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Transmission Network Expansion Planning Considering Optimal Allocation of Series Capacitive Compensation and Active Power Losses

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Abstract: This paper presents a modeling and solution approach to the static and multistage transmission network expansion planning problem considering series capacitive compensation and active power losses. The transmission network expansion planning is formulated as a mixed integer nonlinear programming problem and solved through a highly efficient genetic algorithm. Furthermore, the Villasana Garver's constructive heuristic algorithm is implemented to render the configurations of the genetic algorithm feasible. The installation of series capacitive compensation devices is carried out with the aim of modifying the reactance of the original circuit. The linearization of active power losses is done through piecewise linear functions. The proposed model was implemented in C++ language programming. To show the applicability and effectiveness of the proposed methodology several tests are performed on the 6-bus Garver system, the IEEE 24-bus test system, and the South Brazilian 46-bus test system, presenting costs reductions in their multi-stage expansion planning of 7.4%, 4.65% and 1.74%, respectively.

Keywords: transmission network expansion planning; DC model; series capacitive compensation; power losses; linearization; genetic algorithms

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1. Introduction

The main objective of the transmission network expansion planning (TNEP) is to add new elements (lines or transformers) to the current transmission network at the lowest possible cost within a long-term horizon considering a set of constraints to meet an expected demand. The TNEP problem can be divided into static planning and multistage planning [1]. In the former, a single planning horizon is considered, and it is determined where and how many new elements should be added to the power grid; in the latter, several planning investments are carried out in different stages over the time horizon. In this case, it is determined where, how many and when the new elements must be added [2].

The TNEP problem is considered to be a highly complex mathematical optimization problem due to a set of characteristics, such as: (1) it is a mixed integer non-linear programming (MINLP) problem, (2) the search space is non-convex, so that solution techniques may converge prematurely to sub-optimal solutions, (3) it presents the phenomenon of combinatorial explosion, which means that the number of candidate solutions grows exponentially with the size of the system, (4) it requires a high computational effort to find the optimal global solution or to find a high-quality solution, (5) isolated portions of the system may appear during the solution process, and (6) there are uncertainties associated with the expected values of future demands and generation [3].

There is a wide variety of solution techniques that have been implemented to solve the TNEP problem, such as classical optimization algorithms, constructive heuristic algorithms, and metaheuristic algorithms [4,5]. Within the classical optimization algorithms used to solve the TNEP problem are the Benders decomposition method [6], Branch and Bound [7,8], linear programming algorithms [9,10], quadratic programming [11], mixed integer linear programming [12], and mixed integer nonlinear programming [13]. Classical mathematical techniques are able to find globally optimal solutions for small and medium-sized systems. Nonetheless, for large electrical power systems, they require a high computational effort [14]. In contrast, metaheuristic approaches are able to find high-quality solutions for real-size power systems with less computational effort.

Constructive heuristic algorithms can be defined as simplified procedures that have the capacity to identify feasible solutions of good quality for problems with medium mathematical complexity. These algorithms rarely find the optimal global solution to the problem, the best known applied to the TNEP problem are: constructive algorithms using the transport model, DC model, and the hybrid model [15,16]. In [17], a constructive heuristic algorithm is proposed, based on sensitivity indices of a hyperbolic tangent function to initiate a multimodal optimization process and solve the TNEP problem.

Metaheuristic algorithms are techniques inspired by natural processes. These algorithms are used to solve complex combinatorial problems, finding high-quality or even global optimal solutions with an acceptable computational effort. Several metaheuristic techniques have been applied to solve the TNEP problem, such as: genetic algorithms (GA) [2,18,19], tabu search [20], simulated annealing [21], ant colony optimization [22], coronavirus optimization algorithm [23], Grasp algorithm [24], scattered search [25], path relinking [26], and variable neighborhood search [27]. Moreover, there are methodologies in the specialized literature that formulate the TNEP as a multi-objective problem. In [28], the objective function is divided into three parts: investment cost, reliability, and congestion cost. In [29], the TNEP problem is solved through as a multi-objective algorithm that considers the investment cost of lines and/or transformers, the cost of unserved wind energy, and a cost for non-supplied energy. The multi-objective nature of the models proposed in [28,29] is solved using NSGA II (Non-dominated Sorting Genetic Algorithm-II).

Hybrid algorithms are also reported in the literature, in which two metaheuristics are combined to solve the TNEP problem more efficiently. In [30], the authors combine a tabu search algorithm with an ordinal optimization algorithm; in [31], a simulated annealing algorithm is used together with a local search algorithm, and in [18], the Chu–Beasley genetic algorithm is used, combined with a path relinking algorithm to solve static and multistage TNEP considering series compensation.

In the TNEP problem, there is a constant need to improve the representation of mathematical modeling, including different parameters, variables, and/or constraints that make the problem even more realistic. For example, solving the problem takes into account the natural effects that happen in the transport of energy. One of the most important effects that can be considered in expansion planning is the power losses. Power losses represent a small percentage of the total energy of the power grid; nonetheless, inaccurate estimates of power losses can alter the functioning of the power grid and lead to a greater economic imbalance, forcing utilities to buy more energy to satisfy the energy balance [32,33]. Bearing in mind its importance, several authors have considered the effect of power losses when solving the TNEP problem. In [34], a mixed integer linear programming formulation is presented to solve the TNEP problem in a competitive electricity market, where the future demand scenarios are defined considering power losses. In [12], a mixed integer linear programming approach is presented to solve the TNEP problem considering power losses. The linearization of power losses is carried out by means of piecewise linear functions. In the same way in [35], power losses are also considered by means of piecewise linear functions within an AC mathematical model. In [36], a new mathematical modeling is presented considering power losses. In this case, a sigmoid function is considered, and to model the optimal power flow, the primal-dual interior-point technique is used. In [37], a hybrid algorithm is proposed to reduce the search space of the TNEP, using Lagrange multipliers, also considering the N-1 contingency criterion, and several loads and power loss scenarios. The authors in [38] present three mathematical models to account for power losses in the TNEP problem: (1) considering a single linear equality constraint, (2) tangent or transversal constraints of linear inequality, and (3) piecewise linear approximation.

Nowadays, considering FACTS (Flexible AC Transmission Systems) devices within the TNEP problem is a topic of great interest for energy companies. These elements bring along some advantages, such as the redistribution of power flows, enhancement of transmission capacity, improvement of voltage stability and reduction of power losses [39]. Nonetheless, the installation of these devices might cause adverse effects in the network, such as resonance problems and limitations related to the thermal capacity of the transmission lines.

The installation of series controllers draws special attention within the TNEP since they increase the active power flow through transmission lines keeping the same voltage angles differences. Moreover, this type of compensation can be done with minimum infrastructure adjustments and low out-of-time service. In [40], series compensation is included within the multistage TNEP problem considering N-1 security constraints. In [41], the authors introduce a continuously variable series reactor to the TNEP problem, also considering security constraints. In this case, a decomposition approach is proposed to reduce the computational burden of the model. In [42], the authors include thyristor-controlled series compensators and battery energy storage within an investment model for transmission expansion planning. The proposed planning strategy uses a linearized AC optimal power flow and a Benders' decomposition technique to find the optimal solution to the expansion plan.

As evidenced in the review of the specialized literature, no TNEP model has been reported that considers simultaneously the planning of series compensation and power losses. Therefore, the main contribution of this paper is a mathematical modeling to solve the problem of static and multistage TNEP that simultaneously incorporates the effect of active power losses and series capacitive compensation (SCC). The proposed methodology for computing power losses is divided into two phases: In the first phase, a PL is solved to calculate the bus angles; in the second phase, the power losses of the transmission lines are calculated from the results obtained in the first phase. These losses are distributed as loads on the power system buses. Once the losses are added, a new PL is executed to obtain the results of the power flows, dispatched generation, load shedding, and the new voltage angles. To solve the TNEP problem, a highly efficient genetic algorithm (HEGA) based on the approach presented in [43] is employed. In addition, the VGCH algorithm is implemented to make the configuration proposed by the proposed algorithm feasible in each generational cycle, if such configuration is unfeasible.

This paper is organized as follows: Section 2 presents the mathematical models for static and multistage TNEP, as well as the mathematical expressions used to compute active power losses of transmission lines. Section 3 presents the HEGA implemented to solve the TNEP problem, as well as the VGCH algorithm. Section 4 presents the results obtained by the proposed methodology for different test power systems, Section 5 presents a critical analysis of the results, and finally, conclusions are presented in Section 6.

2. Mathematical Modeling

This section presents the mathematical model of the TNEP problem considering the optimal placement of SCC devices and active power losses. Initially, the process of linearizing active power losses is described step by step in Section 2.1; then, the modeling of SCC is explained in Section 2.2. Finally, both mathematical models are integrated within the TNEP problem in Section 2.3.

2.1. Linearization of Active Power Losses

The active power flow in a line connecting buses i and j, denoted as P_{ij}, can be represented by (1), whereas the power flow in the opposite direction (P_{ji}) is given by (2). V_i and V_j represent the voltage magnitudes at nodes i and j, respectively, while g_{ij} and b_{ij} are the conductance and susceptance of line ij, respectively. Finally, θ_{ij} is the angular difference between nodes i and j.

$$P_{ij} = V_i^2 g_{ij} - V_i V_j g_{ij} \cos\theta_{ij} - V_i V_j b_{ij} \sin\theta_{ij} \tag{1}$$

$$P_{ji} = V_j^2 g_{ij} - V_i V_j g_{ij} \cos\theta_{ij} + V_i V_j b_{ij} \sin\theta_{ij} \tag{2}$$

Active power losses, denoted as φ_{ij}, can be expressed as the sum of the power flows in both directions, as indicated in (3).

$$\varphi_{ij} = P_{ij} + P_{ji} = g_{ij}\left(V_i^2 + V_j^2 - 2V_i V_j \cos\theta_{ij}\right) \tag{3}$$

Assuming the following approximations:

$$V_i \approx V_j \approx 1 \;\; p.u. \tag{4}$$

$$\cos\theta_{ij} \approx 1 - \frac{\theta_{ij}^2}{2} \tag{5}$$

Replacing (4) and (5) in (3) and performing some algebraic operations, the power losses can be expressed as follows:

$$\varphi_{ij} = g_{ij}\theta_{ij}^2 \tag{6}$$

where g_{ij} and θ_{ij} represent the conductance of circuit i-j, and the angular difference between buses i and j, respectively. Note that Equation (6) is non-linear; nonetheless, it can be linearized through piecewise linear functions as follows:

$$\theta_{ij}^2 \approx \sum_{y=1}^{Y} m_{ij,y}^s \cdot \Delta\theta_{ij,y}; \forall (i,j) \in \Omega_l; \;\; y = 1, \cdots, Y \tag{7}$$

$$\theta_{ij} = \theta_{ij}^+ - \theta_{ij}^-; \;\; \forall (i,j) \in \Omega_l \tag{8}$$

$$|\theta_{ij}| = \sum_{y=1}^{Y} \Delta\theta_{ij,y} = \theta_{ij}^+ + \theta_{ij}^-; \;\; \forall (i,j) \in \Omega_l \;\; y = 1, \cdots, Y \tag{9}$$

$$0 \le \Delta\theta_{ij,y} \le \frac{\Delta\theta_{ij}^{max}}{Y}; \;\; \forall (i,j) \in \Omega_l \tag{10}$$

$$m_{ij,y}^s = (2y-1)\frac{\Delta\theta_{i,j}^{max}}{Y}; \;\; \forall (ij) \in \Omega_l; \;\; y = 1, \cdots, Y \tag{11}$$

$$\theta_{ij}^+ \ge 0; \;\; \text{and} \;\; \theta_{ij}^- \ge 0; \tag{12}$$

Note that $\Delta\theta_{ij,y}$ is a continuous voltage angle variable associated with the *Y-th* number of piecewise linear functions, which is used to represent active power losses. Equation (7) represents the linearized losses calculated by adding the linear functions. In (8), two slack variables are used to substitute θ_{ij}. In (9) the sum of the slack variables is used to represent the absolute value of θ_{ij}. Equation (10) ensures that the linearization variables do not exceed the pre-established value. Finally, (11) indicates the slope of each linearized line in the Y-th number of linear functions. Figure 1 depicts the linearization of θ_{ij}^2 with Y piece-wise linear functions, where the slope $m_{ij,y}^s$ represents the square of the voltage angle to linearize θ_{ij}.

2.2. Series Capacitive Compensation

Series capacitive compensation (SCC) plays a key role in the operation of electrical networks, since it modifies the inductive reactance (x_{ij}) of the transmission lines, and consequently, its power flow. As power flows are redistributed, in some cases, there might be an alleviation of lines close to overload. In this paper, we propose to modify the transmission line inductive reactance in a given percentage. This is carried out aiming to have identical power flows among parallel lines in a right-of-way. It is assumed that if a line of right-of-way *i-j* is compensated, then all the other lines in that same right-of-way should be equally compensated.

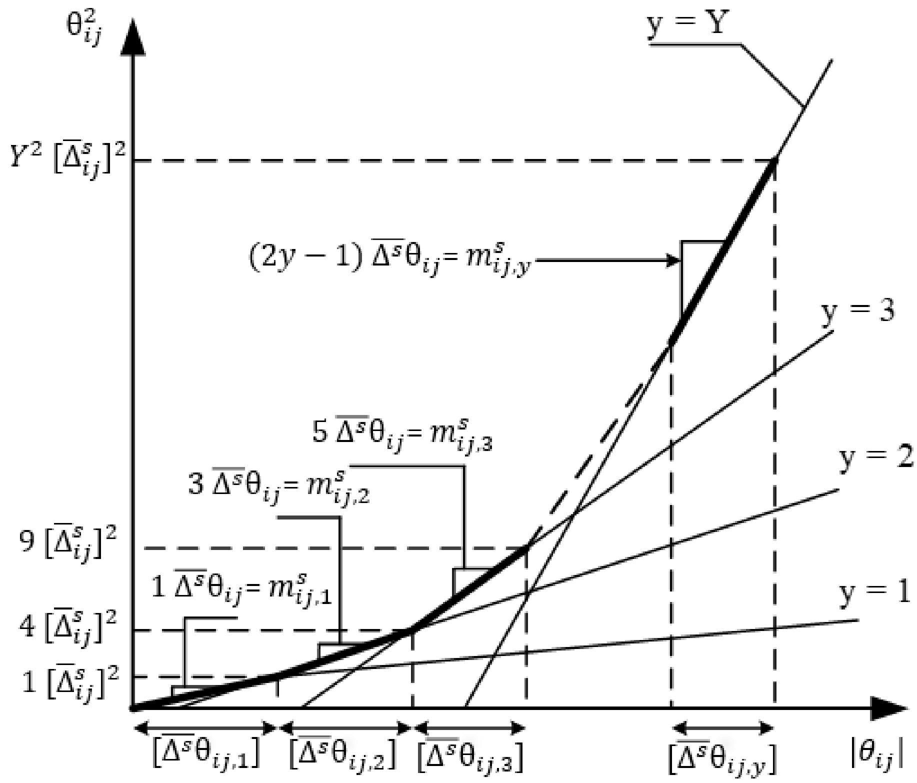

Figure 1. Piecewise linearization of θ_{ij}^2.

When SCC devices are installed in a transmission line, then the total inductive reactance of the circuit changes; that is, if the inductive reactance of the original circuit is x_{ij} and the reactance associated with the SCC is x_{ij}^{scc}, then the total reactance of the circuit will be as shown in (13), where x_{ij}^{scc} is calculated as a percentage of x_{ij}, and λ_{ij} is a value between 0 and 1 that corresponds to the compensation percentage of the SCC devices installed in the right-of-way *i-j*.

$$x_{ij}^{total} = x_{ij} - x_{ij}^{scc} = x_{ij} - \lambda_{ij}x_{ij} = x_{ij}(1-\lambda_{ij}) \tag{13}$$

The total inductive susceptance of the compensated right-of-way can be calculated as:

$$\gamma_{ij}^{total} = \frac{1}{x_{ij}(1-\lambda_{ij})} = \gamma_{ij}\left(\frac{1}{1-\lambda_{ij}}\right); \quad \forall (i,j) \in \Omega_l \quad \forall \lambda_{ij} \in [0,1]; \tag{14}$$

Note that if $\lambda_{ij} = 0$, indicates that the circuits of the right-of-way *i-j* are not compensated; therefore, γ_{ij}^{total} and γ_{ij} are equal. Otherwise, if $\lambda_{ij} \neq 0$, it indicates that circuits in the right-of-way *i-j* are compensated.

The cost associated with the optimal placement of SCC devices in the right-of-way *i-j* is a percentage of the original network circuit investment cost and can be calculated as follows:

$$c_{ij}^{scc} = \beta_{ij}c_{ij} \tag{15}$$

where β_{ij} is a value between 0 and 1, and represents the cost percentage of the SCC devices in the right-of-way *i-j*.

2.3. Modeling of SCC Devices and Active Power Losses in the TNEP Problem

The mathematical model presented in [1] for the multistage TNEP problem is modified in this paper to consider SCC devices and active power losses, and assumes the following form:

$$\text{minimize } v = \sum_{t\in\Omega_t}\left\{\delta^t_{inv}\left[\sum_{\forall ij\in\Omega_l} c^t_{ij}n^t_{ij} + \sum_{\forall ij\in\Omega_s}\beta_{ij}c^t_{ij}(n^o_{ij}+n^t_{ij}) + \alpha\sum_{\forall i\in\Omega_b} r^t_i\right]\right\} \tag{16}$$

Subject to:

$$S^t f^t - \frac{1}{2}\sum_{ij\in\Omega_l} g_{ij}\sum_{y=1}^{Y} m^{s^t}_{ij,y}\Delta\theta^t_{ij,y} + g^t_i + r^t_i = d^t_i;\ \ \forall(i,j)\in\Omega_l;\ \ \forall y = 1,\cdots,Y \tag{17}$$

$$f^t_{ij} - \left(\theta^t_i - \theta^t_j\right)\left(n^o_{ij} + \sum_{t\in\Omega_t} n^t_{ij}\right)\gamma_{ij}\left(\frac{1}{1-\lambda_{ij}}\right) = 0;\ \ \forall(i,j)\in\Omega_l \tag{18}$$

$$| f^t_{ij} | \le \left(n^o_{ij} + \sum_{t\in\Omega_t} n^t_{ij}\right)\overline{f}_{ij};\ \forall(i,j)\in\Omega_l \tag{19}$$

$$\theta^t_{ij} = \theta^+_{ij} - \theta^-_{ij} \quad \forall(i,j)\in\Omega_l \tag{20}$$

$$\sum_{y=1}^{Y}\Delta\theta^t_{ij,y} = \theta^+_{ij} + \theta^-_{ij} \quad \forall(i,j)\in\Omega_l;\quad \forall y = 1,\cdots,Y \tag{21}$$

$$0 \le \Delta\theta_{ij,y} \le \frac{\Delta\theta^{max}_{ij}}{Y} \quad \forall(i,j)\in\Omega_l \quad \forall y = 1,\cdots,Y \tag{22}$$

$$\theta^+_{ij} \ge 0; \tag{23}$$

$$\theta^-_{ij} \ge 0; \tag{24}$$

$$0 \le g^t_i \le \overline{g}^t_i \quad \forall i\in\Omega_b \tag{25}$$

$$0 \le r^t_i \le d^t_i \quad \forall i\in\Omega_b \tag{26}$$

$$0 \le n^t_{ij} \le \overline{n}^t_{ij} \quad \forall(i,j)\in\Omega_l \tag{27}$$

$$\sum_{t\in\Omega_t} n^t_{ij} \le \overline{n}_{ij} \quad \forall(i,j)\in\ \Omega_l \tag{28}$$

$$n^t_{ij} \quad \text{integer};\quad \forall(i,j)\in\Omega_l \tag{29}$$

$$\theta^t_i \quad \text{unbounded};\quad \forall i\in\Omega_b \tag{30}$$

$$f^t_{ij} \quad \text{unbounded};\quad \forall(i,j)\in\Omega_l \tag{31}$$

$$\gamma_{ij} \quad \text{discrete};\quad \forall(i,j)\in\Omega_l \tag{32}$$

Equation (16) is the objective function that minimizes the total cost of new transmission lines or transformers plus the cost associated with the optimal placement of SCC devices, and the cost of load shedding. In this case, Ω_t, Ω_l, Ω_s and Ω_b are the set of planning years, rights-of-way, branches to be compensated and system buses, respectively. δ^t_{inv} indicates the discount factor of year t to find the present investment value. c^t_{ij} is the cost of a circuit in the branch i-j where n^t_{ij} circuits were added; n^0_{ij} are the branches in the initial configuration, r^t_i represents the lost of load at bus i in stage t, and α is the factor to compatibilize cost units with loss of load. Note that the cost percentage of the SCC devices in right-of-way i-j given by is included in the objective function.

Constraint (17) represents the power balance for each node. Where, S^t is the incidence matrix, f^t represents the power flows in branches for year t, while g^t_i and d^t_i are the generation and demand at bus i in year t, respectively. Note that the linearization of power losses is included in the second term of this expression. In this case, the power losses of a given right-of-way are split in half and added to the buses connecting it. Constraint (18) indicates the power flow in every right-of-way considering the effect of the SCC. Constraint (19) represents the power flow through each line or transformer and their power flow limits. Constraints (20)–(24) are derived from the linearization of power losses detailed in Section 2.1. Constraints (25) and (26) establish the generation and load shedding limits, respectively. The maximum number of circuits that should be added in a given right-of-way, per stage and considering all stages of the planning process are enforced in (27) and (28), respectively. Constraint (29) is an integer variable declaration of the number of circuits that should be added in the right-of-way *i-j* and, finally, constraints given by (30)–(32) indicate the nature of decision variables, namely; angle, power flow and compensation percentage of SCC, respectively.

3. Highly Efficient Genetic Algorithm (HEGA)

GAs are metaheuristic optimization techniques inspired by the process of evolution. They adapted to deal with combinatorial problems of high mathematical complexity. In this paper, the GA proposed in [2] is used to solve the static and multistage TNEP problems when power losses and the optimal placement of SCC devices are considered.

The main features of the HEGA that make it competitive for solving the TNEP problem are as follows: (1) it employs a fitness and an unfitness function; the former is the total investment costs, while the latter is a measure of the unfeasibility of the proposed solution; (2) only one individual is substituted in the current population in each iteration, and (3) to be included in the current population, the new individual must be better and different than those individuals already in the current population. Several papers have been reported in the specialized literature that resort to this HEGA for solving the TNEP problem [5].

3.1. Codification

Codification plays a key role when solving mathematical optimization problems. A proper codification facilitates the implementation of different stages of the HEGA. The codification adopted in the paper consists of integer variables to represent both the number of circuits added in a given right-of-way and the type of SCC. Figure 2 illustrates the codification adopted in this paper applied to the Garver system. The first section of the vector indicates the addition of new circuits in the respective right-of-way, while the second section establishes the type of SCC. Note for example that this solution candidate considers type 1, 2, and 3 SCC in right-of-ways 3–6, 1–4, and 4–6, respectively. It is worth mentioning that the algorithm must validate the existence of the line before proposing SCC.

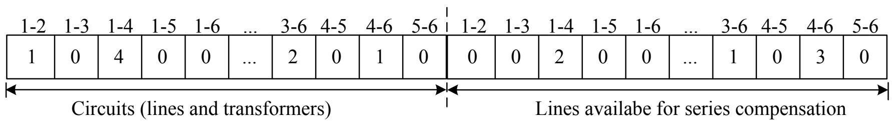

Figure 2. Proposed codification.

3.2. Initial Population

The initial population can be randomly generated, bearing in mind the limits of the decision variables, or through a constructive heuristic approach. The latter case is implemented in this paper, which provides a better starting point to the HEGA. In this paper, the VGCH algorithm is used to generate a feasible individual (one without load shedding). The other individuals of the initial population are generated from this one by adding random transmission lines or transformers until a population of k_p individuals is reached. Figure 3 shows the codification of the TNEP problem. Note that a three-dimension matrix is considered, in which the third dimension indicates the number of stages.

3.3. Selection

Selection in GAs can be carried out by the roulette method or by the tournament method. Tournament selection is used in this paper. The fundamental idea of the tournament is to randomly choose k_s individuals from the current population to create two groups. In each group, competition is performed among individuals, in order to select the two best ones from each group, who will be the parents.

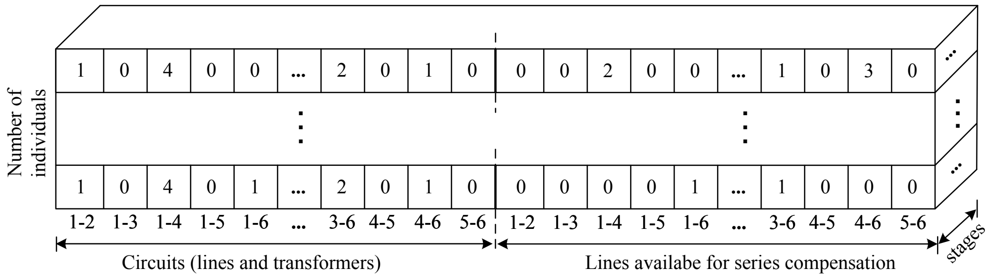

Figure 3. Initial Population.

3.4. Recombination

Once the two best parents are obtained in the selection process, the recombination process begins. This consists of exchanging a part of the information that each parent has, generating two offspring as illustrated in Figure 4. In the proposed algorithm, a single-point recombination is adopted. Then, the objective function is calculated to assess the quality of the newly created individuals, and the best one, that is, the offspring with the lowest investment cost goes to the mutation process. When applying recombination in the SCC, it must be validated that the compensations are proposed in existing lines.

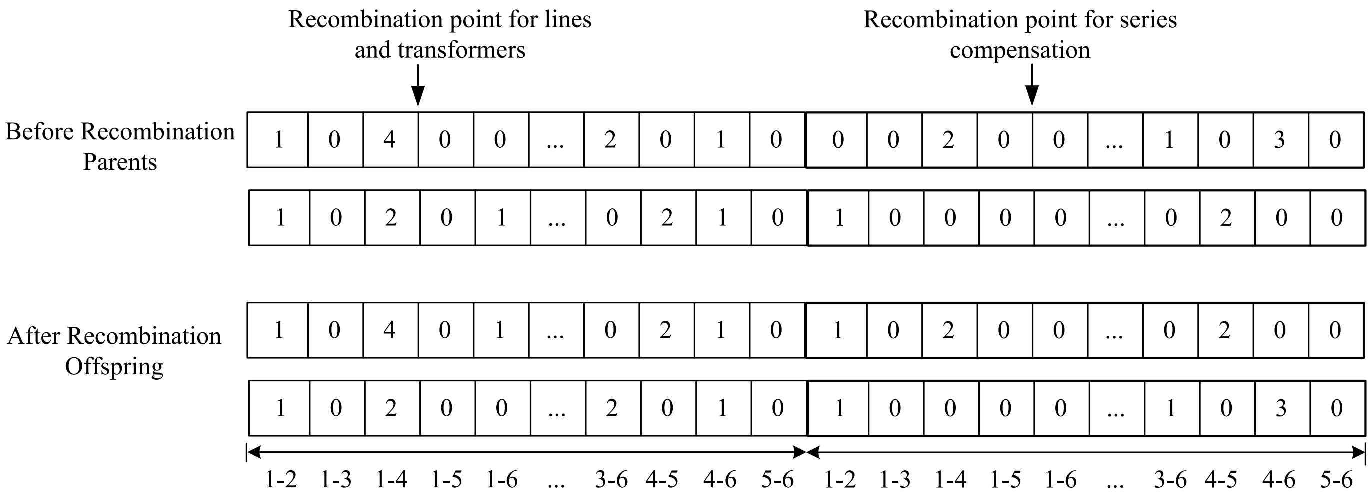

Figure 4. Illustration of the recombination process.

3.5. Mutation

The mutation is a mechanism that allows the introduction of new features in the individuals of the population. This process is performed by adding, eliminating, and/or changing characteristics (lines and/or transformers) in individuals. In Figure 5, the mutation process is presented, in which an element is added. This process depends on a mutation rate of k_m, which normally ranges from 5% to 10%. The mutation must be performed, bearing in mind the limits of the decision variables and the feasibility of solutions. For example, if a given right-of-way already has the maximum number of circuits, the mutation operator should not add new circuits. Moreover, SCC must only be added to existing lines.

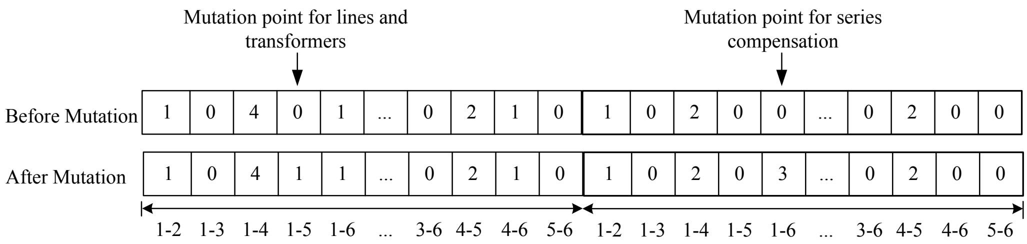

Figure 5. Illustration of the mutation process.

3.6. Local Improvement

After the selection, recombination, and mutation processes are carried out, a new individual is available. Such an individual may be feasible or unfeasible (with or without load shedding). The objective function of the HEGA employed in this paper is divided into two functions: the first one is the fitness function which corresponds to the investment cost, and the second one is the unfitness function, which represents the degree to which a given individual is unfeasible (different from zero). If the new individual is unfeasible, it must pass through the stage of improvement of the unfitness function; otherwise, it moves to improving the fitness function.

3.6.1. Improvement of the Unfitness Function

In this step, the VGCH algorithm presented in [10] is used to render the individual feasible; that is to say, with a load shedding equal to zero. The VGCH algorithm is divided into two phases. In Phase I, the power flow limits of the network circuits are disregarded, allowing overloaded circuits. The fundamental idea of this phase is to add circuits to the corridor that has the largest violation of power flow limits. The process is repeated until there are no corridors with overloads. At the end of this step, a configuration without overload is found. Nonetheless, there is the possibility of having unnecessary circuits; therefore, in phase II, these circuits are eliminated according to their cost, without incurring new load shedding.

3.6.2. Improvement of the Fitness Function

In this step, a feasible individual is obtained thanks to the improvement of the unfitness function. After the steps of selection, recombination, mutation, and improvement of the unfitness function are performed, it may be the case that the individual has redundant or unnecessary elements (lines, transformers, or SCC devices), leading to investment costs being higher than necessary. Therefore, in this step, the unnecessary elements are removed according to the cost of each of them, without changing the load-shedding.

3.7. Acceptation Criterion

The following conditions must be met for the new individual to be part of the current population: (1) the individual must be different in k_c characteristics from each individual in the current population, with k_c being the diversity factor. This value is calculated using a k_{dr} diversity rate, which normally ranges from 2% to 5%. If the individual is different from all individuals in the population fulfilling the diversity factor, then that individual can be included in the current population, and (2) if the fitness function of the individual is better than one of the worst individual of the current population, then the descendant replaces such an individual. The diversity factor can be calculated using Equation (33), where n_l is the total number of circuits in the electrical network.

$$k_c = k_{dr} \times n_l \tag{33}$$

3.8. Stopping Criterion

The process stops when a predetermined number of iterations is reached, or when the objective function does not change during a pre-defined number of iterations. Figure 6 shows the flowchart of the proposed algorithm.

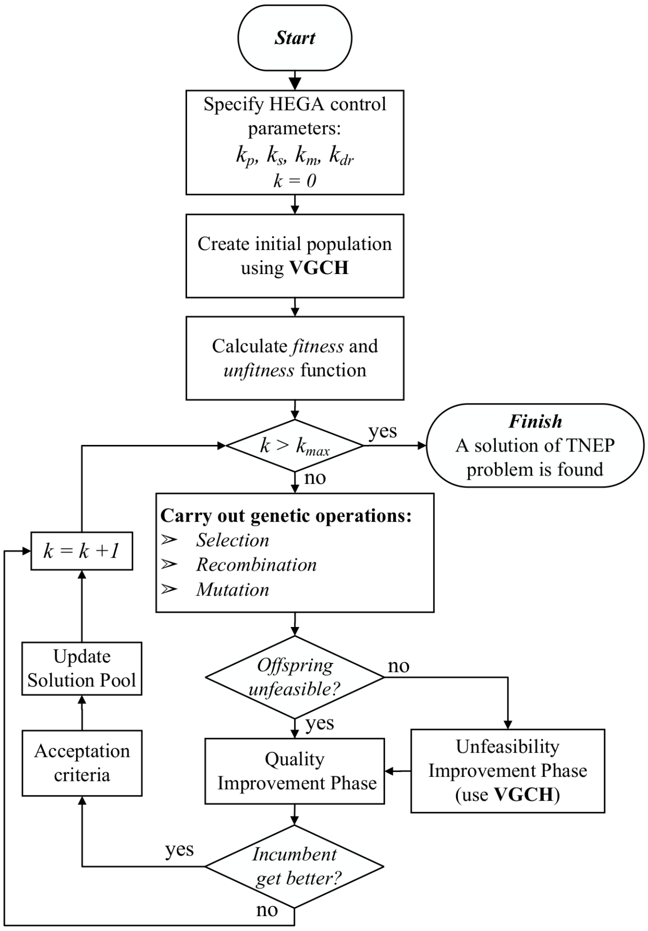

Figure 6. Flowchart of the HEGA.

4. Test and Results

This section presents the results found by the HEGA to solve the static and multistage TNEP problem. The Garver, IEEE 24-bus, and South Brazilian 46-bus were used to show the applicability of the proposed approach. The data of these systems can be found in [15] or via authors. Four tests were performed for each electrical network for both static and multistage TNEP. Test 1 corresponds to the traditional planning (static or multistage), Test 2 corresponds to the planning considering SCC devices, Test 3 corresponds to the planning considering active power losses, and Test 4 corresponds to the planning considering both SCC devices and active power losses.The number of piecewise linear blocks is Y = 5, 7 and 10 for the Garver system, IEEE-24 bus test system and the South Brazilian 46-bus system, respectively. For all simulations, the penalty factor α is equal to 1 US$MW and the maximum voltage angle θ_{ij}^{max} is equal to $\pi/4$ [44]. To solve the TNEP problem considering active power losses, the number of linear piecewise blocks is Y = 5.

Table 1 presents the types of SCC devices implemented in the tests. Note that the compensation rate and installation cost of each type of SCC are indicated in columns 2 and 3, respectively. Furthermore, the compensation costs for each case were assumed as a percentage of the investment cost of the transmission line. Note that the higher the cost of the capacitor bank, the higher its compensation.

Table 1. Series Capacity Compensation Types.

Type	Compensation Rate (% of Circuit Reactance)	Compensation Cost (% of Circuit Inves. Cost)
1	30%	10%
2	40%	15%
3	50%	20%

All of the algorithms proposed in this paper are implemented in the C++ programming language. The simulations are executed using a personal computer with an Intel® Core (TM) i7-8850H processor (2.6 GHz) with 16 GB of RAM.

4.1. Static TNEP

To solve the static TNEP problem, only one stage is considered ($t = 1$) in Equations (16)–(32). In this case, the annual discount rate (I) is zero, which leads to a nominal cost of 1 for this stage ($\delta_{inv}^{t=1} = 1$). The number of constraints of the static TNEP is smaller compared to the multistage problem, so the computational effort is lower.

4.1.1. Garver System

The Garver system has 6 buses and 15 right-of-ways for the addition of new circuits (lines and transformers). The generation capacity is 1110 MW and the expected demand is 760 MW. In this case, it is supposed a maximum of 4 circuits in each right-of-way. For all simulations, a population of 20 individuals (k_p) was considered, with k_s equal to 3%, k_{dr} equal to 5% and k_m equal to 5% (selection, diversification and mutation rates, respectively). A summary of results for this system is presented in Table 2.

Table 2. Summary of results for the Garver system (static TNEP).

Test	Total Cost (10^6 US$)	Power Losses (MW)	LPs Executed	Time (min)	Configuration	Compensated Lines
1	110.00	–	40	0.045	$n_{3-5} = 1$, $n_{4-6} = 3$	–
2	110.00	–	–	–	$n_{3-5} = 1$, $n_{4-6} = 3$	No compensated lines
3	130.00	29.51	129	0.121	$n_{2-3} = 1$, $n_{3-5} = 1$, $n_{4-6} = 3$	–
4	116.00	36.62	139	0.181	$n_{2-6} = 1$, $n_{3-5} = 1$, $n_{4-6} = 2$	$n_{4-6} = 2$ (type 1)

Test 1: The best solution found by HEGA for the static TNEP problem without SCC and active power losses has a total investment cost of US$110.00 × 10^6 and no load shedding. This solution is equal to the one reported in [15]. This solution is found by the HEGA after executing 46 LPs with a computational time of 0.047 min. The configuration is: $n_{3-5} = 1$, and $n_{4-6} = 3$.

Test 2: The solution found by HEGA for the static TNEP problem with SCC and without active power losses is equal to test 1 (no lines compensation).

Test 3: The best solution found by HEGA for the static TNEP problem considering active power losses and without SCC has a total investment cost of US$130.00 × 10^6 and no load shedding. This solution is found by the HEGA after executing 13 LPs with a computational time of 0.046 min. The found configuration is: $n_{2-3} = 1$, $n_{3-5} = 1$, $n_{4-6} = 3$.

Test 4: The best solution found by HEGA for the static TNEP problem with SCC and active power losses has a total investment cost of US$116.00 × 10^6 and no load shedding. This solution is found by the HEGA after executing 139 LPs with a computational time of 0.18 min. The total active power loss is equal to 36.62 MW. The added circuits have an investment cost equal to US$110.00 × 10^6, and are added in the following right-of-ways: $n_{2-6} = 1$, $n_{3-5} = 1$, and $n_{4-6} = 2$. The investment cost of the SCC devices is equal to US$6.00 × 10^6, and the compensated line is: $n_{4-6} = 2$ (type 1).

4.1.2. IEEE 24-Bus System

The IEEE 24-bus has 24 buses and 41 right-of-ways for the addition of new circuits. The generation capacity is 10,215 MW, and the demand is 8550 MW. This system has a limit of 5 circuits that can be added in each right-of-way. In this case, a population of 40 individuals (k_p) was considered, with k_s equal to 3%, k_{dr} equal to 5% and k_m equal to 5% (selection, diversification and mutation rates, respectively). A summary of results for this system is presented in Table 3.

Table 3. Sumary of results for the IEEE 24-bus system (static TNEP).

Planning Type	Total Cost (10^6 US$)	Power Losses (MW)	LPs Executed	Time (min)	Configuration	Compensated Lines
1	152.00	–	46	0.045	$n_{6-10} = 1$, $n_{7-8} = 2$, $n_{10-12} = 1$, $n_{14-16} = 1$	–
2	152.00	–	120	0.605	$n_{6-10} = 1$, $n_{7-8} = 2$, $n_{10-12} = 1$, $n_{14-16} = 1$	No compensated lines
3	182.00	216.19	20	0.121	$n_{6-10} = 1$, $n_{7-8} = 2$, $n_{10-12} = 1$, $n_{14-16} = 1$, $n_{20-23} = 1$	–
4	154.40	225.52	8170	3.3	$n_{6-10} = 1$, $n_{7-8} = 2$, $n_{10-12} = 1$, $n_{14-16} = 1$	$n_{15-16} = 2$ (type 1)

Test 1: The best solution found by the HEGA for the static TNEP problem without SCC and active power losses has a total investment cost of US$152.00 × 10^6 and no load shedding. This solution is equal to the one reported in [15]. The TNEP problem is solved by the HEGA after executing 46 LPs with a computational time of 0.046 min. The configuration found is: $n_{6-10} = 1$, $n_{7-8} = 2$, $n_{10-12} = 1$, and $n_{14-16} = 1$.

Test 2: The solution found by the proposed approach for the static TNEP problem with SCC and without active power losses is equal to the one of test 1 (no lines compensation).

Test 3: The best solution found by the HEGA for the static TNEP problem considering active power losses and without SCC devices has a total investment cost of US$182.00 × 10^6 and no load shedding. This solution is found by the HEGA after executing 20 LPs with a computational time of 0.06 min. The configuration found is: $n_{6-10} = 1$, $n_{7-8} = 2$, $n_{10-12} = 1$, $n_{14-16} = 1$, and $n_{20-23} = 1$.

Test 4: The best solution found by HEGA for the static TNEP problem with SCC devices and active power losses has a total investment cost of US$154.40 × 10^6 and no load shedding. This solution is found by the HEGA after executing 8170 LPs with a computational time of 3.3 min. The total active power loss is equal to 225.525 MW. The added circuits have an investment cost of US$152.00 × 10^6, and are added in the following right-of-ways: $n_{6-10} = 1$, $n_{7-8} = 2$, $n_{10-12} = 1$, and $n_{14-16} = 1$. On the other hand, the SCC devices have an investment cost of US\$2.40 $\times$ 10^6, and the compensated line is: $n_{15-16} = 2$ (type 1).

4.1.3. South Brazilian 46-Bus System

The South Brazilian 46-bus system has 46 buses and 71 right-of-ways for the addition of new circuits. The generation is 10,545 MW, and the demand is 6880 MW. This system has no limits in the number of circuits that can be added to the right-of-ways. In this case, a population of 50 individuals (k_p) was considered, with k_s equal to 4%, k_{dr} equal to 5% and k_m equal to 5% (selection, diversification and mutation rates, respectively). A summary of results for this system is presented in Table 4.

Table 4. Summary of results for the South Brazilian 46-bus system (static TNEP).

Test	Total Cost (10^6 US\$)	Power Losses (MW)	LPs Executed	Time (min)	Configuration	Compensated Lines
1	72.87	–	274	0.131	$n_{2-5} = 1$, $n_{13-20} = 1$, $n_{20-23} = 1$, $n_{20-21} = 2$, $n_{42-43} = 1$, $n_{46-6} = 1$, $n_{5-6} = 1$	–
2	63.16	–	3154	2.28	$n_{20-23} = 1$, $n_{20-21} = 2$, $n_{42-43} = 1$, $n_{46-6} = 1$, $n_{5-6} = 2$	$n_{5-8} = 1$ (type 1), $n_{13-20} = 1$ (type 2)
3	75.90	603.18	608	0.36	$n_{18-20} = 1$, $n_{20-23} = 1$, $n_{20-21} = 2$, $n_{42-43} = 1$, $n_{46-6} = 1$, $n_{5-6} = 2$	–
4	75.45	642.66	16,698	9.84	$n_{13-18} = 1$, $n_{20-23} = 1$, $n_{20-21} = 2$, $n_{42-43} = 1$, $n_{46-6} = 1$, $n_{5-6} = 2$	$n_{13-20} = 1$ (type 1)

Test 1: The best solution found by the proposed approach for the static TNEP problem without SCC and active power losses has a total investment cost of US\$72.87 $\times$ 10^6 and no load shedding. The solution is equal to the one reported in [15]. This solution is found by the HEGA after executing 274 LPs with a computational time of 0.131 min. The found configuration is: $n_{2-5} = 1$, $n_{13-20} = 1$, $n_{20-23} = 1$, $n_{20-21} = 2$, $n_{42-43} = 1$, $n_{46-6} = 1$, and $n_{5-6} = 1$.

Test 2: The solution found by the algorithm for the static TNEP problem with SCC and without active power losses has a total investment cost of US\$64.98 $\times$ 10^6 and no load shedding. This solution is found by the HEGA after solving 3154 LPs with a computational time of 2.28 min. The added circuits have a total investment cost of US\$63.16 $\times$ 10^6, and are added in the following right-of-ways: $n_{20-23} = 1$, $n_{20-21} = 2$, $n_{42-43} = 1$, $n_{46-6} = 1$, $n_{5-6} = 2$. The SCC devices have investment cost equal to US\$1.82 $\times$ 10^6, and the compensated lines are: $n_{5-8} = 1$ (type 1), and $n_{13-20} = 1$ (type 2).

Test 3: The best solution found by the HEGA for the static TNEP problem considering active power losses and without SCC has a total investment cost of US\$75.90 $\times$ 10^6 and no load shedding. This solution is found by the HEGA after solving 608 LPs with a computational time of 0.36 min. The found configuration is: $n_{18-20} = 1$, $n_{20-23} = 1$, $n_{20-21} = 2$, $n_{42-43} = 1$, $n_{46-6} = 1$, and $n_{5-6} = 2$.

Test 4: The best solution found by the HEGA for the static TNEP problem with SCC and active power losses has a total investment cost of US$75.45 $\times 10^6$ and no load shedding. The active power loss equal to 642.664 MW. This solution is found by the HEGA after solving 16,698 LPs with a computational time of 9.84 min. The added circuits have an investment cost equal to US$74.73 $\times 10^6$, and are added in the following right-of-ways: $n_{13-18} = 1$, $n_{20-23} = 1$, $n_{20-21} = 2$, $n_{42-43} = 1$, $n_{46-6} = 1$, and $n_{5-6} = 2$. The SCC devices have an investment cost of US$0.713 $\times 10^6$, and the compensated line is: $n_{13-20} = 1$ (type 1).

4.2. Multistage TNEP Problem

The tests for the multistage TNEP problem were simulated with an annual discount rate I = 10% and considering three stages for all systems under study. In this case, the circuits that are added in Stage 1, are presented in the objective function with their nominal costs, and the costs of the circuits added in Stage 2 and 3 are multiplied by 0.729 and 0.478, respectively as indicated in [1].

4.2.1. Garver System

Four tests were also carried out for this system considering a multistage TNEP. The same parameters for the static TNEP were used. The results obtained are summarized in Table 5.

Test 1: The best solution found by the HEGA for the multistage TNEP problem without SCC and active power losses has a total investment cost of US$80.79 $\times 10^6$ and no load shedding. This solution is equal to the one reported in [15] and found after solving 924 LPs with a computational time of 0.277 min.

Test 2: The solution found by the HEGA for the multistage TNEP with SCC is equal to the one of test 1.

Test 3: The best solution found by the HEGA for the multistage TNEP problem considering power losses presents a total investment cost of US$90.35 $\times 10^6$, and no load shedding. This solution is found after solving 571 LPs with a computational time of 0.241 min.

Test 4: The best solution found by the HEGA for the multistage TNEP with SCC and power losses has a total investment of US$82.22 $\times 10^6$, and no load shedding. This solution is found after solving 12,415 LPs with a computational time of 3.94 min.

Table 5. Summary of results for the Garver system (multistage TNEP).

Test	Total Cost (10^6 US$)	LPs	Time (min)	Stage	Stage Cost (P10^6 US$)	Power Losses (MW)	Configuration	Compensated Lines
1	80.79	924	0.277	1	30.00	–	$n_{4-6} = 1$	–
				2	36.45	–	$n_{3-5} = 1$, $n_{4-6} = 1$	–
				3	14.34	–	$n_{4-6} = 1$	–
2	80.79	924	0.277	1	30.00	–	$n_{4-6} = 1$	No compensated lines
				2	36.45	–	$n_{3-5} = 1$, $n_{4-6} = 1$	No compensated lines
				3	14.34	–	$n_{4-6} = 1$	No compensated lines
3	90.35	571	0.241	1	30.00	19.267	$n_{4-6} = 1$	–
				2	36.45	27.673	$n_{2-6} = 1$, $n_{3-5} = 1$	–
				3	17.21	31.643	$n_{2-3} = 1$, $n_{4-6} = 1$	–
4	82.22	12,415	3.94	1	30.00	19.607	$n_{4-6} = 1$	No compensated lines
				2	36.45	27.531	$n_{3-5} = 1$, $n_{4-6} = 1$	No compensated lines
				3	15.77	36.045	$n_{4-6} = 1$	$n_{4-6} = 1$ (type 1)

4.2.2. IEEE 24-Bus System

For this system, the total generation capacity for stage 1 is equal to 10,215 MW, for stage 2 is equal to 10,726 MW, and for stage 3 is equal to 11,262 MW. The total demand for stage 1 is equal to 8560 MW, the total demand for stage 2 is equal to 8988 MW, and the total demand for stage 3 is equal to 9437 MW. For all tests carried out, the HEGA parameters are: $k_p = 20$, $k_s = 3\%$, $k_m = 5\%$ and $k_{dr} = 1\%$ (population size, selection rate, mutation rate, and diversification rate, respectively). The number of linear blocks was Y = 8. A summary of results for this system is presented in Table 6.

Table 6. Summary of results for the IEEE 24-bus system (multistage TNEP).

Test	Total Cost (10^6 US$)	LPs	Time (min)	Stage	Stage Cost (10^6 US$)	Power Losses (MW)	Configuration	Compensated Lines
1	220.286	1685	0.481	1	164.00	–	$n_{6-10} = 1$, $n_{7-8} = 2$, $n_{10-12} = 1$, $n_{10-12} = 1$, $n_{11-13} = 1$, $n_{4-6} = 1$	–
				2	21.87	–	$n_{20-23} = 1$,	–
				3	14.34	–	$n_{1-5} = 1$, $n_{3-24} = 1$	–
2	209.243	190,375	44.09	1	152.00	–	$n_{6-10} = 1$, $n_{7-8} = 2$, $n_{10-12} = 1$, $n_{14-16} = 1$	No compensated lines
				2	48,114	–	$n_{12-13} = 1$	No compensated lines
				3	9.129	–	No add circuits	$n_{1-3} = 1$ (type 3), $n_{14-16} = 1$ (type 2)
3	238.35	15,395	5.82	1	152.00	220.47	$n_{6-10} = 1$, $n_{7-8} = 2$, $n_{10-12} = 1$, $n_{14-16} = 1$	–
				2	48.114	169.40	$n_{12-13} = 1$	–
				3	38.240	115.27	$n_{9-12} = 1$, $n_{20-23} = 1$	–
4	227.264	179,863	60.48	1	152.00	220.47	$n_{6-10} = 1$, $n_{7-8} = 2$, $n_{10-12} = 1$, $n_{14-16} = 1$	No compensated lines
				2	48.114	232.373	$n_{12-13} = 1$	No compensated lines
				3	27.150	263.243	$n_{20-23} = 1$	$n_{1-3} = 1$ (type 3), $n_{2-6} = 1$ (type 1), $n_{14-16} = 1$ (type 3)

Test 1: The best solution found by the HEGA for the multistage TNEP problem without SCC and active power losses has a total investment cost of US$220.286 $\times$ 10^6 and no load shedding. This solution is found after solving 1585 LPs with a computational time of 0.48 min.

Test 2: The solution found by the HEGA for the multistage TNEP with SCC has a total investment cost of US$209.243 $\times$ 10^6 and no load shedding. This solution is found after solving 190,375 LPs with a computational time of 44.09 min.

Test 3: The best solution found by the HEGA for the multistage TNEP problem considering power losses presents a total investment cost of US$238.35 $\times$ 10^6, and no load shedding. This solution is found after solving 15,395 LPs with a computational time of 5.82 min.

Test 4: The best solution found by the HEGA for the multistage TNEP with SCC and power losses has a total investment of US$227.264 × 10^6, and no load shedding. This solution is found after solving 179,863 LPs with a computational time of 60.48 min.

4.2.3. South Brazilian 46-Bus System

For this system, the generation capacity for each stage is equal to 10,845 MW. The total demand for stages 1, 2 and 3 are 7743.52 MW, 8976.83 MW, and 10,406.2 MW, respectively. For all tests carried out, the HEGA parameters are: $k_p = 100$, $k_s = 7\%$, $k_m = 10\%$ and $k_{dr} = 1\%$ (population size, selection rate, mutation rate, and diversification rate, respectively). The number of linear blocks was Y = 5. Table 7 presents a summary of the results.

Table 7. Summary of results for the South Brazilian 46-bus system (multistage TNEP).

Test	Total Cost (10^6 US$)	LPs	Time (min)	Stage	Stage Cost (10^6 US$)	Power Losses (MW)	Configuration	Compensated Lines
1	183.213	8988	2.68	1	116.00	–	$n_{12-14}=1$, $n_{20-21}=1$, $n_{42-43}=2$, $n_{46-6}=1$, $n_{19-25}=1$, $n_{24-25}=2$, $n_{5-6}=2$	–
				2	40.015	–	$n_{2-5}=1$, $n_{32-43}=1$, $n_{20-21}=1$, $n_{5-6}=2$,	–
				3	27.198	–	$n_{18-20}=2$, $n_{18-19}=2$, $n_{42-43}=1$, $n_{31-32}=1$, $n_{28-31}=1$	–
2	183.213	8988	2.68	1	116.00	–	$n_{12-14}=1$, $n_{20-21}=1$, $n_{42-43}=2$, $n_{46-6}=1$, $n_{19-25}=1$, $n_{24-25}=2$, $n_{5-6}=2$	No compensated lines
				2	40.015	–	$n_{2-5}=1$, $n_{32-43}=1$, $n_{20-21}=1$, $n_{5-6}=2$,	No compensated lines
				3	27.198	–	$n_{18-20}=2$, $n_{18-19}=2$, $n_{42-43}=1$, $n_{31-32}=1$, $n_{28-31}=1$	No compensated lines
3	195.08	34,326	13.74	1	116.100	495.40	$n_{12-14}=1$, $n_{20-21}=1$, $n_{42-43}=2$, $n_{46-6}=1$, $n_{19-25}=1$, $n_{24-25}=2$, $n_{5-6}=2$	–
				2	43.557	936.00	$n_{2-5}=1$, $n_{20-21}=1$, $n_{31-41}=1$, $n_{40-41}=1$, $n_{5-6}=1$	–
				3	35.415	488.15	$n_{9-21}=1$, $n_{20-21}=1$, $n_{42-43}=1$, $n_{28-31}=1$, $n_{41-43}=1$	–
4	191.68	782,938	287.88	1	116.10	406.39	$n_{12-14}=1$, $n_{20-21}=1$, $n_{42-43}=2$, $n_{46-6}=1$, $n_{19-25}=1$, $n_{24-25}=2$, $n_{5-6}=2$	No compensated lines
				2	43.558	943.51	$n_{2-5}=1$, $n_{20-21}=1$, $n_{31-41}=1$, $n_{40-41}=1$, $n_{5-6}=1$	No compensated lines
				3	31.433	1064.23	$n_{13-18}=1$, $n_{18-20}=1$, $n_{18-19}=1$, $n_{42-43}=1$, $n_{28-31}=1$, $n_{41-43}=1$	$n_{20-21}=1$ (type 2)

Test 1: The best solution found by the HEGA for the multistage TNEP problem without SCC and active power losses has a total investment cost of US$220.286 × 10^6 and no load shedding. This solution is found after solving 1585 LPs with a computational time of 0.48 min.

Test 2: The solution found by the proposed approach for the static TNEP problem with SCC and without active power losses is equal to the one of test 1 (no lines compensation).

Test 3: The best solution found by the HEGA for the multistage TNEP problem considering power losses presents a total investment cost of US$238.35 × 10^6, and no load shedding. This solution is found after solving 15,395 LPs with a computational time of 5.82 min.

Test 4: The best solution found by the HEGA for the multistage TNEP with SCC and power losses has a total investment of US$227.264 × 10^6, and no load shedding. This solution is found after solving 179,863 LPs with a computational time of 60.48 min.

5. Critical Analysis of the Results

This section presents some analysis and discussion of the results achieved by the proposed approach. In the static planning of the Garver system using the proposed methodology, a difference of 14.00 × 10^6 US$ is found, i.e., 10.78% cheaper than the planning without SCC. For the multistage planning of the same system, 6690 × 10^6 US$ is found, that is, 7.4% more economical than planning without SCC. For the IEEE-24 static bus system, it was 27,600 × 10^6 US$, that is, 15.16% more economical than planning without SCC, and for multistage planning, it was 11,090 × 10^6 US$, that is, 4.65% more economical than planning without SCC. The expansion cost for the southern Brazilian system in the static planning was 0.450 × 10^6 US$, that is, 0.593% more economical than planning without SCC, and for the multistage planning it was 3.40 × 10^6 US $, that is, 1.74% cheaper than planning without SCC.

According to Figure 7, the Garver system in topology (a) presents an investment cost of 110.00 × 10^6 US$ with 4 new circuits, which matches the optimal planning reported in the specialized literature for this system. Topology (b) shows the optimal planning of the same system considering the effect of power losses. In this case, the investment costs increase to US$130.00 × 10^6 US$, and 5 transmission lines are added. This extra cost is attributable to the effect of power losses and evidences the importance of considering them to reach more accurate expansion plans. The result of the planning considering power losses and SCC devices is depicted in Topology (c). In this case, an investment cost of 116.00 × 10^6 US$ is required. Note that the introduction of SCC devices allows an important reduction of the expansion planning cost. Due to the installation of the SCC devices, a transmission line is removed from the n_{2-3} corridor. The installation of the SCC device is carried out in the n_{4-6} corridor.

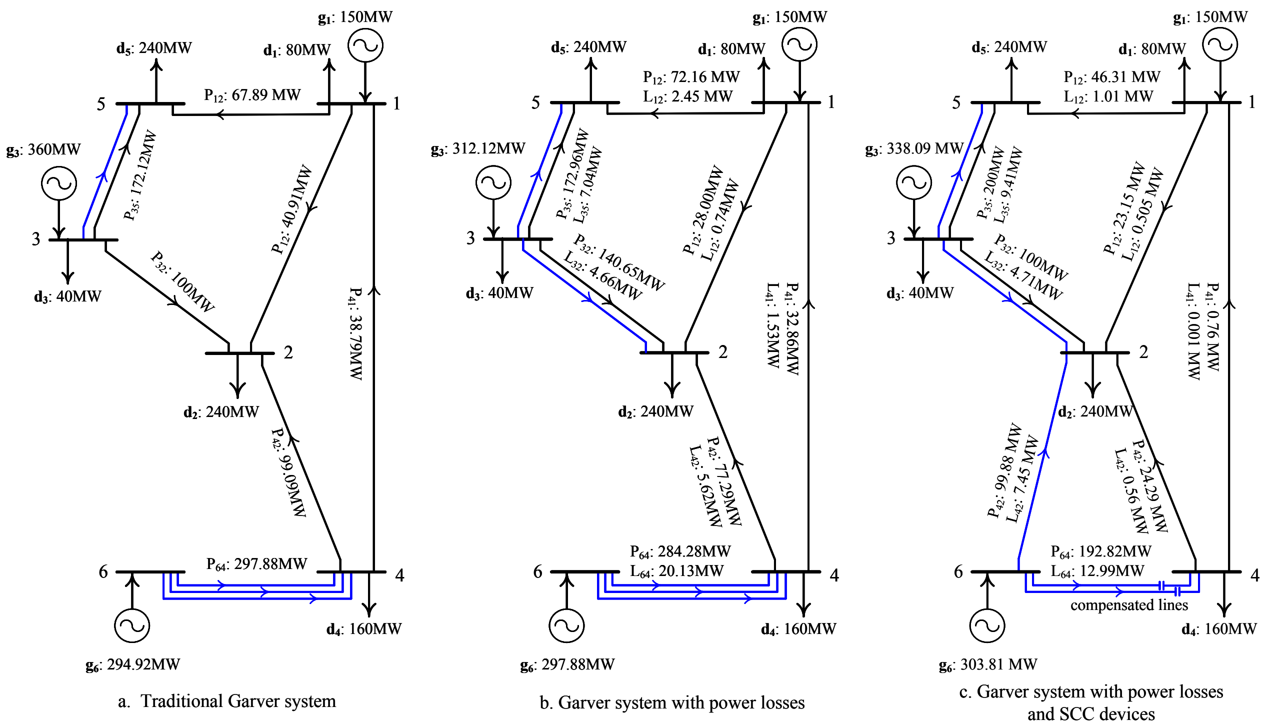

Figure 7. Optimal solution for the Garver system with power losses and SCC devices.

Figure 7 depicts the Garver system with its respective power flows, where power losses are highlighted in blue color. Note that the power flows in some corridors increase when SCC devices are installed, and therefore, it is assumed that these corridors are compensated. Also, it can be seen a reduction in power flows in some corridors diminishing when the SCC devices are installed, due to the change of the reactance in the respective circuit [43]. Table 8 presents a comparison of the computational effort (measured as the number of PLs to reach a solution) when solving the static TNEP with different metaheurstic techniques. In this case, EGA stands for enhanced GA, while TS and SA are tabu search and simulated annealing, respectively. The comparison was carried out with the Garver and South Brazilian system, since the number of PLs was not available for the IEEE-24 bus test system. Note that the proposed HEGA allows an important reduction of the number of PLs required to solve the TNEP problem, which means a lower computational effort.

Table 8. Number of PLs required for solving the static TNEP with different techniques.

Metaheuristic	Garver System	South Brazilian
Proposed HEGA	40–50	200–300
GA [5]	50–70	100–1500
EGA [45]	700–1000	3500–4500
SA [45]	1000–1300	4000–5000
TS [45]	600–700	4100–6900
TS-SA [45]	600–700	1700–2500
TS-EGA [45]	500–620	1400–1900
TS-SA-EGA [45]	550–700	1450–2000

6. Conclusions

Currently, many heuristic and metaheuristic algorithms have been applied for solving the TNEP problem; nonetheless, there are no research works that consider transmission power losses and the installation of SCC devices together within this problem. This paper presented a methodology for solving the TNEP considering power losses for the static and multistage instances of the problem. Furthermore, the VGCH algorithm was implemented to turn the expansion configurations feasible. It was found that the investment cost was considerably reduced in some systems by including SCC devices. In addition, the results show the redistribution of power flows when SCC devices are installed. In this case, there is an alleviation of the system congestion moving lines away from their maximum operating limits.

On the other hand, the consideration of power losses in the TNEP problem allows a better approximation of the operating system. The proposed formulation for the mathematical model in this paper allows finding an accurate optimal solution and is flexible enough to add new transmission lines and SCC devices. The tests, simulations, and results in different test systems evidenced the efficiency and applicability of the proposed approach.

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