdot (1-\delta^c_{ij}) \cdot CRC^c + (1-\lambda^c_{ij}) \cdot \delta^c_{ij} \cdot CNC^c + \\ \sum_{t\in T} \sum_{h\in H} \delta^c_{ij} \cdot \frac{C_{kWh}}{1000} \cdot H^h \cdot R^c_{ij,abcn} \cdot |I^h_{ij,abcn}|^2 \cdot f_{act}]\} + \\ \sum_{k\in\Omega_{kT}} \sum_{d\in\Omega_d} [\lambda^d_k \cdot (1-\delta^d_k) \cdot CRT^d + (1-\lambda^d_k) \cdot \delta^d_k \cdot CNT^d + \delta^d_k \cdot (-CCT^d \cdot \mu(B^d)) + \\ \sum_{t\in T} \sum_{h\in\Omega_h} \delta^d_k \cdot \frac{C_{kWh}}{1000} \cdot H^h \cdot (P_{fe} + P_{PCN} \cdot fp_k \cdot fu_k^{\ 2}) \cdot f_{act}] + \\ \sum_{k\in\Omega_{kE}} \sum_{b\in\Omega_b} (1-\lambda b^b_k) \delta b^b_k \cdot CB + CGRP \end{array} \right) \cdot f_{anual} \tag{1}$$

$$f_{act} = \frac{(1+ie)^t}{(1+i)^t} \tag{2}$$

$$f_{anual} = \frac{i \cdot (1+i)^T}{(1+i)^T - 1} \tag{3}$$

The mathematical model's set of restrictions is presented below in **Equations 4** to **11**. **Equation 4** represents the nodal balance equations for the entire system. **Equation 5** guarantees that the voltage levels will remain within the limits allowed. **Equations 6** and **7** consider the operation limits for current and power in sections of the network and transformers, respectively. **Equations 8** and **9** guarantee that only one caliber of conductor will be installed in each proposed section of the network and only type of transformer will be installed in each proposed node, respectively. The last two equations are associated with the network's radial operation and the maximum investment limit that can be considered for the project, respectively.

$$EQ^u(P^D_{k,abc}, Q^D_{k,abc}, V^D_{k,abc}, \theta^D_{k,abc}) = 0 \tag{4}$$

$$V^{\min}_{k,abcn} \le V^{cal}_{k,abcn} \le V^{\max}_{k,abcn} \tag{5}$$

$$|I^h_{ij,abcn}| \le I^{\max,c}_{ij,abcn} \tag{6}$$

$$\sum_{k\in\Omega_k} P^D_{k,abc} + \sum_{ij\in\Omega ij} R^c_{ij,abcn} \cdot |I^h_{ij,abcn}|^2 \le \sum_{k\in\Omega_{kT}} P^T_{k,abc} \tag{7}$$

$$\sum_{c\in\Omega_c} \delta^c_{ij} \le 1 \ \forall\ ij \in \Omega_{ij} \tag{8}$$

$$\sum_{d\in\Omega_d} \delta^d_k \le 1 \ \forall\ k \in \Omega_k \tag{9}$$

$$N_{ijE} + \sum_{ij \in \Omega_{ijN}} \sum_{c \in \Omega_c} \delta_{ij}^{c} \leq N_{ik} - N_{dE} - \sum_{k \in \Omega_{kT}} \sum_{d \in \Omega_d} \delta_{k}^{d} \qquad \textbf{(10)}$$

$$Z \leq RF_{\max} \qquad \textbf{(11)}$$

3. METHODOLOGY

3.1. Solution Technique

The PSEEDS problem is formulated as a non-linear mixed-integer programming model with a high level of NP type mathematical complexity due to the high *number of solutions*. In this study, a tabu search algorithm is used since it performs well with problems of the nature described (Glover, 1995; Gallego, Escobar & Toro, 2008).

This algorithm considers one solution at a time and therefore requires initiating the search process based on one configuration; this is determined by using *heuristic methods, constructive algorithms*, and *techniques based on sensitivity*. TSA makes transitions through the search space using intensification strategies in order to efficiently explore the space around a configuration *x*, which is called the neighborhood (*N(x)*), and it also uses diversifications strategies to explore other neighborhoods.

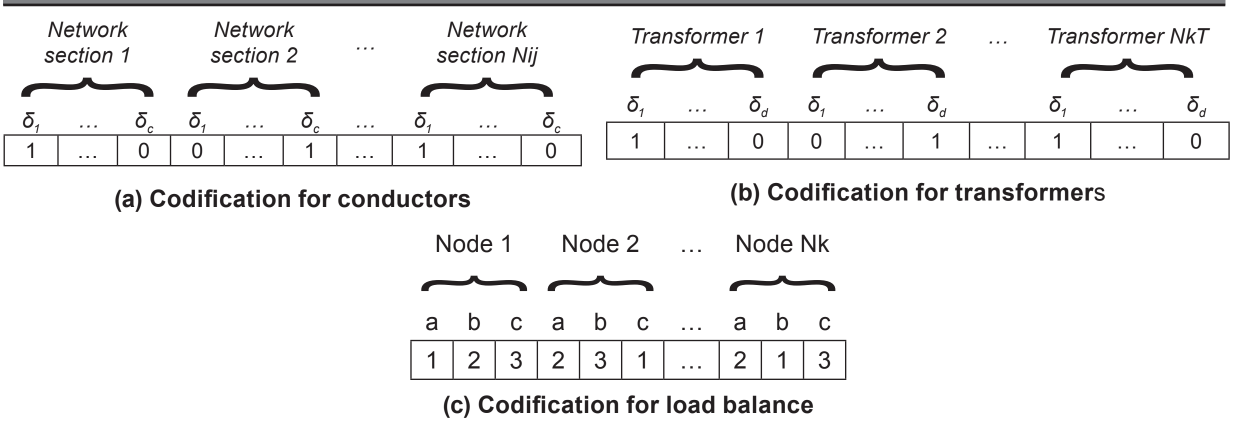
With the neighborhood structure defined, a local search allows for moving on to the best neighboring configuration. In the current configuration is the best, it moves on to the configuration that does not comply with the desired criteria or that is not tabu, in which a new local search is made on the new configuration. This strategy avoids configurations that have already been visited in order to leave optimal locations, which is achieved by storing information from the recent past and short-term (attributes) memories. When moving on to a new configuration, the accepted attributed from the previous step is prohibited during a certain number of iterations in a tabu list. During the process, the best solutions are stored in an elite (or incumbent) solutions memory.

After the local search stage does not find good solutions after a certain number of iterations, the process is restarted, taking a new high-quality solution stored previously. As a diversity criterion, the long-term memory is used to generate a new configuration. Starting from another configuration, the local search process is applied again. If better solutions are not found after a certain number of iterations applying this process cyclically, advanced strategies like strategic oscillation or path-relinking can be applied (Glover, 1995).

3.2. Codification

A full and binary variable vector divided into three parts is used, as shown in **Figure 1**. The first contains information on the location and caliber of the sections in the network (**Figure 1a**); the second involves the location and capacity of the distribution transformers (**Figure 1b**); and the last shows the codification of the load balance (**Figure 1c**).

Figure 1. Problem codification



All sections of the network and distribution transformers are associated to a position on the vector, where each position represents a capacity through a binary value (**Figure 1a** and **1b**). For example, if three conductor capacities (types) are considered, then each proposed section of the network will be associated to three positions on the vector. If one of these positions has a one, then on said network section, a conductor with the capacity associated to that position will be installed; if it has a zero, the opposite will occur. On a proposed section of network, all the positions can have the three values at zero, which indicates that no conductor will be installed on that section. The case is similar for distribution transformers. In addition to complying with **Equations 8** and **9**, it is guaranteed that no more than one type of conductor will be installed on a network section or no more than one transformer on a node.

The node loads are represented by whole numbers with the numbers 1, 2, and 3 being associated to phases a, b, and c, respectively. As can be observed in **Figure 1c**, each note is associated to the order of connection for its loads to the system. Note that a configuration (system topology) can be completely described based on the information contained in a vector, which allows for a better adaptation of the solution technique to the problem.

3.3. Initial Configuration

The initial configuration is obtained using a constructive heuristic algorithm proposed by Cossi (2008). In this algorithm, a radial configuration is constructed based on the selection of a distribution transformer. Every time a network section is added, loadability limits are checked so that in each step, a load flow runs to check these conditions. Once all the load nodes are entered, the route through the sections of the primary network to feed the distribution transformers is calculated. Then a load balance stage is completed in order to improve the loadability of the elements and the network's operating costs.

3.4. Configuration Evaluation

In order to evaluate the objective function and check the feasibility of a solution, a radial triphasic load flow is used (Garcés, Granada & Gallego, 2004). If a solution violates any of the mathematical model's restrictions as presented in section 2, this configuration is penalized in the objective function. This strategy allows the process to oscillate between feasible and infeasible regions, thereby reaching better-quality regions (Gallego, Escobar & Toro, 2008). **Equation 12**, the adaptation function used, is presented below. It consists of the sum of the objective function presented in **Equation 1** plus the penalty factors.

$$fa = Z + fp_{RF}(\Delta RF) + fp_{v}(\Delta V) + fp_{f}(\Delta I) + fp_{S}(\Delta S) \quad \mathbf{(12)}$$

The factors fp_{RF}, fp_V, fp_f and fp_S are associated with the penalties for violations of financial restrictions, voltage limits, and overloads on sections of the network and transformers, respectively. These factors multiply the value in which each restriction was violated (Δ). If a restriction is not violated, the deltas are equal to zero. The units of these factors guarantee that each term is expressed in monetary units.

3.5. Neighborhood Structure

To move from one configuration to another (a neighbor), it is necessary to define the neighborhood criteria that allow for this change. Each neighborhood criteria is associated to the solution of one characteristic of the problem being solved. As indicated in section 3.2, each vector defines a configuration. Thereby, any change made to the vector modifies the system's topology. So, in order to determine a neighbor, one must only make changes to the vector associated with the current configuration. Evaluating the large number of neighbors a configuration has can require excessive computation time, and it is therefore advisable to work with a small number. In order to select a neighbor based on the current configuration, one of the neighborhood criteria used is randomly selected. This process is repeated until the predefined number for the reduced neighborhood size is reached. In the solution to this problem, five criteria were considered. They were the following:

- *System reconfiguration*. The states of a disconnected network section and a connected network section that are part of the same bond are exchanged so that radiality is guaranteed in the network.

- *Reconductoring*. The network section that shows the greatest level of overloads is selected and changed out for a better-quality conductor. When applying this criterion, it is necessary to guarantee that upstream sections of the network do not have a lower caliber.
- *Transformer relocation*. A transformer is randomly selected and relocated in a neighboring node using the electric moments method (Ramírez, 2004).
- *Load balance*. The percent of imbalance is calculated in all system circuits, and that with the highest value is selected. Later, the selected circuit undergoes a genetic algorithm to balance the loads.
- *Changing overloaded transformers*. Overloaded transformers are identified, and the one with the highest index is selected to be changed out for one that does not violate its nominal capacity.

3.6. Stopping Criteria

In TSA application, two search processes are used: one local and one global. The local search stops after a number of iterations, whether the incumbent is not improved or the maximum predefined number of iterations is reached. The global search ends when the entire list of elite solutions has been examined.

3.7. TSA adaptation to PSEEDS

An initial solution is generated in accordance with number 3.3, which is described by a vector with the structure presented in 3.2. The load flow is carried out with this information in order to determine the operating conditions for the proposed system. Based on the results of the load flow, compliance with the system's restrictions or the proposal's feasibility are checked (**Equations 4** to **11**). These values, together with the vector codification (proposed configuration) allow for evaluation of the adaptation function described in **Equation 12**. Since the initial solution is always feasible, evaluating this equation is similar to calculating the objective function in **Equation 1**; this configuration is stored like the process's incumbent (the solution with the best objective function found so far). At this time, the tabu list (short-term memory) is initialized at zero since this is the first iteration. Then the reduced neighborhood is generated based on the criteria specified in number 3.5, the operative conditions for each of the neighbors is found with the load flow, and they are evaluated applying **Equation 12** with the aspects described in number 3.4. From this set, the best neighbor is chosen, bearing in mind the tabu attributes and the desired criteria, and the incumbent and the tabu list are updated. Later, the reduced neighbor generation process is repeated until a stopping criterion is reached, and the elite list is updated with the best configuration found. These steps are part of the local search process. If the local search stopping criterion is fulfilled, the process is reinitiated based on a new configuration, considering the short-term memory, in order to explore other locations in the solution space. This sequence is part of the global search. The process ends when the global search stopping criterion is fulfilled, where the PSEEDS problem solution is the best solution on the elite list. **Figure 2** shows the flow chart of the proposed methodology.

4. RESULTS

The methodology proposed in this paper has been applied to two test cases. In the first, a comparative analysis is done between the results obtained with TSA and a genetic Chu-Besley algorithm (Chu & Beasley, 1997). The second presents its application to a Colombian distribution system. The method is implemented and applied in Matlab. The data for the conductors and distribution transformers used for both systems is described in **Table 1**.

4.1. Case 1

In this case, a distribution system without existing elements is used (**Figure 3**). The network is modeled tripahsically. The power load factor is 0.9. The load is modeled as a constant impedance of 80% and a constant power of 20%. The service life of the elements is 20 years, and the discount rate is 10%. The broken lines correspond to new sections in the network, and the nodes proposed to located transformers are 2, 8, 11, 16, 30, 33, 37, 45, 48, and 51. The system's line-neutral nominal voltage is 127 V, and the allowed regulation is 5%. The cost per kWh is US$0.16. The load and network section data is presented in **Tables 2** and **3**, respectively.

Figure 2. PSEEDS flow chart

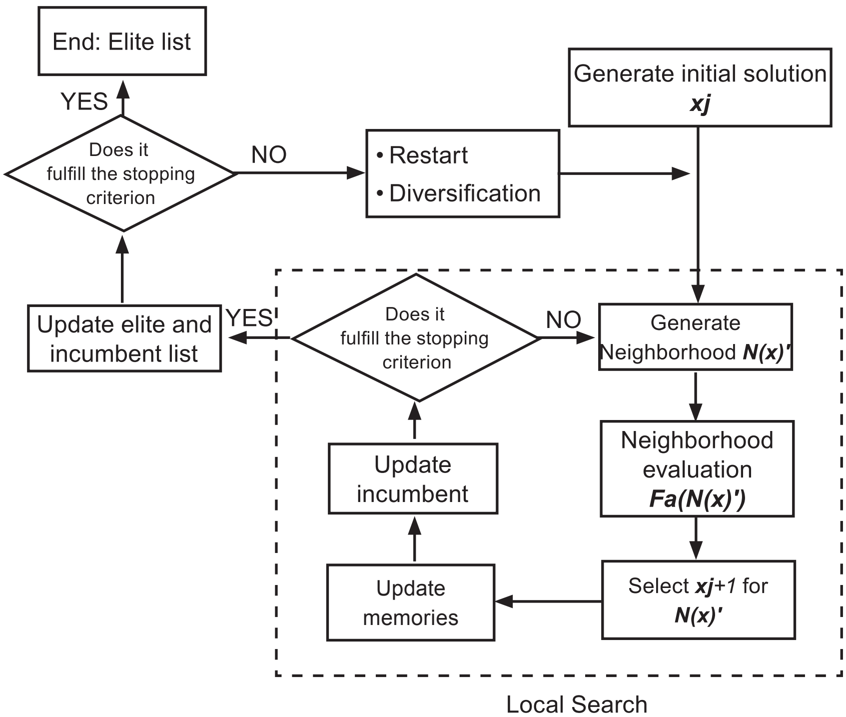


Table 1. Proposed conductor and transformer data

Type	Conductors					Transformers	
	Caliber [AWG]	Section [mm²]	R [Ω/km]	Imax [A]	Cost [US$/m]	Nominal capacity [kVA]	Cost [US$]
1	2	19,66	0,854	150	11,77	30	3.500
2	1/0	25,19	0,548	180	18,52	45	4.345
3	2/0	27,62	0,429	205	24,09	75	5.445
4	4/0	34,9	0,271	275	28,00	112,5	6.985

Figure 3. Text system 1

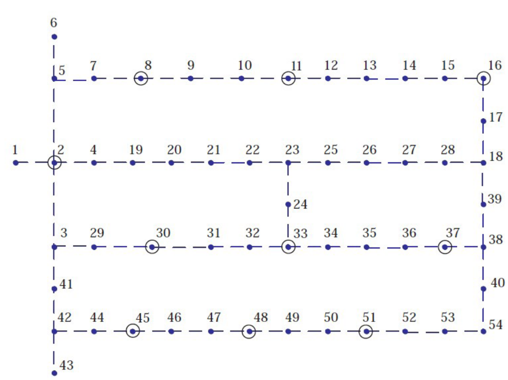


Table 2. Load data in kVA

Node	Phases			Node	Phases			Node	Phases		
	a	b	c		a	b	c		a	b	c
1	0,095	0,095	0,000	19	1,845	1,845	1,750	37	3,240	2,525	2,525
2	0,970	0,970	0,000	20	1,845	1,845	1,750	38	2,995	2,995	2,900
3	1,875	0,970	0,970	21	1,845	1,845	1,750	39	2,525	2,525	1,620
4	0,970	0,970	0,000	22	1,750	0,970	0,870	40	0,905	0,905	0,810
5	1,770	1,770	1,675	23	1,845	1,845	1,750	41	3,160	2,465	2,465
6	0,885	0,885	0,000	24	0,095	0,095	0,000	42	1,675	1,675	1,580
7	2,465	2,465	1,580	25	3,240	2,525	2,525	43	0,905	0,885	0,790
8	3,255	3,255	3,160	26	3,335	3,335	3,240	44	0,905	0,885	0,790
9	3,255	3,255	3,160	27	3,335	3,335	3,240	45	3,160	2,465	2,465
10	3,255	3,255	3,160	28	2,525	2,525	1,620	46	3,255	3,255	3,160
11	4,835	4,045	3,950	29	1,845	1,845	1,750	47	3,255	3,255	3,160
12	3,255	3,255	3,160	30	12,155	12,155	11,465	48	4,835	4,045	3,950
13	3,255	3,255	3,160	31	1,845	1,845	1,750	49	3,255	3,255	3,160
14	3,160	2,465	1,580	32	1,845	1,845	1,750	50	3,255	3,255	3,160
15	3,255	3,255	3,160	33	1,845	1,845	1,750	51	3,255	3,255	3,160
16	2,465	2,465	1,580	34	3,335	3,335	3,240	52	1,770	1,770	1,675
17	0,095	0,095	0,000	35	3,335	3,335	3,240	53	1,675	1,675	1,580
18	0,095	0,095	0,000	36	3,335	3,335	3,240	54	0,095	0,095	0,000

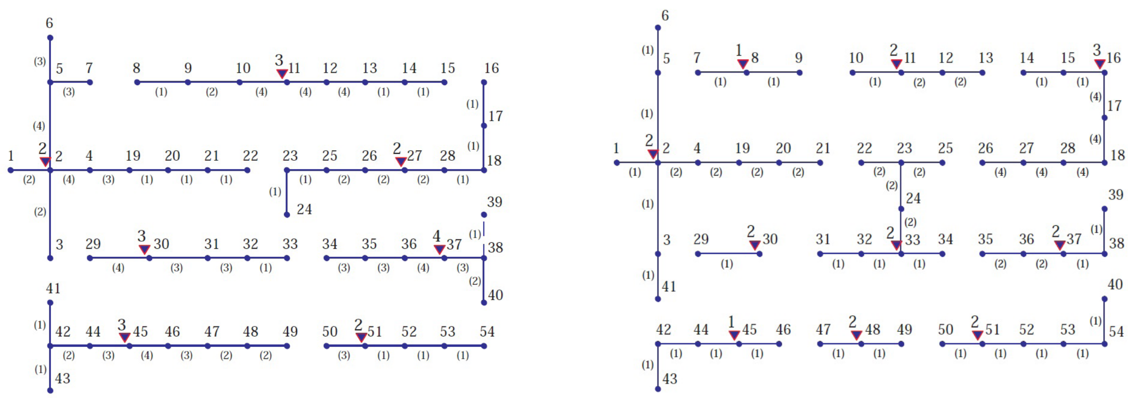
Table 3. Network section data in meters

Initial Node	Final Node	Longitude	Initial Node	Final Node	Longitude	Initial Node	Final Node	Longitude
1	2	30	17	18	21	35	36	24,9
2	3	30	18	28	37,5	36	37	37,5
2	4	28	18	39	30	37	38	40
2	5	30	19	20	18	38	39	37,5
3	29	30	20	21	31,6	38	40	30
3	41	30	21	22	28	40	54	30
4	19	22	22	23	37,5	41	42	33
5	6	22	23	24	37,5	42	43	32,5
5	7	34	23	25	37,5	42	44	32,5
7	8	30	25	26	33,5	44	45	21
8	9	32,5	26	27	37,5	45	46	31,7
9	10	30	27	28	38	46	47	37,5
10	11	37,5	29	30	32,5	47	48	37,5
11	12	37,5	30	31	40	48	49	30
12	13	37,5	31	32	26	49	50	37,5
13	14	37,5	32	33	34,6	50	51	36
14	15	37,5	33	24	37,5	51	52	30
15	16	37,5	33	34	28,7	52	53	30
16	17	30	34	35	37,5	53	54	37,5

For the genetic Chu-Beasley algorithm (GCBA), a recombination rate of 0.9 and a mutation rate of 0.05 are used. The population size is 100 individuals. The maximum number of iterations is 100. In the TSA, the following penalty factors are used: 1.5 in the financial restriction, 150 and 100 for voltages and overloads in sections of the network, and 1000 for voltages and overloads in transformers: these values are the result of completing various tests. Two stopping criteria are used for the local search: 10 iterations without improving the incumbent and a maximum number of iterations equal to 40. The parameterization values used for both methods were the best ones obtained after completing different calibration tests.

Figures 4a and **4b** present the configurations found by the GCBA and the TSA, respectively. The conductor type used is indicated in parentheses. **Figure 5** shows the behavior of each of the algorithms, where it can be seen that the stopping criterion used is appropriate, since it allows each method to complete a suitable search in the solution space to find good-quality answers in reasonable lapses of time.

Figure 4. Results obtained



(a) Solution found by GCBA (b) Solution found by TSA

Figure 5. Behavior of each algorithm

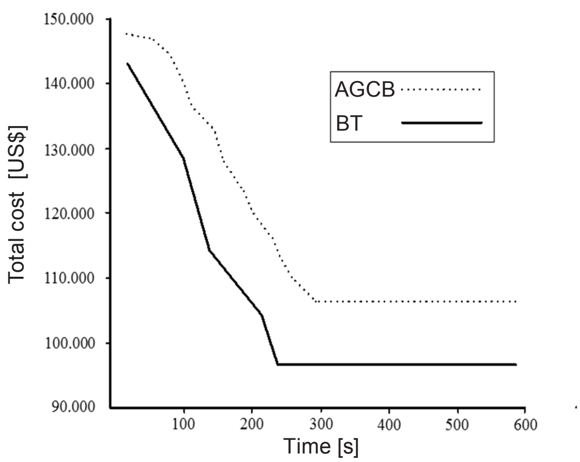
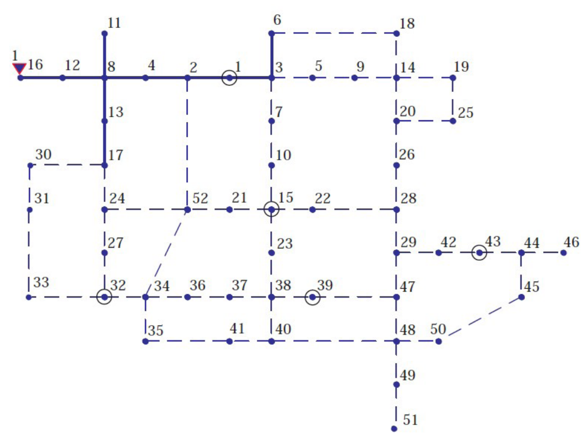


Figure 6. Test system 2



With the GCBA, installation of transformers is proposed on the following nodes: 2 (45 kVA), 11 (75 kVA), 27 (45 kVA), 30 (75 kVA), 37 (112,5 kVA), 45 (75 kVA), and 51 (45 kVA). With TSA, installation of transformers is proposed on the following nodes: 2 (45 kVA), 8 (30 kVA), 11 (45 kVA), 16 (75 kVA), 30 (45 kVA), 33 (45 kVA), 37 (45 kVA), 45 (30 kVA), 48 (45 kVA), and 51 (45 kVA). **Table 4** shows the results obtained with each solution technique.

GCBA differs from TSA, proposing installation of few transformers with a high capacity and conductors with a higher caliber. However, investment costs are similar for each, given that the TSA installs more lower-capacity transformers and lower-caliber conductors, making up for this value. The difference in project cost is found in the operative costs evaluation. This is due to the fact that the configuration found by the TSA has a better distribution of power flows circulating through the system. The results obtained show the validity of the proposed method, given that lower total costs are found while complying with the technical and operative requirements.

4.2. Case 2

Application to a Colombian distribution system is shown below (**Figure 6**). The data on loads and network sections are presented in **Tables 5** and **6**, respectively.

This distribution system has ten existing network sections (full lines) fed by a 30 kVA transformer (black triangle at node 16). To feed the appearance of new loads and the growth of existing ones, 5 possible locations for transformers are proposed (nodes 1, 15, 32, 39, and 43) along with 53 secondary network sections (broken lines). The system is triphasic, the nominal voltage is 208/120, and the regulation percent is 5%. The cost per kWh is US$0.16. The power load is 0.9. The load is modeled as a constant impedance of 80% and as a constant power of 20%. The service life of the elements is 20 years, the discount rate is 10%, and the annual energy cost increase is 2%. A duration curve of annual load discretization is used in three levels of 100%, 70%, and 30% of the nominal demand value with a duration of 1000, 6760, and 1000 hours, respectively.

In the TSA, the following penalty factors are used: 1.5 in the financial restriction, 150 and 100 for voltages and overloads in sections of the network, and 1000 for voltages and overloads in transformers: these values are the result of completing various tests. The same stopping criteria from case 1 are used. **Figure 7** shows the best configuration found by the TSA. The transformers selected are located at nodes: 1 (75kVA), 15 (75 kVA), 32 (45 kVA), and 39 (30 kVA). In this figure, the solid lines represent the proposed sections of the secondary network, and the broken lines are associated with the primary network designed to feed the distribution transformers. The type of conductor selected for each section of the network is indicated in parentheses. The investment and operation costs for the project are US$45,378 and US$44,256, respectively, giving a total project cost of US$89,634.

In the solution, it can be seen that the existing 30 kVA transformer was relocated from node 16 to node 39. The concept of telescopic networks is fulfilled in all circuits. The voltage regulation and loadabilities for the transformers and conductors are within the allowed limits.

Table 4. Results obtained

Algorithm	Investment Costs [USD]	Operation Costs [USD]	Total Cost [USD]
GCBA	64,830	42,510	107,340
TSA	64,275	31,084	95,359

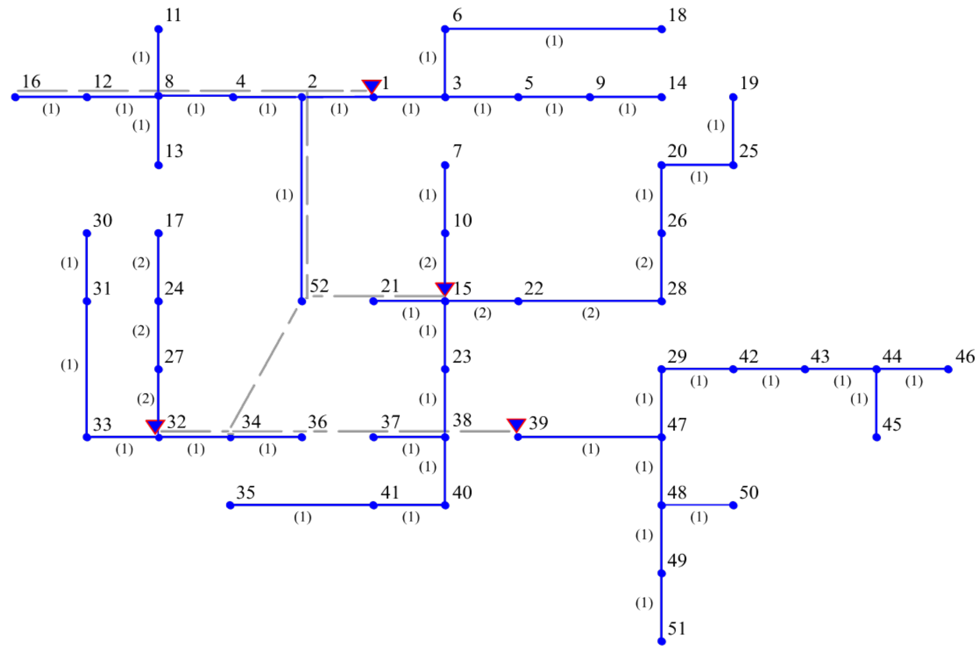
Table 5. Load data in kVA

Node	Phases			Node	Phases			Node	Phases		
	a	b	c		a	b	c		a	b	c
1	0,000	2,450	0,000	19	0,000	1,316	1,200	37	0,625	0,625	0,000
2	2,508	1,165	0,000	20	1,729	3,025	1,304	38	0,633	0,000	0,000
3	1,814	2,450	1,841	21	1,636	0,332	0,000	39	0,000	0,949	0,949
4	0,000	0,000	0,000	22	0,625	0,625	0,000	40	2,508	1,165	0,000
5	0,000	0,101	1,829	23	0,633	0,000	0,000	41	0,000	0,000	0,000
6	0,000	0,000	0,000	24	0,000	0,949	0,949	42	0,625	0,625	0,000
7	3,565	2,211	2,805	25	3,172	1,520	0,000	43	0,633	0,000	0,000
8	1,046	1,493	0,000	26	2,820	1,617	1,906	44	0,000	0,949	0,949
9	0,922	0,540	1,941	27	0,803	2,037	3,164	45	0,000	0,101	1,829
10	0,000	0,000	0,000	28	0,922	0,540	1,941	46	0,000	0,000	0,000
11	1,459	0,791	0,668	29	0,000	0,000	0,000	47	3,565	2,211	2,805
12	1,814	2,450	1,841	30	1,459	0,791	0,668	48	1,046	1,493	0,000
13	0,818	1,725	0,706	31	1,814	2,450	1,841	49	0,922	0,540	1,941
14	2,095	1,937	2,242	32	0,818	1,725	0,706	50	0,000	0,000	0,000
15	5,803	6,586	5,668	33	2,095	1,937	2,242	51	1,459	0,791	0,668
16	0,000	0,000	0,000	34	0,000	1,316	1,200	52	0,000	0,949	0,949
17	5,402	1,178	4,000	35	1,729	3,025	1,304	---	---	---	---
18	1,837	3,125	4,190	36	1,636	0,332	0,000	---	---	---	---

Table 6. Network section data in meters

Initial Node	Final Node	Longitude	Initial Node	Final Node	Longitude	Initial Node	Final Node	Longitude
1	2	30,0	15	21	21,0	34	35	36,0
1	3	28,0	15	23	30,0	34	36	37,5
2	4	30,0	15	22	28,0	34	52	42,0
2	52	65,0	17	24	32,5	35	41	37,5
3	7	34,0	17	30	36,0	36	37	37,5
3	6	32,5	19	25	37,5	37	38	37,5
3	5	33,0	20	26	37,5	38	39	30,0
4	8	30,0	20	25	34,6	38	40	30,0
5	9	32,5	21	52	28,7	38	23	21,0
6	18	70,0	22	28	48,0	39	47	49,5
7	10	40,0	24	27	26,0	40	41	30,0
8	12	30,0	24	52	37,5	40	48	37,5
8	11	22,0	26	28	28,7	42	43	30,0
8	13	22,0	27	32	37,5	43	44	37,5
9	14	31,6	28	29	37,5	44	45	29,0
10	15	32,5	29	42	30,0	44	46	35,3
12	16	30,0	29	47	30,0	45	50	42,0
13	17	18,0	30	31	21,0	47	48	37,5
14	19	34,6	31	33	51,5	48	49	37,5
14	18	31,7	32	33	38,0	48	50	37,5
14	20	37,5	32	34	40,0	49	51	35,0

Figure 7. Solution for test system 2



5. CONCLUSIONS AND RECOMMENDATIONS

To solve the PSEEDS problem, we propose a methodology that uses the tabu search algorithm as a solution technique. This algorithm determines the size and location of secondary circuits, distribution transformers, and primary network sections. It also considers the relocation of distribution transformers and the costs associated with energy losses in distribution transformers and connections between the primary and secondary networks; these strategies allow for modeling the problem more generally, making it more representative of real operation. The method is general and flexible since it can be applied to voltage 1 networks.

The mathematical model solution uses a tabu search algorithm, which has presented satisfactory results when applied to two test cases. The first checks effectiveness by comparing it with the results obtained with a genetic Chu-Beasley algorithm using a test system with real dimensions. The second test case uses a Colombian distribution system which contains existing elements. In both cases, all technical and operating restrictions are satisfied.

The methodology shows excellent performance when applied to distribution systems of different sizes. In addition, the network model proposed includes all the elements of a real system, which, when resolved with an efficient methodology, shows high-quality solutions in terms of investment and operating costs, as well as the system's technical requirements.

It is important for distribution companies to have trustworthy strategies for their secondary system planning studies in order to generate lower investment and operation costs.

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NOMENCLATURE

Z: objective function.
k: index that covers nodes.
ij: index that covers network sections.
c: index that covers the available types of conductors.
d: index that covers the available types of transformers.
h: index that covers the discretized periods of the year.
b: index that covers load configurations in phases.
(Ω_k, N_k): set and total number of nodes in the system.
(Ω_{kE}, N_{kE}): set and number of nodes with existing network.
(Ω_{ij}, N_{ij}): set and total number of lines in the system.
(Ω_{ijE}, N_{ijE}): set and number of existing lines.
(Ω_{ijN}, N_{ijN}): set and number of new lines in the system.
(Ω_c, N_c): set and number of available conductors.
(Ω_d, N_d): set and number of available transformers.
(Ω_{kT}, N_{kT}): set and number of nodes where it is possible to install transformers.
(B^d): number of type d transformers in storage.
(Ω_h, N_h): set and number of discretized periods in the year.
(Ω_b, N_b): set and number of load configurations in the phases.
CRC^c: cost of removing a type c conductor
CNC^c: cost of installing a type c conductor.
CRT^d: cost of removing a type d transformer.
CNT^d: cost of installing a type d transformer.
CB: cost of changing the load configuration at a node.
$CGRP$: global cost of installing the primary network.
C_{kwh}: energy cost expressed in [$/kWh].
L_{ij}: length of network section ij.
$R^c_{ij,abcn}$: resistance of type c conductor on line ij for phases a-b-c and neutral phases.
$X^c_{ij,abcn}$: reactance of type c conductor on line ij for phases a-b-c and neutral phases.
$I^h_{ij,abc}$: current in line ij for a-b-c phases in period h.
$I^{max,c}_{ij}$: maximum current allowed for conductor installed in line ij.
$V_{k,abc}$: drop in voltage at node k for phases a-b-c.
$V^{max}_{k,abc}$: maximum voltage allowed at all system nodes for phases a-b-c.
$V^{min}_{k,abc}$: minimum voltage allowed at all system nodes for phases a-b-c.
$P^T_{k,abc}$: nominal active power for transformer installed at k.
$Q^T_{k,abc}$: nominal reactive power for transformer installed at k.
$P^D_{k,abc}$: active power consumed at node k.
$Q^D_{k,abc}$: reactive power consumed at node k.
H^h: number of hours in planning period h.
λ^c_{ij}: binary parameter that defines whether a type c conductor has been installed in line ij.
δ^c_{ij}: decision variable that defines whether to install a type c conductor on line ij.
λ^d_k: parameter that defines if a type d transformer has been installed at node k.

$\delta^d{}_k$: decision variable that defines whether to install a type d transformer at node k.

$\lambda b^b{}_k$: parameter that defines whether there is a type b load configuration at node k.

$\delta b^b{}_k$: binary variable that defines whether to change the load configuration in phases for a type b configuration at node k.

$\mu(B^d)$: This parameter's value is 1 if B^d is greater than zero. For a different value of B^d, this parameter's value is zero.

RF_{MAX}: maximum financial resources to be invested in the expansion plan.

fp_{RF}: penalty factor when maximum available resources are exceeded.

fp_V: penalty factor when allowed voltage limits are exceeded.

fp_f: penalty factor when overloads appear on sections of the network.

fp_S: penalty factor for overloads in transformers.

fp_k: loss factor in the transformer.

fu_k: use factor for the transformer.

P_{fe}: iron loss in the transformer obtained from norm NTC 818.

P_{PCN}: power load loss obtained from norm NTC 819.

T: planning period time.

i, ie: rates of discounts and energy cost growth, respectively.