Journal of Applied Science and Engineering, Vol. 22, No. 3, pp. 569–578 (2019) *DOI: 10.6180/jase.201909_22(3).0018*

A Hybrid Genetic Algorithm Applied to the Transmission Network Expansion Planning Considering Non-conventional Solution Candidates

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Abstract

This paper presents a metaheuristic approach to solve the transmission network expansion planning (TNEP) problem considering non-conventional solution candidates. The TNEP consists on finding the set of new elements required in a power system to meet a given future demand at a minimum cost. The TNEP traditionally considers as candidate solutions the addition of new lines and transformers. The main contribution of this work is the inclusion of non-conventional solution candidates. Such non-conventional solution candidates are namely: repowering of existing circuits and reactive shunt compensation. Also, an AC modeling of the network that allows obtaining more realistic results than the traditional DC model has been considered. The TNEP is represented by means of a nonlinear mixed integer programming problem which is solved through a hybrid genetic algorithm (HGA). Several tests were performed on two benchmark power systems to show the applicability and effectiveness of the proposed approach.

Key Words: Transmission Network Expansion Planning, Non-conventional Solution Candidates, Genetic Algorithms, Greedy Randomized Search Procedure

1. Introduction

Transmission network expansion planning (TNEP) consists on determining the new circuits that must be added to a power systems in order to meet a forecasted demand at the minimum possible cost [1,2]. In its classical version, the TNEP only considers the addition of new lines and transformers. However, new environmental constraints have made more difficult and costly the acquisition of rights of ways to expand the transmission network. In this context, the implementation of non-conventional solution candidates to the TNEP such as repowering, reconfiguration and allocation of reactive power devices has gain major attention of researchers and system planners [3].

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The most approximate representation of the TNEP problem corresponds to a mixed integer nonlinear programming (MINLP) problem. Such representation involves nonlinear constraints such as power flows in lines and power balance equations, as well as a mix of integer and real variables such as the number of lines to be added in a corridor or the power flow on a circuit, respectively [1]. The TNEP has proven to be a challenging problem since it is non-convex and multi-modal (it might have several optimal and quasi-optimal solutions); therefore, linearized versions of the TNEP have been proposed, turning the original MINLP into a mixed integer linear programming (MILP) problem which can be solvable by commercially available software [3].

Solution approaches to the TNEP problem can be broadly classified in two groups: classical mathematical programming, and metaheuristic techniques. The first group includes techniques such as linear programming [1], mixed integer linear programming [2], dynamic programing [4], Benders decomposition [5] and branch and cut methods [6]. Within the second group some of the most commonly used are: genetic algorithms [7], tabu search [8], simulated annealing [9] and differential evolution [10].

The main feature of classical mathematical programming approaches is that, under convexity conditions, they are able to find global optimal solutions. Nevertheless, they are usually time-consuming, especially when addressing large-scale systems. To apply a classical mathematical programming approach to the TNEP problem, this one has to be converted into a set of linear equations losing information regarding the real state of the system. As regards metaheuristic techniques, these methods are easy to implement and do not require a linearization of the power system model. Furthermore, power system analysis such as power flows, optimal power flows or stability studies can be carried out using independent software and then be fed into the optimization method. Nevertheless, a common critique of metaheuristic techniques is the fact that they do not guarantee the global optimality of the solutions found, and they also depend on the settings of several parameters. A more detailed classification of models and solution techniques applied to the TNEP problem can be consulted in [11–13].

Although there are many studies regarding the TNEP problem, the inclusion of non-conventional solution candidates has not been studied in depth. Regarding this issue, only few studies have approached separately the inclusion of series and shunt compensation as well as repowering and reconfiguration of existing circuits [3]. In this sense, the main contribution of this paper is the consideration of non-conventional solution candidates to the TNEP problem (repowering of existing circuits and optimal allocation of shunt compensations), considering an AC modeling of the transmission network. Several tests were performed on the 6-bus Garver System and the IEEE 24 bus power test system showing the applicability of the proposed model and solution technique. Results show that the inclusion of non-conventional solution candidates allows exploring a larger search space and finding less expensive expansion plans.

2. Mathematical Modeling

A compact mathematical model of the AC TNEP is given by (1)-(9). A detailed description of this model can be consulted in [14]. In this case c and n are the vectors of cost and number of circuits to be added to the network, respectively. The objective function given by (1) consists on minimizing the total cost of the expansion plan expressed as v. Equations (2) and (3) are the active and reactive power balance constraints. $P(v, \theta, n)$ and $Q(v, \theta, n)$ are the net active and reactive power injections, respectively; where θ and v are the set of voltage angles and magnitudes, respectively. P_G, Q_G, P_D, and Q_D are the active and reactive generation and demand, respectively. Equations (4) and (5) represent the limits of active and reactive power generation, respectively. Equation (6) represents the limit of voltage magnitudes. Equations (7) and (8) are the power flow limits on new and existing lines; in this case N and N^0 are diagonal matrixes that contain vector n (new circuits) and the existing circuits in the base case, respectively. Finally, equation (9) stands for the limits of new circuits to be added to the network.

$$\text{Min } v = C^T n \tag{1}$$

Subject to

$$P(V, \theta, n) - P_G + P_D = 0 \tag{2}$$

$$Q(V, \theta, n) - Q_G + Q_D = 0 \tag{3}$$

$$\underline{P}_G \le P_G \le \overline{P}_G \tag{4}$$

$$\underline{Q}_G \le Q_G \le \overline{Q}_G \tag{5}$$

$$\underline{V} \le V \le \overline{V} \tag{6}$$

$$(N + N^0)S^{from} \le (N + N^0)\overline{S} \tag{7}$$

$$(N + N^0)S^{to} \le (N + N^0)\overline{S} \tag{8}$$

$$0 \le 0 \le \overline{n} \tag{9}$$

When using an AC representation of the network the model given by (1)–(9) corresponds to a MINLP problem. These types of problems are better handled by metaheuristic techniques than by conventional mathematical programing [15,16]. In this case a hybrid genetic algorithm (HGA) is proposed and described in the next section.

3. Solution Approach

The solution approach to the model given by (1)–(9), including repowering and allocation of shunt compensation as non-conventional solution candidates, is described in this section. In this case a HGA, that includes a greedy randomized search procedure GRASP as a mutation strategy was proposed. The mutation stage of a GA is in charge of providing diversification and allows the algorithm to eventually scape from local optimal solutions. The proposed approach takes advantage of this stage to introduce a local search. Along with a heuristic to find the initial solution candidates, the GRASP mutation is the distinctive feature of the proposed HGA.

3.1 Problem Codification

Figure 1 depicts the codification of a candidate solution (or individual) for the 6 bus Garver system depicted in Figure 2. Note that an integer number is assigned in every entry of the vector. In this case the maximum number of new transmission lines in each right of way or corridor is 5; therefore, if a given entry of the vector is 6 it indicates that the corresponding line must be repowered. Note that the individual depicted in Figure 1 indicates repowering in corridors 1-2 and 2-4 plus the adding of 4 lines in corridor 3-5, 1 line in corridor 2-3 and 3 lines in corridor 1-4. On the other hand, the last three elements of the vector are associated with nodes N2, N4 and N5 where it is possible to install shunt compensation. A number different than zero in these entries, indicates a shunt compensation. For simplicity purposes the number indicates the steps of 20 Mvars compensation. In this case 60 Mvars are installed in bus N2 and 20 Mvars in bus N5.

Corridor (right of way)															Shunt Compensation		
1-2	1-3	1-4	1-5	1-6	2-3	2-4	2-5	2-6	3-4	3-5	3-6	4-5	4-6	5-6	N2	N4	N5
6	0	3	1	0	1	6	0	0	0	4	0	0	0	0	3	0	1

Figure 1. Example of solution candidate for the Garver system.

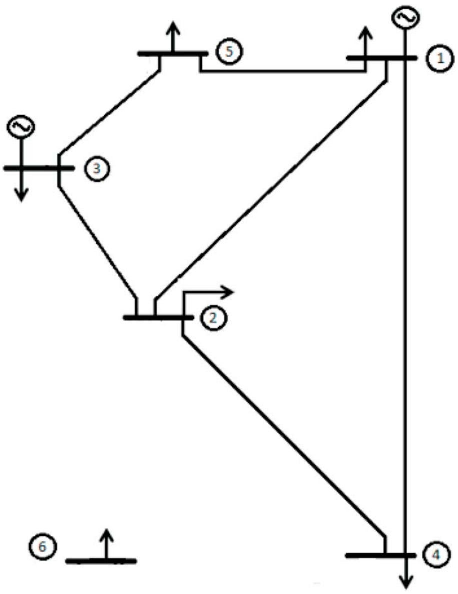

Figure 2. Illustration of the Garver system (base case).

3.2 Fitness Evaluation

Every candidate solution has an associated cost. In the proposed HGA this cost is referred to as the fitness of the individual (or solution candidate). Once a given number of solution candidates are proposed, their associated costs (fitness) are evaluated. The fitness function must also consider the cost of non-conventional solution candidates and the cost of non-serve demand.

3.3 Initial Population

A constructive heuristic, depicted in Figure 3, was designed to produce the initial population. Such heuristic starts introducing new elements in the allowed right of ways to form different candidate solutions though random movements.

3.4 Tournament Selection

The tournament selection process consists of taking two individuals from the initial population, evaluating their fitness function and determining which of them corresponds to the least expensive expansion plan. Later this individual is admitted to a new population. The number of tournaments held is "*k*". This process is illustrated

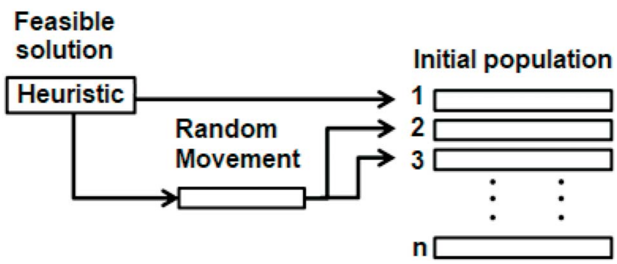

Figure 3. Illustration of the constructive heuristic for the initial population.

in Figure 4. The same individual may eventually participate in more than one tournament. However, the probability of this happening is low since only two individuals are taken per tournament, and the value of "n" (size of the initial population) is higher respect two.

3.5 Recombination

The recombination process is carried out starting from the new population generated in the previous step. This one consists on generating two new individuals from two parents as illustrated in Figure 5. In this case, recombination is done in a single point selected at random. Recombination is performed k/2 times, generating a new recombined population of size k.

3.6 GRASP Mutation

In genetic algorithms, the mutation operator has the property of making an alteration to an individual that comes from the recombination process. In the proposed HGA, the alteration made by the mutation operator is an intensification of the search from a feasible candidate solution. Such intensification is carried out through a GRASP procedure. The mutation process consists on performing a local search, which explores better solutions for each generation of the HGA. In this case, the value of each one of the bits from left to right is modified, the process is illustrated in Figure 6, and described in detail below.

Before starting the local search, the objective function (or fitness function) of the current vector (individual) is evaluated and this information is stored as a reference. Additionally, an operator "w" is defined which takes the values $w = \{1, 2, 3\}$. The first value indicates the reduction of a line in the corridor that is being evaluated. The second value indicates the addition of a line; finally, the third value indicates the repowering the corridor that is being evaluated (if there are existing circuits in the base case). In each of the bits of the vector (except from those corresponding to the capacitors) the operator "w" is evaluated. In the case of shunt compensation, the value of the bit is replaced by a random integer number in the range between 0 and 5 (maximum steps of the capacitors bank).

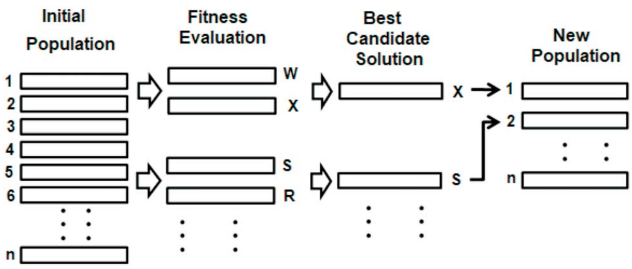

Figure 4. Tournament selection.

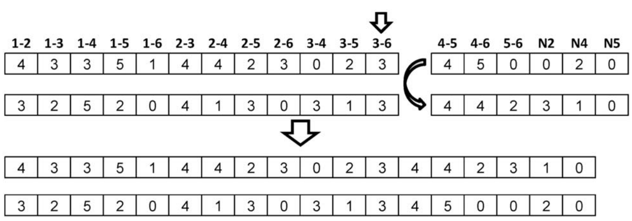

Figure 5. Illustration of the recombination stage.

3.7 General Outline of the HGA

An illustrative diagram of the HGA is presented in Figure 7. The algorithm begins with the construction of a feasible individual by means of a constructive heuristic algorithm, followed by the generation of the initial population, starting from the aforementioned individual. Then, the selection by tournaments is made and the recombination process is executed. The best individual of the re-

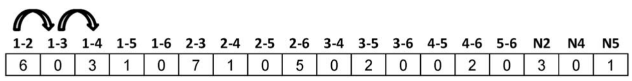

Figure 6. Illustration of the GRASP stage (mutation).

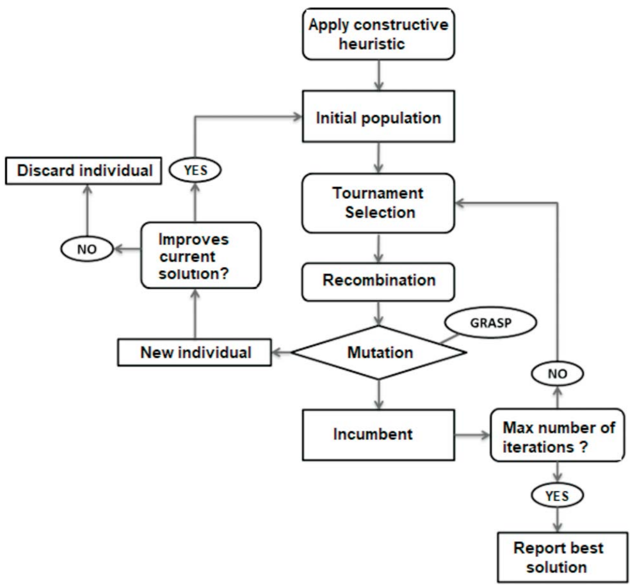

Figure 7. Flowchart of the GRASP metaheuristic.

combined population goes to the mutation operator, where a local search is performed (GRASP). The individual obtained after the mutation process is compared with the best solution found so far (incumbent). If the new individual is better, the incumbent is updated.

The process executed by the HGA ends when the number of generations that were established as an initial parameter to the algorithm is completed. To improve the quality of the initial population, after the mutation process, the individual obtained is compared with those existing in the initial population and if this one improves the population, it is replaced by the worst one.

4. Tests and Results

The proposed methodology was tested with the 6-bus Garver system and the IEEE 24 bus test system. In order to calibrate the settings of the HGA several runs were made, modifying the size of the initial population, the number of tournaments and the probability of mutation. The adjusted data, through a sensitivity analysis, that yielded the best results are presented in Table 1. In this case, satisfactory results were found with the same parameters for both test systems. However, it is important to mention that the process of parametrizing meta-heuristic techniques can vary from one system to another. The results obtained with the HGA were contrasted and validated with results reported in the technical literature. The first validation case was done with the original publication of Garver [17]; the second validation case was made with the same system, but adopting the network modifications proposed in [18].

4.1 Results with the Garver System

Initially, to reproduce the results reported in [17], the non-conventional solution candidates are penalized with a high cost (see [19] for details). Figure 8 illustrates the best solution obtained by proposed HGA.

Table 1. Settings of the implemented HGA

Parameter	Value
Initial population (n)	100
Number of tournaments (k)	100
Mutation probability	50%
Number of generations	2000

This solution coincides with the one reported in [17]. In this case the addition of 1 line in 3-5, 4 lines in 2-6 and 2 lines in 4-6 are indicated, with a cost of US $ 200. Figure 9 depicts the power system with the implemented solution.

In a second test, competitive costs are assumed for non-conventional candidates (see [19] for details). The results obtained are illustrated in Figure 10. The solution vector indicates the repowering of the existing circuit in 3-5, the addition of 4 lines in 2-6 and 2 lines in 4-6, at a cost of US $ 190. Figure 11 illustrates the power system with the solution implemented. It can be seen that for this first validation case the inclusion of non-conventional solution candidates in the TNEP problem leads to a cost reduction of US $ 10. In this case, the solution does not contemplate the addition of shunt capacitors.

A second validation case was carried out adjusting system data as indicated in [18] and [20]. Initially a high cost of non-conventional solution candidates is considered, reaching the same results reported in [18] and [20]. This solution is illustrated in Figure 12. In this case it is

1-2	1-3	1-4	1-5	1-6	2-3	2-4	2-5	2-6	3-4	3-5	3-6	4-5	4-6	5-6	N2	N4	N5
1	0	1	1	0	1	1	0	4	0	2	0	0	2	0	0	0	0

Figure 8. Expansion plan considering high cost of non-conventional solution candidates (first validation case).

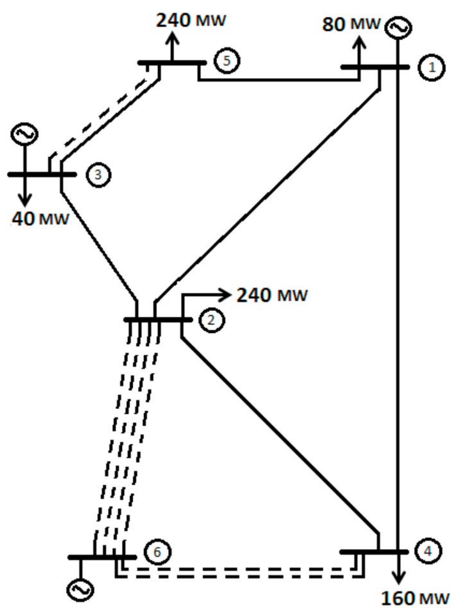

Figure 9. Illustration of the expansion plan considering high cost of non-conventional solution candidates (first validation case).

necessary to add 2 lines in 3-5, 2 lines in 2-6 and 2 lines in 4-6, for a cost of US $ 160. Figure 13 illustrates the power system with the implemented solution.

Subsequently, competitive costs are considered for non-conventional candidates (see [19] for details), obtaining the solution illustrated in Figure 14, which indicates 1 repowered circuit in 3-5, adding 2 lines in 2-6, 1 line in 4-6, 1 bank of 2-step capacitors (40 Mvar) in node 4 and 1 bank of 1-step capacitor (20 Mvar) in node 5, for a cost of US $ 106. Figure 15 illustrates the power system with the solution implemented. In this case, a cost reduction of US $ 54 is obtained due to the implementation of non-conventional solution candidates.

4.2 Results with the IEEE 24-bus Test System

As previously mentioned, the data of this system can be consulted in [3]. For the repowering of lines, a relative cost is assumed equal to half the cost of installing new

1-2	1-3	1-4	1-5	1-6	2-3	2-4	2-5	2-6	3-4	3-5	3-6	4-5	4-6	5-6	N2	N4	N5
1	0	1	1	0	1	1	0	4	0	**6**	0	0	2	0	0	0	0

Figure 10. Expansion plan considering competitive costs of non-conventional solution candidates (first validation case).

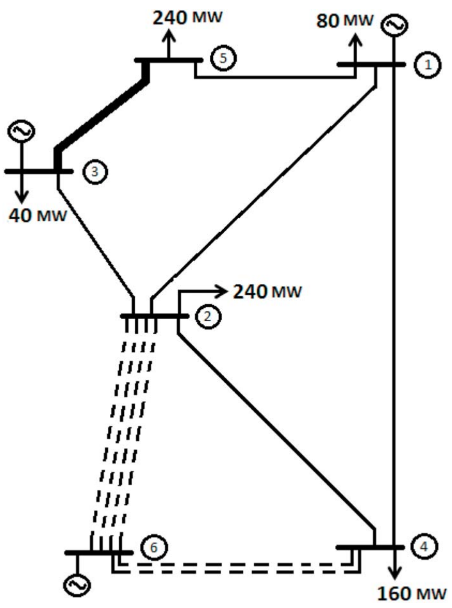

Figure 11. Illustration of the expansion plan considering competitive cost of non-conventional solution candidates (first validation case).

1-2	1-3	1-4	1-5	1-6	2-3	2-4	2-5	2-6	3-4	3-5	3-6	4-5	4-6	5-6	N2	N4	N5
1	0	1	1	0	1	1	0	2	0	3	0	0	2	0	0	0	0

Figure 12. Expansion plan considering high cost of non-conventional solution candidates (second validation case).

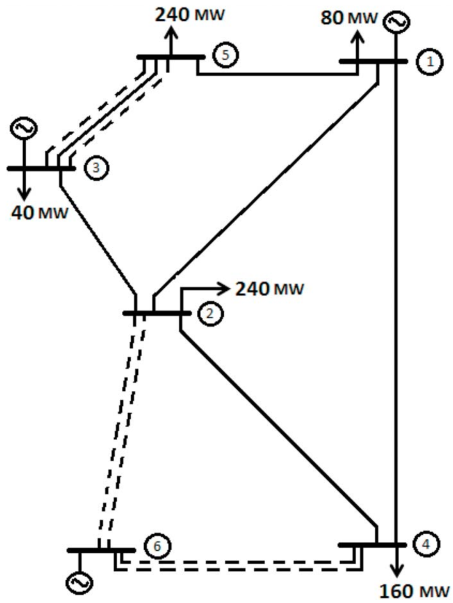

Figure 13. Illustration of the expansion plan considering high cost of non-conventional solution candidates (second validation case).

1-2	1-3	1-4	1-5	1-6	2-3	2-4	2-5	2-6	3-4	3-5	3-6	4-5	4-6	5-6	N2	N4	N5
1	0	1	1	0	1	1	0	2	0	**6**	0	0	**1**	0	0	**2**	**1**

Figure 14. Expansion plan considering competitive cost of non-conventional solution candidates (second validation case).

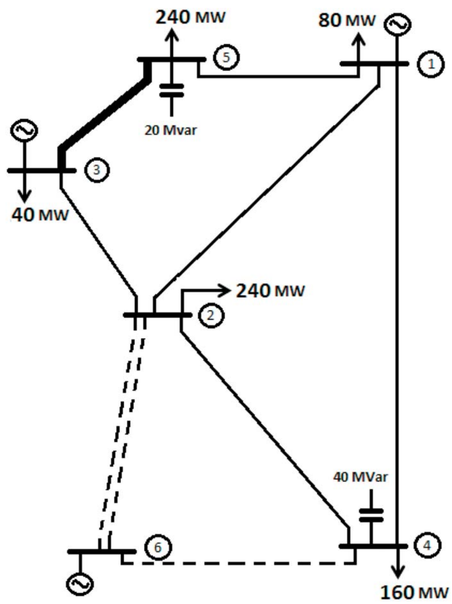

Figure 15. Illustration of the expansion plan considering competitive cost of non-conventional solution candidates (second validation case).

circuits. Additionally, in each of the corridors a maximum of 3 lines is allowed (see [19] for details).

Initially, high costs are assumed for non-conventional solution candidates. Figure 16 illustrates the best solution obtained. In this case, the addition of 1 line is indicated in corridors 3-24, 12-13, 14-23, 15-16 and 15-24, 2 lines in corridors 6-10 and 7-8, for a total cost of US $ 362 Million. The results are consistent with those reported [17,18]; especially with respect to the corridors in which the proposed HGA adds new transmission lines. The lack of accuracy of the results obtained for this system, with respect to the publications mentioned above, is mainly due to differences in the AC/DC model. Figure 17 illustrates the power system with the solution implemented.

Subsequently, competitive costs are assumed for non-conventional solution candidates, obtaining the result illustrated in Figure 18. This indicates the repowering of the existing circuits in 2-4, 3-24, 7-8, 9-12, 11-13, the addition of 1 line at 6-10, the location of a 5-step capacitor bank (100 Mvar) at nodes 3 and 10, and the location a 3-step capacitor bank (60 Mvar) in node 8, at a cost of US $ 149.5 Million. Figure 19 illustrates the power system with the solution implemented. It can be seen that considering non-conventional solution candidates in the TNEP problem leads, in this case, to a cost reduction equivalent to US $ 212.5 Million.

The summary of results obtained by the HGA for the 6-bus Garver system and the IEEE 24 bus test system are presented in Table 2. This shows when the expansion plan considering competitive cost of non-conventional solution candidates, the results for TNEP problem are better than the results obtained for the typical solutions (addition of new lines and transformers – high cost of non-conventional solution candidates).

5. Conclusions

This paper presented a new model and solution approach to the transmission network expansion planning problem. The main contribution of this work is the introduction of non-conventional solution candidates, namely: repowering of existing circuits and optimal allocation of shunt compensations. In addition, the use of an AC mo-

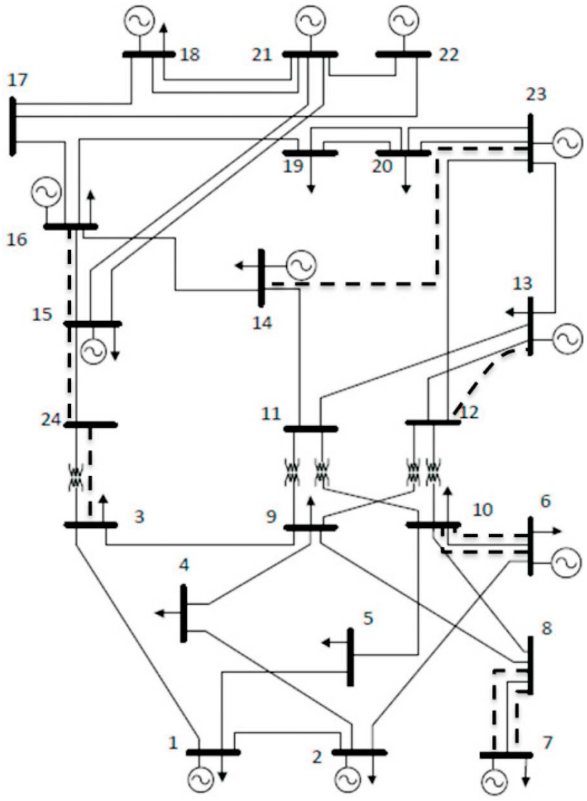

Figure 17. Illustration of the expansion plan considering high cost of non-conventional solution candidates.

1-2	1-3	1-5	1-8	2-4	2-6	2-8	3-9	3-24	4-9	5-10	6-7	6-10	7-8	8-9	8-10	9-11	9-12	10-11	10-12	11-13	11-14	12-13
1	1	1	0	1	1	0	1	**2**	1	1	0	**3**	**3**	1	1	1	1	1	1	1	1	**2**

12-23	13-14	13-23	14-16	14-23	15-16	15-21	15-24	16-17	16-19	16-23	17-18	17-22	18-21	19-20	19-23	20-23	21-22
1	0	1	1	**1**	**2**	2	**2**	1	1	0	1	1	2	2	0	2	1

Figure 16. Expansion plan considering high cost of non-conventional solution candidates.

1-2	1-3	1-5	1-8	2-4	2-6	2-8	3-9	3-24	4-9	5-10	6-7	6-10	7-8	8-9	8-10	9-11	9-12	10-11	10-12	11-13	11-14	12-13	12-23
1	1	1	0	**4**	1	0	1	**4**	1	1	0	**2**	**4**	1	1	1	**4**	1	1	**4**	1	1	1

13-14	13-23	14-16	14-23	15-16	15-21	15-24	16-17	16-19	16-23	17-18	17-22	18-21	19-20	19-23	20-23	21-22	N3	N8	N10	N14
0	1	1	0	1	2	1	1	1	0	1	1	2	2	0	2	1	**5**	**3**	**5**	0

Figure 18. Expansion plan considering competitive cost of non-conventional solution candidates.

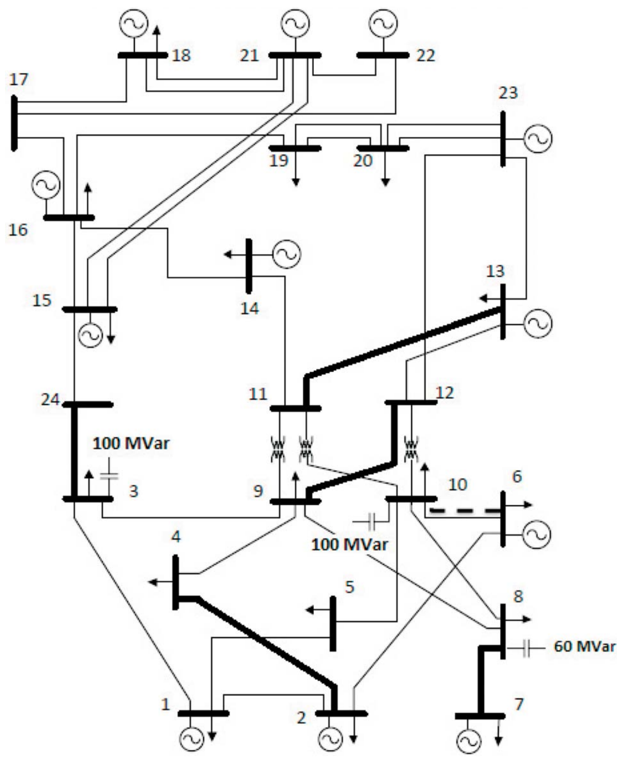

Figure 19. Illustration of the expansion plan considering competitive cost of non-conventional solution candidates.

del to represent the network allows a closer look at real phenomena of electric power systems.

The inclusion of non-conventional solution candidates in the TNEP problem allows exploring a larger set of possible solutions and finding new alternatives for expansion plans that involve lower costs, compared with those obtained by considering only traditional solution candidates (new lines and transformers). The HGA showed satisfactory results, finding and improving the solutions for the TNEP problem that have been previously reported in the technical literature.

Future work will consider other aspects of the TNEP problem, such as new non-conventional solution candidates, reliability, changes in voltage levels, voltage stability, and also the use of other metaheuristic techniques.

Acknowledgements

The authors want to acknowledge the "Proyecto de sostenibilidad" of Universidad de Antioquia, and Colciencias project 2016-10306 for their support in the development of this work.

Table 2. Summary of results obtained by the HGA

Hybrid GA			
First Validation Case – Garver System		Second Validation Case – Garver System	
High cost of non-conventional solution candidates	Competitive cost of non-conventional solution candidates	High cost of non-conventional solution candidates	Competitive cost of non-conventional solution candidates
US \$200 n_{3-5} = 1 n_{2-6} = 4 n_{4-6} = 2	US \$190 n_{3-5} = Repowering n_{2-6} = 4 n_{4-6} = 2	US \$160 n_{3-5} = 2 n_{2-6} = 2 n_{4-6} = 2	US \$106 n_{3-5} = Repowering n_{2-6} = 2 n_{4-6} = 1 N_4 = 40 Mvar N_5 = 20 Mvar

IEEE 24-bus System	
High cost of non-conventional solution candidates	Competitive cost of non-conventional solution candidates
US \$ 362 Million	US \$ 149.5 Million
n_{3-24} = 1 n_{12-13} = 1 n_{14-23} = 1 n_{15-16} = 1 n_{15-24} = 1 n_{6-10} = 2 n_{7-8} = 2	n_{2-4} = Repowering n_{3-24} = Repowering n_{7-8} = Repowering n_{9-12} = Repowering n_{11-13} = Repowering n_{6-10} = 1 N_3 = 100 Mvar N_{10} = 100 Mvar N_8 = 60 Mvar

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Manuscript Received: Feb. 20, 2019
Accepted: May 2, 2019