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RESEARCH ARTICLE OPEN ACCESS

MODIFIED BAT ALGORITHM FOR TRANSMISSION NETWORK EXPANSION PLANNING CONSIDERING ACTIVE POWER LOSSES

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ABSTRACT

This paper presents a metaheuristic algorithm, called BATp optimizer, to solve the combinatorial problem of static transmission networks expansion planning (STNEP) considering the effect of active power losses in the circuits. The optimizer is composed of two modules. One module generates candidate solutions, using the modified Bat Algorithm (BA), and the other that makes solutions with over costs or infeasibilities competitive. The modification made to the original BA consists in the inclusion of a local search intensification operator that acts on the elements of the current global optimal solution to improve the convergence rate and hinder stagnation in a suboptimal solution. The number of elements modified in the current global optimal solution is defined as a function of the number of buses and branches in the analyzed system. The size of the initial population is also defined as a function of the number of buses and branches. The active power losses are represented in the equality constraints of the mixed-integer nonlinear programming (MINLP) problem. The performance evaluation of the transmission network of the analyzed system is done by a linear power flow. The performance of the BATp optimizer was tested in three systems well known in the literature: the IEEE 24-bus and the South Brazilian - SB 46-bus. In each of the analyzed systems, situations were simulated with and without the possibility of generation redispatch. The BATp optimizer was able to find good results compared to those published in the literature, with relatively low computational effort.

I. INTRODUCTION

I.1 PURPOSE OF TNEP

Transmission network expansion planning - TNEP of any power electric system is a task of great importance, because it involves large investments in transmission lines, transformers, and substation and voltage control equipment. The TNEP aims to determine a transmission network capable of transporting the electric power produced in one or more generation centers (existing and future) to the load centers (existing and future) meeting technical, quality and security requirements, to minimize the costs involved in the expansion [1].

I.2 FACTORS THAT AFFECT TNEP

The TNEP depends on factors such as; i) locations of future generation and load centers; ii) topology of the existing transmission network; (iii) list of candidate circuits; (iv) electrical parameters and costs of candidate circuits; v) maximum allowed number of parallel circuits per branch; vi) mathematical model used to represent the transmission grid (via direct current - DC or via alternating current - AC; vii) number of years of the planning periods (one period or several periods); viii) reliability criteria (deterministic N-0, N-1, or probabilistic); ix) representation of power losses in the circuits; x) representation of uncertainties.

I.3 PLANNING PERIODS

Regarding the number of planning periods, TNEP has been classified as either static or dynamic [2]. When only the last year of the planning horizon is analyzed, the TNEP is called static TNEP (STNEP), and it is determined where and how many new circuits should be added to the existing transmission network. In [3] several articles are cited that address the STNEP problem.

When more than one year of the planning horizon is analyzed, the TNEP is called dynamic TNEP (DTNEP), and it is also determined when they should be added as well as where and how many. This model is more complex than the STNEP model due to the larger number of variables and constraints that must be considered in the mathematical model. In [1] and [4] several articles are cited that address the DTNEP problem.

I.4 SAFETY CONSTRAINTS

In both STNEP and DTNEP, the transmission grid can be expanded either to meet safety constraints (deterministic reliability criterion N-1, used in Brazil) [5], where all existing and future demand must be met without violations of circuit loading limits in the event of any simple contingency, or to meet the N-0 reliability criterion [6], where only part of the total system demand must be met in the event of any simple contingency. It is implicit in the deterministic N-1 criterion that transmission network sizing is done to meet the worst-case availability condition of the components.

II.5 POWER FLOW MODELS

With respect to the representation of the transmission network in the TNEP mathematical model, it can be done by a linear power flow model or a non-linear model. In [4] several papers are cited that have used these two models, pointing out the advantages and disadvantages of each.

The non-linear model, called the alternating current power flow (pfAC), despite being realistic, is complex due to the larger number of variables and restrictions that are considered. The linear model, called the direct current power flow (pfDC), on the other hand, is not complex. Therefore, it has been extensively used in TNEP studies because it calculates the active power flows in circuits in a simple, fast and accurate manner suitable for long-term planning studies.

I.6 ACTIVE POWER LOSSES

In the TNEP problem, there is a need to include parameters, variables, constraints and/or natural effects, to make the problem representation more realistic. A very important natural effect that should be considered in the mathematical modeling is related to power losses arising from the circulations of power flows in the transmission network circuits.

Despite representing a small percentage of the energy produced in the system, the consideration of power losses in the mathematical model is important due to the increase in generation output and, consequently, increase in power flows in the circuits. This fact may cause the need for additional investments if certain circuits are operating at the limit of their maximum transmission capacities. Thus, if losses are neglected, the circuits that are actually congested appear to be uncongested, resulting in no need for additional circuits and in different solution.

According to the specialized literature, three ways of including the effects of power losses have been used in the STNEP optimization model with losses (STNEPp): i) in the objective function - OF (Table 1), ii) in the equality constraints - EC (Table 2) and iii) in the OF and EC (Table 3).

The Tables 1, 2 and 3 show the optimization algorithms that have been used in the published work Classical Optimization Algorithm (COA), Constructive Heuristic Algorithm (CHA) and Metaheuristic Algorithm - MHA), the power flow models (pfDC or pfAC) and systems generally used in the testing of the algorithms: Garver - 6 buses/15 branches (G-6/15); Modified Garver - 6 buses/15 branches (GM-6/15); IEEE - 24 buses/41 branches (IEEE-24/41); South Brazilian - 46 buses/79 branches (SB-46/79); North-West Iranian - 17 buses/21 branches (NWI-18/21); Hypothetical System - 8 buses/12 branches (HS-8/12); IEEE -9 buses/9 branches (IEEE-9/9); Spanish System - 425 buses/628 branches (SS-425/628) and North-East Iranian - 12 buses/21 branches (NEI-12/21).

Table 1: Active power loss represented in the OF.

Year, Ref.	PF Model	Algorithm	PES Tested
1988, [6]	pfDC	COA	G-6/15
2008, [6]	pfDC	MHA	G-6/15
2010, [6]	pfDC	MHA	NWI-18/21
2014, [6]	pfDC	MHA	G-6/15
2015, [6]	pfAC	MHA	G-6/15
2016, [6]	pfDC	MHA	GM-6/15
2021, [6]	pfDC	MHA	G-6/15, IEEE-24/41

Source: Authors, (2022).

Table 2: Active power loss represented in the EC.

Year, Ref.	PF Model	Algorithm	PES Tested
2003, [6]	pfDC	COA	G-6/15, IEEE-24/41 e SB-46/79
2005, [7]	pfDC	CHA	G-6/15 e SB-46/79
2006, [6]	pfAC	COA	HS-8/12
2008, [6]	pfDC	COA	G-6/15 e IEEE-24/41
2008, [6]	pfDC	COA	G-6/15, IEEE-24/41 e SB-46/79
2008, [6]	pfDC	MHA	SB-46/79
2011, [6]	pfAC	CHA	IEEE-9/9
2012, [8]	pfAC	COA	G-6/15 e NEI 12/21
2013, [6]	pfAC linearized	COA	G-6/15 e IEEE-118/177
2016, [6]	pfDC	COA	G-6/15, IEEE118/177 e SS-425/628
2018, [9]	pfDC	CHA	G-6/15, IEEE-24/41 e SB-46/79
2019, [10]	pfDC	COA	G-6/15
2020, [11]	pfDC	MHA	G-6/15 e SB-46/79
2022, [12]	pfDC	MHA	G-6/15, IEEE-24/41 e SB-46/79

Source: Authors, (2022).

Table 3: Active power loss represented in the OF and EC.

Year, Ref.	PF Model	Algorithm	PES Tested
2017, [13]	pfDC	COA	SB-46/79

Source: Authors, (2022).

I.7 SOLUTION ALGORITHMS

The STNEPp consists of a mixed-integer nonlinear programming (MINLP) problem that requires non-convex mathematical models with non-deterministic polynomial time (NP-hard) to be solved [14]. These particularities illustrate the difficulties in designing algorithms that are robust, efficient, and fast to solve STNEPp problems, especially large systems.

The COA explore the entire search space, in general, find the global optimal solution for small to medium-sized power system with little computational effort. However, for real or large systems, they consume large computational effort and present a convergence problem [15]. For this reason, they in several situations, become inadequate [16].

The CHA does not explore the entire search space (space of candidate solutions), and use simplified procedures for exploring the search space (diversification and intensification). Therefore, they rarely find the global optimal solution for real or large systems [17], [18].

The MHA are inspired by natural processes and use a diversification procedure, where the entire search space is explored, and another intensification procedure, where only a specific part of the search space is explored, much more elaborate than the procedures used in CHA, to avoid premature convergence and escape from suboptimal solutions. According to [19] and [20], MHA, in the vast majority of cases, find the global optimal solution to complex problems with acceptable computational effort.

In view of the good trade-off between the quality of the proposed solution and the computational effort, MHA have been widely used to solve STNEP [21] and STNEPp problems, as shown in the researches indicated in the tables.

Some MHA are inspired by the nature and, as an example, can be cited those based on swarm intelligence, which implement the collectivity of groups formed by agents of nature such as birds, fireflies, bats, and others.

The Bat Algorithm (BA) [22] was inspired by the echolocation phenomenon that bats use during flight, and uses a pulse emission frequency tuning technique to balance diversification (general search in space) and intensification (local search in space). However, it sometimes fails to escape from a point of local optimum, causing it to converge to a suboptimal solution [23]. To improve the performance of the original BA, several works have been proposed, as shown in the papers by [24], [25], [26], [27], [28].

In [29] a CHA was employed to solve the STNEP problem, considering the standard BA to generate candidate solutions. The transmission network was represented by an pfCC. The algorithm proposed in [29] was tested on the G-6/15 and IEEE-24/41 systems.

I.8 PROPOSED ALGORITHM

To solve STNEPp problems, only article [30] applied the standard BA [22], as can be seen in the articles indicated in the tables. In this paper, the transmission network was represented by an pfCA and the proposed algorithm was tested on G-6/15 system. This scarcity shows that the application of BA-based MHA is open for discussion and research.

To fill this gap, this paper presents an algorithm, called the BATp optimizer, derived from the standard BA, where the search intensification mechanism has been changed aiming at improving the convergence rate and making it difficult to stagnate at a suboptimal solution. The proposed operator acts on the elements of the vector representing the position of the bat that is closest to the prey.

In the BATp optimizer, the STNEPp problem is represented by a MINLP problem, with the transmission network represented by an fpCC and the power losses included in the equality constraints.

The BATp optimizer is composed of a module that generates candidate solutions and another that uses the local improvement procedures proposed by [31] to make solutions that present load shedding and those that present over costs competitive. These procedures have also been successfully used in [5], [32] in STNEP studies considering security constraints. The joint application of these two procedures is important, especially, when analyzing large meshed systems.

The performance evaluation of the BATp optimizer was done with the IEEE-24/41 and SB-46/79 test systems.

The remainder of this paper is organized as follows: In the second section, the main concepts of the original BAT algorithm are presented. The third section presents the mathematical model used in the representation of STNEPp. The fourth section presents the structure and operation of the BATp optimizer. The fifth section presents the case studies and analysis of the results performed with the three systems mentioned above. The sixth section presents the main conclusions. And finally, the last two sections present the main conclusions and the bibliographical references.

II. BAT ALGORITHM

This section presents the main characteristics of the original BA and the proposed variant for generating candidate solutions to the STNEPp problem.

II.1 ORIGINAL BAT ALGORITHM

According to [22], BA is inspired by the sophisticated echolocation ability that bats of the microchiroptera species use during flights to detect prey and avoid obstacles. Echolocation is based on the emission of ultrasonic waves and measurements of the times taken for these waves to return to their sources after being reflected from targets (prey or obstacles) [33].

In BA, each virtual bat (i) occupies a position (x_i) in the hunting environment, flies randomly with speed (v_i) and emits sound waves with frequency (f_i) and amplitude (A_i). The frequency is related to the emitted wavelength. At each iteration of the algorithm, each virtual bat flies in the direction of the bat that is closest to the prey, i.e., it flies in the direction of the current leader bat (x_g). The Figure 1 illustrates a flock of Nm virtual bats positioned at various locations in a hunting environment of dimension (D), emitting sound waves to identify prey.

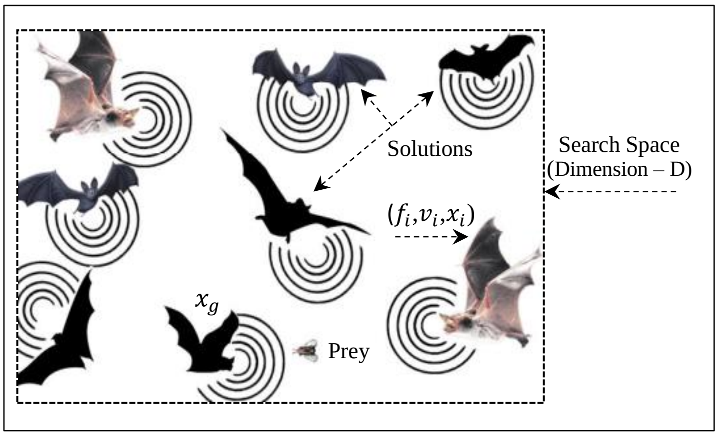

Figure 1: Flock of Bats in search of prey.
Source: Authors, (2022).

The BA, besides updating the positions of the bats (x_i), it controls the local and global searches, as in the other swarm intelligence algorithms. The control is done, respectively, by varying the amplitude and the rate of pulse emission (r_i).

In the context of the STNEPp problem, the hunting environment represents the search space where the candidate solutions are; the dimension of the hunting environment represents the number of candidate branches; a flock of virtual bats represents the population; the number of bats in the flock represents the number of candidate solutions; a bat occupying a position represents a candidate solution, encoded as a vector; the quality of a bat represents its distance from the prey; the bat located near the prey represents a local optimal solution; and the bat located at the same position as the prey represents the global optimal solution.

To diversify the search in the dimension hunting environment, the BA updates the position, velocity, and frequency of each virtual bat i using equations (1) to (3), where: $\beta \in [0,1]$ is a vector of random numbers drawn from a uniform distribution; f_{min} and f_{max} are the minimum and maximum frequency bounds of the sound wave emitted by each virtual bat, respectively [22].

$$f_i = f_{min} + (f_{max} - f_{min}).\beta \quad (1)$$

$$v_i^{t+1} = v_i^t + \left(x_i^t - x_g^t\right).f_i \quad (2)$$

$$x_i^{t+1} = x_i^t + v_i^{t+1} \quad (3)$$

To intensify the search, the BA moves each virtual bat i in the direction occupied by the leader bat (x_g) in the hunting environment, using equation (4), where $\bar{A}^t$ is the average loudness of all virtual bats and $\mathcal{E} \in [-1,1]$ is a vector of random numbers drawn from a uniform distribution.

$$x_{new}^{t+1} = x_g^t + \mathcal{E}\bar{A}^t \quad (4)$$

When one of the virtual bats i identifies a prey, depending on its distance to the prey, it increases its pulse emission rate (r_i) and decreases its amplitude (A_i). The amplitude (loudness) and the pulse emission rate of each virtual bat i are calculated, respectively, by the functions (5) and (6), where α and γ are constants.

$$A_i^{t+1} = \alpha A_i^t, \quad 0 < \alpha < 1 \quad (5)$$

$$r_i^{t+1} = r_i^0[1 - exp(-\gamma t)], \quad \gamma > 0 \quad (6)$$

These update functions indicate that when virtual bat i (candidate solution i in STNEPp) approaches a prey, i.e., when the objective of the problem (minimization of investment cost in STNEPp) is achieved, after a few iterations (t→∞), the amplitude of the pulse emitted by virtual bat i tends to zero ($A_i^t \rightarrow 0$) and the pulse emission rate tends to its initial value r_i^o, i.e., ($r_i^t \rightarrow r_i^o \in [0,1]$).

II.2 PSEUDOCODE OF THE ORIGINAL BA

The Algorithm 1 shows the pseudocode of the original BA [22]. The iterative cycle of the algorithm simulates the temporal evolution of the flock of bats. Before entering the iterative cycle (lines 5 to 21) the initial conditions of the algorithm are established.

Typical values suggested by [22] are: $f_{min} = 0$, $f_{min} = 2$, α=0.97, γ =0.10, $A_i^0 = 1, r_i^0 = 1$ (line 1). The size of the flock of bat (Nm) and the maximum number of iterations (Nit) are also defined depending on the problem type.

Next (row 2) the first bat population ($X_{i,dim}^0$) is generated randomly (7), using random numbers ($\xi_{i,dim} \in [0,1]$) drawn from a uniform distribution. The dim parameter depends on the number of variables in the problem. Lb and Ub are lower and upper bounds of the initial positions (x_i^0).

$$X_{i,dim}^0 = Lb + \xi_{i,dim}.(Ub - Lb) \quad (7)$$

Then (row 3) the quality (fitness) of all initial bats (x_i^0) are evaluated according to the objective function of the optimization problem ($f(x_i^0)$) to enable their classification and the identification of the first leader bat (x_g^0) of the flock (row 4).

Next, the algorithm enters the iterative cycle (lines 5 to 21) that simulates the flights of the virtual bats, updating their current positions in the hunting environment to reach prey. The new positions (x_i^{t+1}) that the bats will occupy in the hunting environment are determined as a function of their current velocities (v_i^{t+1}), which are defined from their distances relative to the leader bat ($x_i^t - x_g^t$) and the frequencies of the emitted pulses (f_i) (lines 7 to 9).

Once the new bat positions are determined, the bats perform a local search around the position occupied by the current leader bat (x_g^t) to get closer to the prey (lines 10 and 12). This search is done by applying the random operator $\mathcal{E} \in [-1,1]$on the average amplitude of the pulses emitted by all bats ($\bar{A}^t$) (line 11).

Confirmation of the approach is done through an acceptance test (lines 14 to 18) that depends on the sound amplitudes (A_i) and performance evaluations between the bat positioned as a function of velocity (x_i^{t+1}) and the one positioned as a function of pulse rate ($\hat{x}_i^{t+1}$). If the test is true, the bats occupy positions close to the leader bat and, consequently, occupy positions closer to the prey (line 15).

Algoritmo 1: Bat Algorithm (BA)	
1:	Initialize constants: Nit, Nm, f_{min}, f_{max}, α, γ, A_i^0, r_i^0
2:	Initialize Bat flocks: x_i e v_i, $(i = 1,2, \ldots, \mathrm{Nm})$
3:	Evaluates the quality of each bat in the flock: $f(x_i^0)$ {objective function}
4:	Identify the first bat leader of the flock: x_g^0
5:	**while** *stop condition* **do** {maximum number of iterations – Nit }
6:	**for** i=1 **to** N **do**
7:	$f_i = f_{min} + (f_{max} - f_{min}).\beta,\ \beta \in [0,1]$
8:	$v_i^{t+1} = v_i^t + \left(x_i^t - x_g^t\right).f_i$
9:	$x_i^{t+1} = x_i^t + v_i^{t+1}$
10:	**if** $\xi_1 < r_i,\ \xi_1 \in [0,1]$ **then** {perform local search}
11:	$\hat{x}_i^{t+1} = x_g^t + \mathcal{E}\bar{A}^t,\ \mathcal{E} \in [-1,1]$
12:	**end if**
13:	Performs perturbation in one dimension of x_{new}^{t+1}
14:	**if** $\xi_2 < A_i$ or $f(\hat{x}_i^{t+1}) \leq f(x_i^{t+1})$, $\xi_2 \in [0,1]$ **then** {update position: x_i^{t+1}}
15:	$x_i^{t+1} = \hat{x}_i^{t+1}$
16:	$A_i^{t+1} = \alpha A_i^t$ {increase pulse amplitude}
17:	$r_i^{t+1} = r_i^0[1 - \exp(-\gamma t)]$ {decrease the pulse emission rate}
18:	**end if**
19:	Identifies the current global leading bat: x_g^{t+1}
20:	**end for**
21:	**end while**
22:	Displays best bat (x_g^*) {global leader bat}

The pulse amplitudes (A_i^{t+1}) are increased and the pulse emission rates (r_i^{t+1}) are decreased (lines 16 and 17), respectively.

At this point in the algorithm, the positions of all virtual bats in the flock have been updated, and it is therefore necessary to identify the current leader bat (x_g^{t+1}) of the flock (line 19).

Then the iterative cycle continues until the set stopping criterion (line 5), i.e., the maximum number of iterations, is reached (line 20). Finally, the leading bat of the whole flock is presented.

II.3 MODIFIED BAT ALGORITHM

The BA is a technique capable of finding good results in a reasonable convergence time. However, it can converge prematurely [34], i.e., it converges to a local optimal solution instead of to the global optimal solution. Premature convergence occurs due to the decrease in search diversification in the solution space [35], which leads the algorithm to a stagnant state.

To reduce the problems that can be caused by premature convergence, this paper proposes to add a search intensification operator ($int(.)$), after line (20). This operator acts on the current position of the current leader bat (x_g^{t+1}), positioning the leader bat (x'_g) at a new position. The proposed operator $int(x_g^{t+1})$ randomly changes several elements (Ne) of the vector (x_g^t), according to the rule in equation (8).

$$x'_g = int(x_{g,Ne}^{t+1}) = \begin{cases} x_g^{t+1} - 1 \; se \; \xi > 0.5 \\ x_g^{t+1} + 1 \; se \; \xi < 0.5 \end{cases} \tag{8}$$

III. MATHEMATICAL MODEL OF STNEPp

This section presents the mathematical MINLP model used in BATp to represent the STNEPp problem, without deterministic security constraint (reliability criterion N-0), with the transmission network represented by an pfCC and active power losses included in the constraints.

III.1 CALCULATION OF LOSSES IN CIRCUITS

The calculation of the active power loss (p_{ij}) in each branch ij of the network is done as a function of the angular aperture of the terminal bar voltages (θ_{ij}) and their conductance (g_{ij}), as shown in the approximate nonlinear expression (9) [36], where (r_{ij}) is the resistance and (x_{ij}) is the reactance of branch ij.

$$p_{ij} \approx \; g_{ij}\theta_{ij}^2, \; g_{ij} = r_{ij}/(r_{ij}^2 + x_{ij}^2) \tag{9}$$

III.2 MODELING THE OPTIMIZATION PROBLEM

In the mathematical model of STNEPp, the active losses in the circuits are treated as virtual loads and equally distributed among the respective terminal bars. With the losses added to the terminal bars of the configuration, new values of angles, power flows in the circuits and generated power at the reference bar are obtained. In the model it was considered that the reference bus supplies the system losses, that is, it balances the active power of the current configuration.

Therefore, to consider the effect of active circuit losses, in the mathematical model of the STNEPp problem, a term was added in the equality constraint of the model presented in [37]. With this adjustment, the modified model takes the form presented in (10) to (16), where neither the circuits added to the existing transmission network nor the angles of the bars are initially known.

$$Min \; v = \sum_{(ij)\in\Omega_C} c_{ij}n_{ij} + \alpha \sum_{i\in\mathcal{B}} cc_i \tag{10}$$

Subject to:

$$g_i - \sum_{j\in\Omega_i} f_{ij} + cc_i = d_i + (\sum_{j\in\Omega_i} p_{ij})/2 \,, \forall i \in \Omega_B \tag{11}$$

$$f_{ij} = \gamma_{ij}(n_{ij}^0 + n_{ij}).\theta_{ij} \,, \forall ij \in \Omega_L \tag{12}$$

$$|f_{ij} + p_{ij}/2| \le (n_{ij}^0 + n_{ij})\bar{f}_{ij} \,, \forall ij \in \Omega_L \tag{13}$$

$$0 \le g_i \le \bar{g}_i \,, \forall i \in \Omega_B \tag{14}$$

$$0 \le cc_i \le d_i \,, \forall i \in \Omega_B \tag{15}$$

$$0 \le n_{ij} \le \bar{n}_{ij}, \; n_{ij} \in \mathbb{Z} \,, \forall ij \in \Omega_L \tag{16}$$

Where: Ω_C – set of all candidate circuits; $\mathcal{B}$ - set of all load shedding bars; Ω_i – set of circuits connected to bus i; Ω_B – set of all buses (existing and candidate); Ω_L – set of all circuits (existing and candidate); v – total cost of each candidate solution; c_{ij} – cost of circuits added to branch ij; n_{ij} – number of circuits added on branch ij; α – penalty factor ($/MW); cc_i- active load shedding at bus i; g_i – generation of bus i; d_i – active load of bus i; f_{ij} – active power flow on branch ij; p_{ij} – active power loss on circuit ij; γ_{ij} – susceptance of circuit ij; n_{ij}^0 – number of existing circuits on branch ij; n_{ij} – number of circuits added on branch ij; θ_{ij} – opening of the angles of the voltages of buses i and j; $\bar{f}_{ij}$ – maximum active power flow that can circulate in circuit ij; $\bar{g}_i$ – maximum generation that can be produced in bus i; $\bar{n}_{ij}$ – maximum number of circuits that can be added in branch ij.

Equation (10) represents the objective function of the problem that minimizes the total cost of circuits (lines and transformers) added to the existing transmission network, with the total cost of load shedding the solutions that have circuit loading limit violations. The second term is intended to enable solving problem (10) to (16) by the modified BA module of the BATp optimizer.

The constraint (11) models the active power balance (Kirchhoff's 1st law) of each bus. Constraint (12) models the active power flow through each branch, considering the active power loss. The channelization constraint (13) sets the limit on the active power flow that can flow through each branch.

Channeling constraints (14) to (16) set the limits on generation and load shedding at each bus and the number of new circuits that can be added to each branch.

The set of circuits for each feasible candidate solution is defined by a specific module of the BATp optimizer responsible for formulating candidate solutions. If the generated candidate solution is infeasible, i.e., has load shedding, another module of the optimizer acts to make it economically competitive

IV. STRUCTURE OF BATp OPTIMIZER

This section presents the proposed algorithm, called the BATp optimizer, for solving the STNEPp problem, whose structure and operation is similar to that used in [5].

IV.1 BATp ALGORITHM FLOWCHART

The BATp proposed to solve the STNEPp problem uses the structure composed of the eight stages described in Figure 2.

In each iteration of the BATp, the solutions proposed by the modified BA go through the sieve of feasibility (stage 4) and competitiveness (stage 5) procedures.

- **STAGE 1**

In this stage, the data required by the BATp optimizer is defined, that is, the data that the original BA uses and the data of the system to be planned. The data for the BA are the same as presented above.

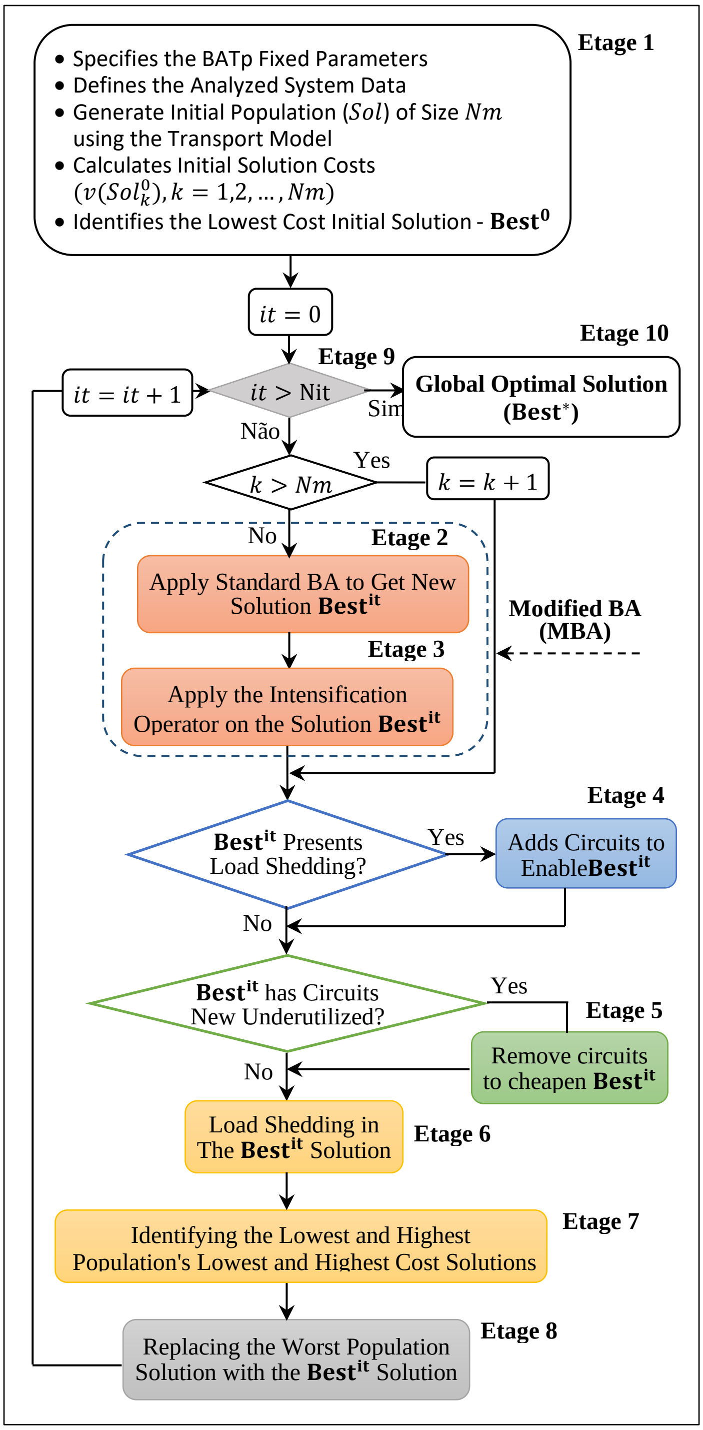

Figure 2: Simplified BATp optimizer flowchart.
Source: Authors, (2022).

The data related to the system are: existing transmission network topology; existing and future bar data (g_i, $\bar{g}_i$, d_i); existing and candidate circuit data (n_{ij}^0, n_{ij}, γ_{ij}, c_{ij}, $\bar{f}_{ij}$). The maximum number of circuits that can be added in each branch ($Ncir$) is also defined in this stage.

In this step, the first set of solutions to the problem is also defined, i.e., an initial population (Sol^0) composed of (Nm) bats (candidate solutions). Each candidate solution of the initial population ($Sol_k^0, k = 1,2, \dots, Nm$), has dimension equal to the number of branches (NR) of the analyzed system and each element of the vector corresponds to a candidate branch to add one or more circuits (n_{ij}). The value of each element of Sol_k^0, can assume a value between zero and $Ncir$.

The Figure 3 shows an example of a solution Sol_k^0 of a hypothetical system consisting of eight branches ($NR = 8$) and that $Ncir = 4$. In this solution, branches 1-2, 1-4, 1-5, 2-3, 2-4 have one circuit, branch 3-5, 4-6 have two circuits, and branch 2-6 have four circuits.

Ramos	#1-2	#1-4	#1-5	#2-3	#2-4	#3-5	#6-4	#6-2
n_{ij}	1	1	1	1	1	2	2	4

Figure 3: Representation of a candidate solution.
Source: Authors, (2022).

In the specialized literature, there is no rule that defines what should be the number of individuals in the population (Nm) and the number of iteration (Nit). In BATp, these values are defined as a function of the number of branches (NR) of the transmission network analyzed, as shown in equations (17) and (18). Note that NR is equivalent to the size (D) of the bats' hunting environment.

$$Nm \geq \text{NR} \qquad (17)$$

$$Nit \geq 10 \cdot Nm \qquad (18)$$

The way of defining the components of the initial solutions affects the qualities of the candidate solutions of the initial population and the number of iterations required for convergence, since the characteristics of the initial solutions are transferred to the descendant solutions throughout the iterations of the algorithm [38].

Therefore, generating a good initial population and using an appropriate population size tends to improve the performance of the algorithm [39]. In general, if the initial population is generated randomly, the computational effort tends to be high [5].

In the original BA, the initial population (Sol^0) is generated randomly (7), i.e., it does not consider the topology of the existing transmission network, the data of bars (g_i, $\bar{g}_i$, d_i) and circuits ($n_{ij}^0, n_{ij}, \bar{f}_{ij}$). This way of generating the initial population can delay the achievement of the global optimal solution, especially if the system to be planned is large.

In BATp, the initial population (Sol^0) is composed of (Nm) candidate solutions ($\{Sol_1^0, \dots, Sol_k^0, \dots, Sol_{Nm}^0\}$) being generated according to the system topology and its bus and circuit data. It is obtained in two steps:

Step 1: Solve the transport model, represented by the integer linear programming (ILP) problem (19) to (23) [37], [40], using the *linprog* function of MatLab, to obtain the first solution (Sol_1^0) of the initial population.

$$Min\ v(Sol_1^0) = \textstyle\sum_{(i,j) \in \Omega_C} c_{ij} n_{ij} \qquad (19)$$

Subject to:

$$g_i - \textstyle\sum_{j \in \Omega_i} f_{ij} = d_i\ , \forall i\ \in \Omega_B \qquad (20)$$

$$\left| f_{ij} \right| \leq \left(n_{ij}^0 + n_{ij} \right) \bar{f}_{ij}\ , \forall ij \in \Omega_L \qquad (21)$$

$$0 \leq g_i \leq \bar{g}_i\ , \forall i\ \in \Omega_B \qquad (22)$$

$$0 \leq n_{ij} \leq \bar{n}_{ij},\ n_{ij} \in \mathbb{Z}\ , \forall ij \in \Omega_L \qquad (23)$$

Step 2: Generate the other ($Nm - 1$) initial candidate solutions ($\{Sol_2^0, \dots, Sol_k^0, \dots, Sol_{Nm}^0\}$) by randomly changing the positions and circuit numbers of the branches of the solution Sol_1^0, until the population size (Nm) is reached.

This way of generation produces some infeasible solutions (solutions with load shedding), due to the simplified model (19) to (23), which considers only Kirchhoff's first law. However, these solutions are systematically eliminated over the iterations (step 4) of the BATp optimizer.

Once the parameters (n_{ij}) and (c_{ij}) of each solution (Sol_k^0) of the initial population are known, the costs $(v(Sol_k^0))$ are determined by summation $(\sum c_{ij}n_{ij})$ and the solution of lowest overall cost $(v(Best_k^0) = min\ (\sum c_{ij}n_{ij}))$ is identified.

In this step, the load shedding $cc(Sol_{inf}^0)$ of the infeasible solutions (Sol_{inf}^0), i.e., those with violations of the maximum circuit capacities, are also calculated. The values of the load shedding are obtained by solving the linear programming (LP) problem (24) to (29), using the *linprog* function of MatLab.

$$Min\ \ cc(sol_{inf}^0) = \sum_{i\in\mathcal{B}} cc_i \tag{24}$$

Subject to:

$$g_i - \sum_{j\in\Omega_i} f_{ij} + cc_i = d_i\ , \forall i\ \in \Omega_B \tag{25}$$

$$f_{ij} = \gamma_{ij}(n_{ij}^0 + n_{ij})(\theta_i - \theta_j) = 0\ , \forall ij \in \Omega_L \tag{26}$$

$$|f_{ij}| \le (n_{ij}^0 + n_{ij})\bar{f}_{ij}\ , \forall ij \in \Omega_L \tag{27}$$

$$0 \le g_i \le \bar{g}_i\ , \forall i\ \in \Omega_B \tag{28}$$

$$0 \le r_i \le d_i\ , \forall i\ \in \Omega_B \tag{29}$$

➢ STAGE 2

After the completion of step 1, BATp effectively sets out to search for the local optimal solutions $(Best^{it})$ of each iteration $(it = 1,2,\dots,Nit)$ and the global optimal solution $(Best^*)$. To this end, it performs, at each iteration, the sequence of calculations and tests described in equations (30) to (44), which perform the steps of the modified BA (MBA). The round operator "*round*" and the absolute value operator "*abs*" were used because the number of circuits that must be added in each branch of the transmission network must always be integer and positive.

$$f_k^{it} = f_{min} + (f_{max} - f_{min}).\beta,\ \beta \in [0,1] \tag{30}$$

$$v_k^{it+1} = v_k^{it} + abs((sol_k^{it} - Best^{it})).f_k^{it} \tag{31}$$

$$sol_k^{t+1} = sol_k^t + round(v_k^{t+1}) \tag{32}$$

$$if\ \xi_1 < r_k,\ \ \xi_1 \in [0,1] \tag{33}$$

$$\widehat{sol}_k^{it+1} = Best^{it} + \mathcal{E}\bar{A}^{it}, \mathcal{E} \in [-1,1] \tag{34}$$

$$end\ if \tag{35}$$

$$if\ \xi_2 < A_k^{it}\ or\ f(\widehat{sol}_k^{it+1}) \le f(sol_k^{it+1}), \xi_2 \in [0,1] \tag{36}$$

$$sol_i^{t+1} = \widehat{sol}_i^{t+1} \tag{37}$$

$$A_k^{it+1} = \alpha A_k^{it} \tag{38}$$

$$r_k^{it+1} = r_k^0[1 - \exp(-\gamma t)] \tag{39}$$

$$end\ if \tag{40}$$

$$if\ f(\widehat{sol}_k^{it+1}) \le f(Best^{it}) \tag{41}$$

$$Best^{it} = \widehat{sol}_k^{it+1} \tag{42}$$

$$f(Best^{it}) = f(\widehat{sol}_k^{it+1}) \tag{43}$$

$$end\ if \tag{44}$$

➢ STAGE 3

This stage has the purpose of applying a local search intensification operator $(int(.))$ on the current global optimal solution $(Best^{it})$, obtained in step 2, to obtain a new solution $Best_{new}^{it}$ that subsequently passes the sieves of the infeasibility (stage 5) and competitiveness (stage 6) improvement procedures.

The operator $int(.)$ changes the number of circuits of (Ne) branches of the solution $Best^{it}$ current by increasing or decreasing, by one unit, the number of circuits of the randomly selected branches (45). Where ξ_3 is an integer random number between $[1, NR]$ and ξ_4 is a random number between [0,1].

$$Best_{new}^{it}(\xi_3) = \begin{cases} int(\xi_3) = Best^{it}(\xi_3) - 1\ se\ \xi_4 > 0.5 \\ int(\xi_3) = Best^{it}(\xi_3) + 1\ se\ \xi_4 < 0.5 \end{cases} \tag{45}$$

The parameter (Ne) is defined as a function of the size of the analyzed system, that is, it is defined as a function of the number of branches (NR) and the number of bars (NB), through equation (46). The floor function rounds the result of the division (NR/NB) towards negative infinity, and the ceil function rounds it towards positive infinity.

$$Ne = \begin{cases} ceil(\mathrm{NR/NB}) & se\ \ NR/NB \ge 2{,}5 \\ floor(2NR/NB + 1) & caso\ contrário \end{cases} \tag{46}$$

➢ STAGE 4

This stage is intended to make the current $Best_{new}^{it}$ solution, modified in step 3, viable, in case it exhibits load shedding, to compete with the other solutions in the current population. The elimination of load shedding is done by adding in $Best_{new}^{it}$ a set of new circuits $\{n_{ij}^{VGS}\}$, which are obtained based on the sensitivity index (IS_{ij}) (47) that was used in the Villasana-Garver-Salon (VGS) constructive heuristic algorithm (CHA) [41], [42].

$$IS_{ij} = max\left\{n_{ij}^{vgs}\overline{f}_{ij}\right\}, n_{ij}^{VGS} \ne 0 \tag{47}$$

The solution resulting from joining the solution $Best_{new}^{it}$ with the set of circuits $\{n_{ij}^{VGS}\}$, called the solution $Best_{VGS}^{it}$, is submitted to the feasibility procedure, performed in stage 5, and the competitiveness procedure, performed in stage 6.

Obtaining the circuit set $\{n_{ij}^{VGS}\}$ is done by solving the LP problem (48) to (54), during the execution of the CHA steps of VGS [43].

$$Min\ \ v(n_{ij}^{VGS}) = \sum_{(i,j)\in\Omega_C} c_{ij}n_{ij}^{VGS} \tag{48}$$

Subject to:

$$g_i - \sum_{j\in\Omega_i} f_{ij}^{Best} - \sum_{j\in\Omega_i} f_{ij}^{VGS} = d_i\ , \forall i\ \in \Omega_B \tag{49}$$

$$f_{ij}^{Best} = \gamma_{ij}n_{ij}^{Best}(\theta_i - \theta_j)\ , \forall ij \in \Omega_C \tag{50}$$

$$|f_{ij}^{Best}| \le n_{ij}^{Best}\bar{f}_{ij}\ , \forall ij \in \Omega_C \tag{51}$$

$$|f_{ij}^{VGS}| \le n_{ij}^{VGS}\bar{f}_{ij}\ , \forall ij \in \Omega_C \tag{52}$$

$$0 \le g_i \le \bar{g}_i\ , \forall i\ \in \Omega_B \tag{53}$$

$$0 \le n_{ij}^{VGS} \le \bar{n}_{ij}\ , \forall ij \in \Omega_C \tag{54}$$

The execution of the CHA steps ends when the solution coming from solving the results in $\{n_{ij}^{VGS} = 0\}$ and $v(n_{ij}^{VGS}) = 0$, which means that it is no longer necessary to add circuits to eliminate load shedding. That is, the system operates properly without overloads, with the circuits from the solution $Best_{new}^{it}$ and the $\{n_{ij}^{VGS}\}$ circuits from solving LP.

In this LP problem, the power flows in the branches are separated as follows: f_{ij}^{Best} – flow in the branch ij of the solution $Best_{new}^{it}$ current and f_{ij}^{VGS} – flow in the added circuit in branch ij during the execution of the CHA; n_{ij}^{Best} – number of circuits existing in branch ij of the solution $Best_{new}^{it}$ current; n_{ij}^{VGS} – number of circuits added in branch ij during the iterative process of the CHA; Ω_C – set of all candidate circuits.

➢ STAGE 5

In stage 4, some circuits added to the current solution $Best_{VGS}^{it}$ by the approximate CHA model may be unnecessary and should be removed to make this solution competitive, in terms of investment cost. Thus, this stage is intended to eliminate the redundant circuits present in the current solution $Best_{VGS}^{it}$.

Elimination of redundant circuits is done as follows: first, all the circuits in the current solution $Best_{VGS}^{it}$ are placed in descending order of investment cost, and then each circuit is removed. If the removal of the circuits from the current solution $Best_{VGS}^{it}$ does not cause load shedding, it means that it is unnecessary being eliminated from the solution. Thus, only those circuits that if removed do not cause load shedding will be part of the current solution $Best_{VGS}^{it}$.

➢ STAGE 6

In this step, the cost of the current solution $Best_{VGS}^{it}$ ($v(Best_{VGS}^{it})$) and the load shedding ($c(Best_{VGS}^{it})$) are obtained if the current solution $Best_{VGS}^{it}$ has overloads. The investment cost is obtained by the product ($\sum c_{ij} n_{ij}^{VGS}$), given that the number of circuits added (n_{ij}^{VGS}) and their individual costs (c_{ij}) are known.

The amount of load shedding is obtained by the MatLab function *linprog*, which solves a LP problem similar to problem (24) to (29). The load shedding ($c(Best_{VGS}^{it})$) is used in the test for including the solution $Best_{VGS}^{it}$ in the current population, performed in stage 8, to replace the most expensive solution in the population.

➢ STAGE 7

This step aims to identify, among the solutions of the current population ($\{Sol_1^{it}, \dots, Sol_k^{it}, \dots, Sol_{Nm}^{it}\}$), the least cost ($v(Sol_{min}^{it})$) and highest cost ($v(Sol_{max}^{it})$) solutions, and the highest load shedding ($c(Sol_{max}^{it})$). These vectors are used in stage 8.

➢ STAGE 8

This step is intended to verify whether the current solution $Best_{VGS}^{it}$ can enter the current population in replacement of the one with the worst quality in terms of cost and load shedding.

Two conditions are imposed for the current solution $Best_{VGS}^{it}$ to be accepted into the current population: i) the current solution $Best_{VGS}^{it}$ must differ from all other solutions, i.e., it must present a circuit configuration that does not exist in the current population; ii) the current solution $Best_{VGS}^{it}$ must have a lower cost (if it is feasible) or lower load shedding (if it is infeasible) than all other solutions in the current population. Three situations are tested in the BATp optimizer:

1) the current solution $Best_{VGS}^{it}$ has load shedding ($c(Best_{VGS}^{it}) \neq 0$) and there is one or more solutions in the current population with load shedding, then $Best_{VGS}^{it}$ replaces the solution with the largest load shedding ($c(Sol_{max}^{it})$);
2) the solution $Best_{VGS}^{it}$has no load shedding ($c(Best_{VGS}^{it}) \neq 0$) and there is one or more solutions in the current population with load shedding, then $Best_{VGS}^{it}$ replaces the solution with the highest load shedding ($cc(Sol_{max}^{it})$);
3) the solution $Best_{VGS}^{it}$ has no load shedding ($c(Best_{VGS}^{it}) \neq 0$) and there are no solutions in the current population with load shedding, so $Best_{VGS}^{it}$ replaces the solution in the current population with the highest cost ($v(Sol_{max}^{it})$).

➢ STAGE 9

In this stage, the BATp optimizer checks whether the stopping criterion is met, i.e., if the current number of iterations (it) is greater than the specified maximum value (Nit). If it is greater, then the iterative process is terminated and stage 10 is executed. Otherwise, the algorithm increments the iteration counter and returns to stage 2.

➢ STAGE 10

In this step, the BATp optimizer presents the global optimal solution ($Best^*$) found in the iteration (Nit), in terms of investment cost and number of circuits added in each branch of the base transmission network.

V. CASE STUDIES AND ANALYSIS OF RESULTS

This section presents the results obtained with the BATp optimizer on three systems well known i\n the specialized literature: IEEE-24/41 and SB-46/79. The mathematical model of the BATp optimizer was implemented in MatLab R2008a language and the simulations were performed on a computer with Intel® Core™ i5 processor, 2.40 GHz CPU, 8 GB RAM. Some routines used in [5] were adapted to the computational model of the BATp optimizer. The (17) and (18) rules were used to define the number of simulations (Nm) and the number of iterations (Nit).

V.1. IEEE TEST SYSTEM (IEEE-24/41)

This test system was proposed by [44] to perform reliability analysis that, after modifications in generation and load data, was also used for STNEP studies [5], [45], [46], [9], [12], among others. Because it is known by the international community, it is a good option for testing new optimization techniques.

The Figure 4 shows the topology of this test system indicating the 34 existing circuits (solid lines), the 7 new candidate circuits (#1-8, #2-8, #6-7, #13-14, #14-23, #16-23, #19-23 in dotted lines) and the 17 load buses and 10 generation buses. The total load and generation of this system is 8.5550 MW, the number of buses is $NB = 24$, the number of candidate branches is $NR = 41$ and ($NR/NB = 1.708$). There are no isolated buses in this system. All the electrical data and costs of this system are given in [47], [48].

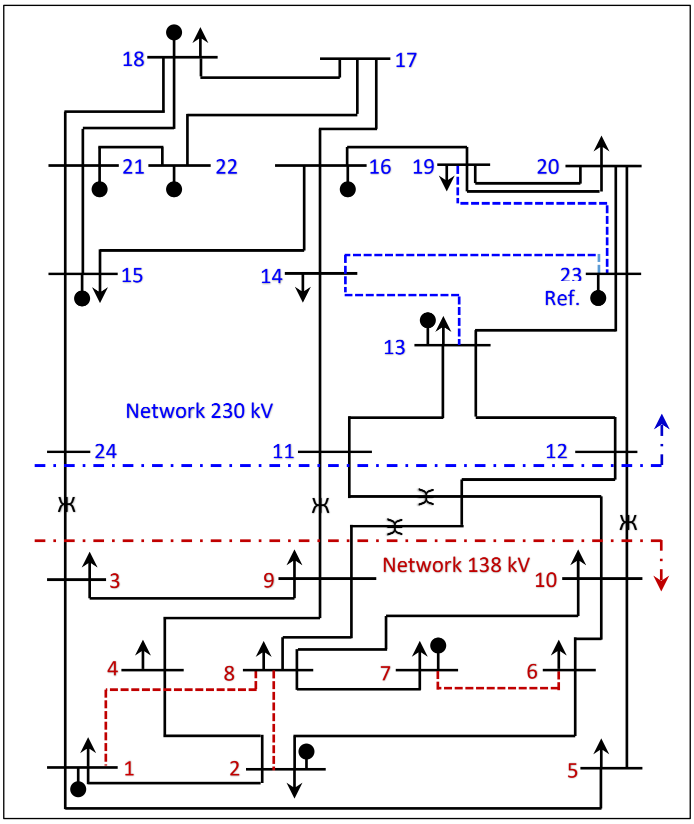

Figure 4: IEEE-24/41 test system topology.
Source: Authors, (2022).

With this test system, two cases were simulated, where one allows generation redispatch and the other does not allow redispatch. The bus #3 was used to close the power balance.

The maximum number of circuit additions per branch allowed was three ($Ncir = 3$). With this assumption, the total number of circuits that can be added in the system branches is 3x41=123.

The number of possible combinations of additions is on the order of 441 ≈ $4.84\text{x}10^{24}$.

In the simulations for the two cases, the following data were used in the BATp: $Ne = round(2\text{x}24/41)$=3, $Nm > NR$ = 50 and Nit =10. Nm = 500.

V.1.1 Lossless Optimal Solutions

According to [5], [12], [49] and several other authors, the optimal solution for this system, without considering the effect of active power losses but allowing generation redispatch (G0 generation scenario in [47], is composed of five circuits connected in four branches (#6-10=1, #7-8=2, #10-12=1, #14-16=1) and costs US$ 152 million.

Without considering losses, and not allowing generation redispatch (generation scenario G1 [47]), according to [50], [51] and other authors, the optimal solution is composed of fifteen circuits connected on nine branches (#1-5=1, #3-24=1, #6-10=1, #7-8=2, #14-16=1, #15-24=1, #16-17=2, #16-19=1, #17-18=2) and costs US$ 390 million. The BATp optimizer, with r_{ij}= 0, has also found this solution.

V.1.2 Case With Generation Redispatch (WR)

The characteristics of the optimal solution obtained by the BATp optimizer, with less than 50 iterations (Figure 5), are as follows:

- Cost and number of circuits (#i-j) of the optimal solution: US$ 182 million and #6-10=1, #7-8=2, #10-12=1, #14-16=1, #20-23=1 (Figure 6);
- Loading levels on the reinforced branches (Figure 7): branch #6-10 (87.63% of its capacity), #7-8 (98.72%), #10-12 (78.56%), #14-16 (74.47%), #20-23 (73.39%);
- Active power losses in the reinforced branches (Figure 7): 48.86 MW (22.82% of system loss). In the system, the active power loss is 214.09 MW (2.50% of the load).

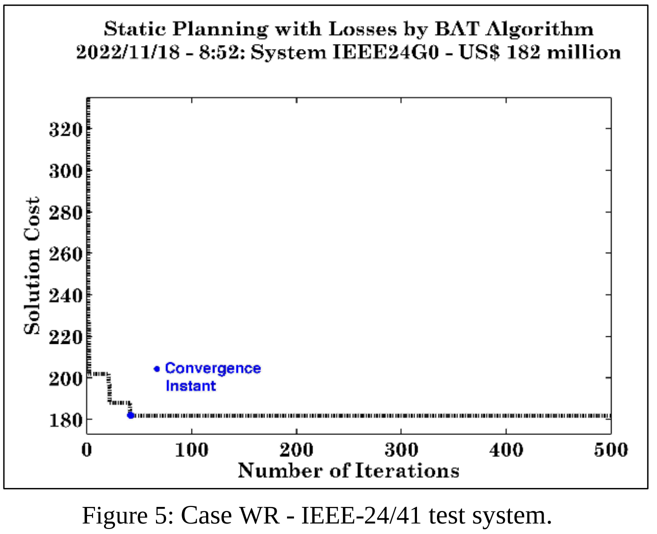

Figure 5: Case WR - IEEE-24/41 test system.
Cost convergence curve. Source: BATp optimizer, (2022).

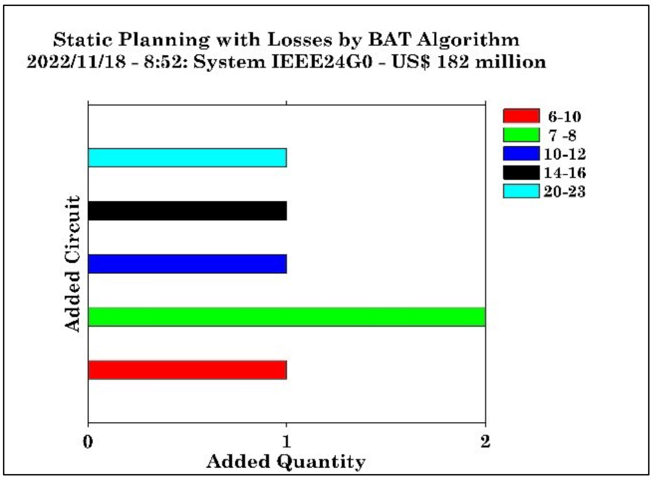

Figure 6: Case WR - IEEE-24/41 test system.
Planned circuits. Source: BATp optimizer, (2022).

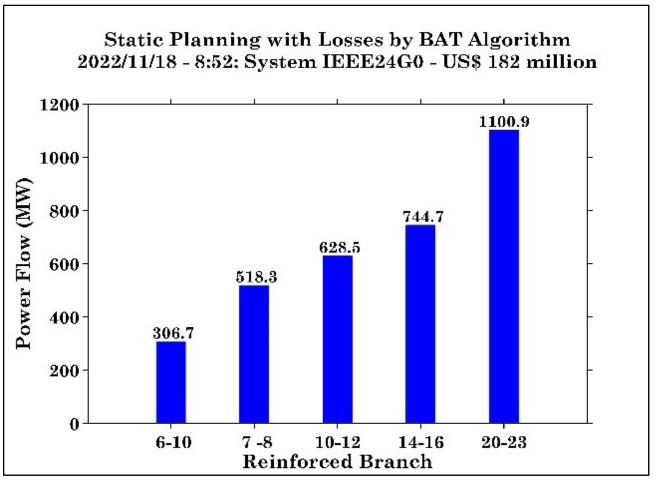

Figure 7: Case WR - IEEE-24/41 test system.
Flows in the branches. Source: BATp optimizer, (2022).

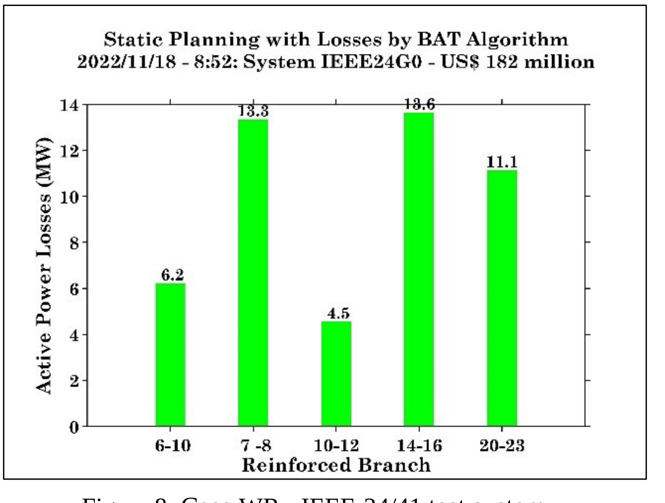

Figure 8: Case WR - IEEE-24/41 test system.
Losses in the branches. Source: BATp optimizer, (2022).

V.1.3 Case Without Generation Redispatch (WOR)

The characteristics of the optimal solution obtained by the BATp optimizer, with less than 100 iterations (Figure 9), are as follows:

- Cost and number of circuits on the branches of the optimal solution: US$ 370 million and #6-10=1, #7-8=2, #10-12=1, #14-16=1, #20-23=1 (Figure 10);

- Loading levels on the reinforced branches (Figure 11): #1-5 (77.13% of their capacity), #3-24 (77.34%), #6-10 (81.40%), #7-8 (98.72%), #14-16 (82.00%), #15-24 (62.75%), #16-17 (82.18%); #16-19 (59.28%), #17-18 (82.99 %);
- Active power losses in the reinforced branches (Figure 12): 87.79 MW (37.26% of system loss). In the system, the active power loss is 235, 60MW (2.76% of the load).

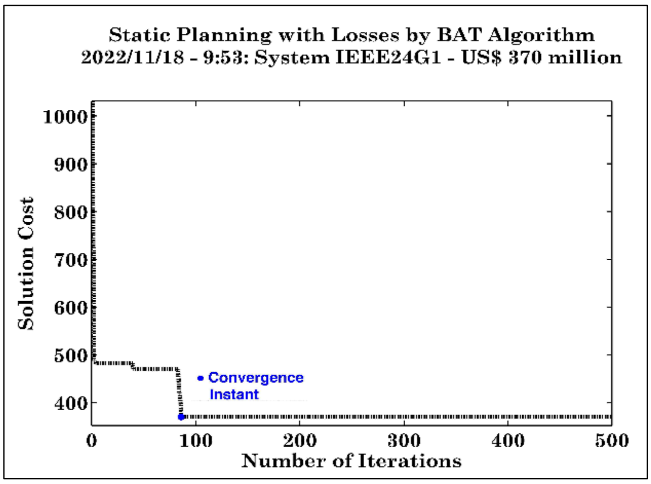

Figure 9: Case WOR - IEEE-24/41 test system.
Cost convergence curve. Source: BATp optimizer, (2022).

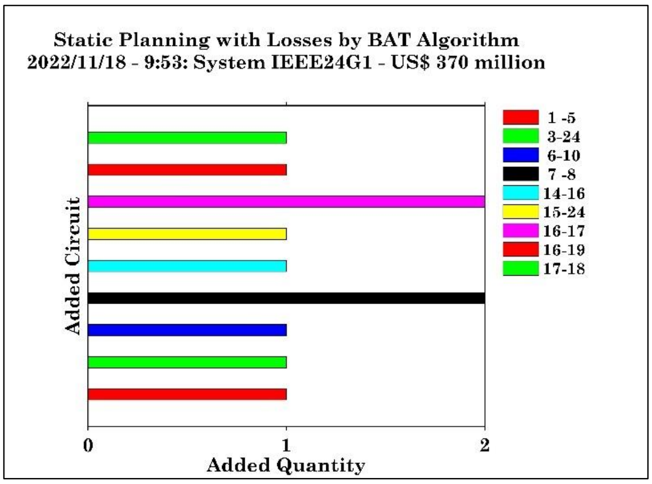

Figure 10: Case WOR - IEEE-24/41 test system.
Planned circuits. Source: BATp optimizer, (2022).

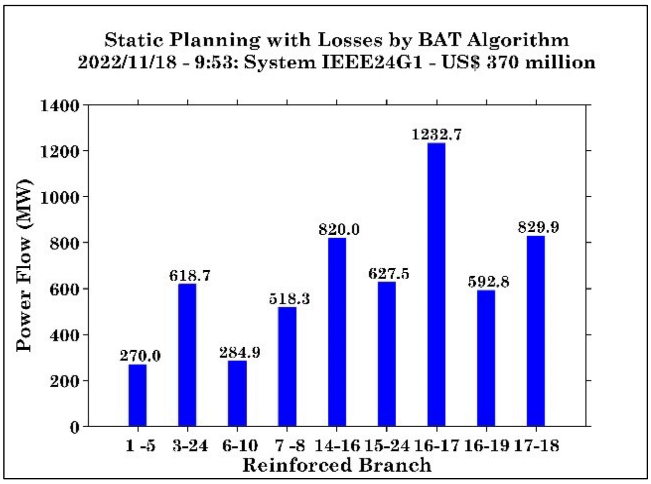

Figure 11: Case WOR - IEEE-24/41 test system.
Flows in the branches. Source: BATp optimizer, (2022).

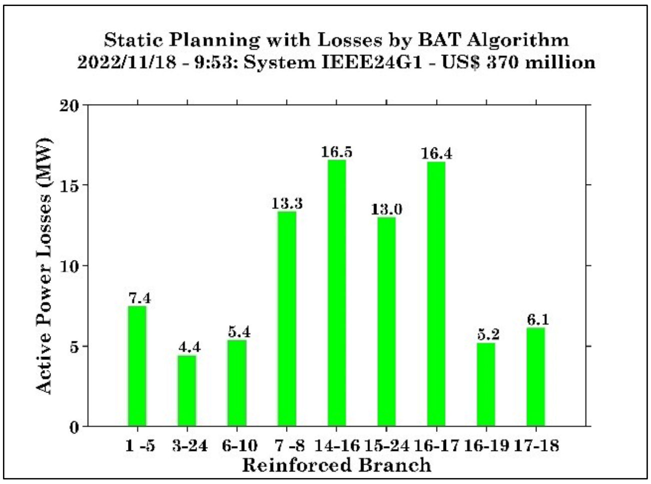

Figure 12: Case WOR - IEEE-24/41 test system.
Losses in the branches. Source: BATp optimizer, (2022).

V.1.4 Summary of Results

The Table 4 shows the summary of the results, illustrated in Figures 21 and 24, where lower amounts of circuits added on the network branches, lower investment cost (US$ million) and lower active power loss (MW) are observed when considering generation redispatch.

Table 4: IEEE-24/41 test system - Comparison of the cases.

Case	Number Circuits	Added Circuits	Cost	Loss
WR	6	#6-10=1, #7-8=2, #10-12=1, #14-16=1, #20-23=1	182 (49.19%)	49.37 (56.24%)
WOR	11	#1-5=1, #3-24=1, #6-10=1, #7-8=2, #14-16=1, #15-24=1, #16-17=2, #16-19=1, #17-18=1	370 (100%)	42.07 (100%)

Source: Authors, (2022).

V.1.5 Solutions Obtained by Other Authors

The Table 5 shows the solutions obtained by other authors, when considering active power losses and allowing generation redispatch (WR). In the articles, it is not explicit which power balance bus was used.

Table 5: IEEE-24/41 test system - Other authors' solutions.

Solution Costs (million) and Circuits	Author
US$ 182: #6-10=1, #7-8=2, #10-12=1, #14-16=1, #20-23=1	[12]
US$ 188: #6-10=1, #7-8=2, #10-12=1, #14-16=1, #16-17=1	[9]

Source: Authors, (2022).

V.2 SOUTH BRAZILIAN TEST SYSTEM (SB-46/79)

This system was first used in [52] to test an iterative method, and since then, it has been widely used to evaluate exact and approximate algorithms. This system, whose topology is shown in Figure 13, is widely used in several works about TNEP.

The total demand of this system is 6880 MW, it has 46 buses ($NB = 46$), 79 candidate branches ($NR = 79$), being 47 existing and 32 new. It has eleven isolated buses on the 230 kV and 500 kV networks (#3, #6, #10, #11, #15, #25, #28, #29, #30, #31, #41) and virtually the same NR/NB ratio = 1.717 as the IEEE-24/41 test system.

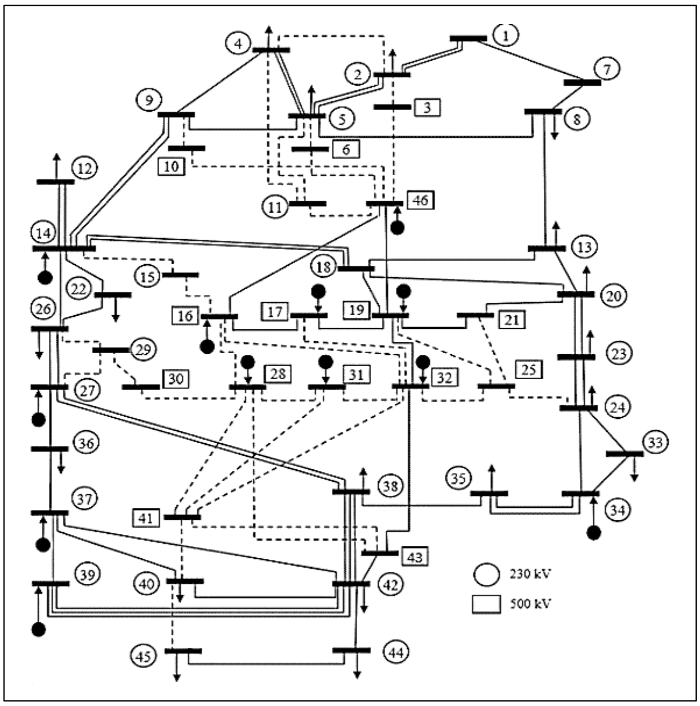

Figure 13: SB-46/79 test system topology.
Source: Authors, (2022) - Adapted from [40].

The bus and circuit data (electrical parameters and costs) are described in [40]. The resistor values for all circuits are 10% of the reactance values.

With this system, two cases were simulated, where one allows generation redispatch and the other does not allow redispatch. The bus #16 was used to close the power balance.

The maximum allowed number of circuit additions per branch is three ($Ncir$=3). With this assumption, the total number of circuits that can be added in the system branches is 3x79=237.

The number of possible combinations of additions is on the order of 479 ≈ 3.65x10^{47}, i.e., 1.18x10^{23} times larger than the possibilities of additions that can be made in the IEEE-24/41 test system, requiring BATp to run a larger number of simulations to reduce the risk of premature convergence to a suboptimal solution.

In the simulations for the two cases, the following data were used in BATp: $Ne = round(2x79/46)$, $Nm > NR$ = 80 and Nit = 10. Nm = 800.

V.2.1 Lossless Optimal Solutions

According to [5], [48] and several other authors, the optimal solution for this system, without considering the effect of active power losses but allowing generation redispatch is composed of nine circuits connected in seven branches (#2-5=1, #5-6=2, #13-20=1, #20-21=2, #20-23=1, #42-43=1, #46-6=1) and costs U$72.870 million. The BATp optimizer, with r_{ij}= 0, also found the same solution.

Without considering power losses, but not allowing generation redispatch, according to [53], [54] and several other authors, the optimal solution is composed of fifteen circuits connected in nine branches #20-21=1, #42-43=2, #46-6=1, #19-25=1, #31-32=1, #28-30=1, #26-29=3, #24-25=2, #29-30=2, #5-6=2) and costs U$154.420 million.

V.2.2 Case With Generation Redispatch (WR)

The characteristics of the optimal solution obtained by the BATp optimizer with less than 50 iterations (Figure 14) are as follows:

- Cost and number of circuits on the branches of the optimal solution: $75.895 million and #18-20=1, #20-23=1, #20-21=2, #42-43=1, #46-6=1, #5-6=2 (Figure 15);
- Loading levels on the reinforced branches (Figure 16): #18-20 (100.00% of its capacity), #20-23 (94.53%), #20-21 (78.00%), #42-43 (100.0%), #46-6 (51.67%), #5-6 (85.27%);
- Active power losses in the reinforced branches (Figure 17): 70.90 MW (19.83% of system loss). In the system, the active power loss is 357.56MW (5.20% of the load).

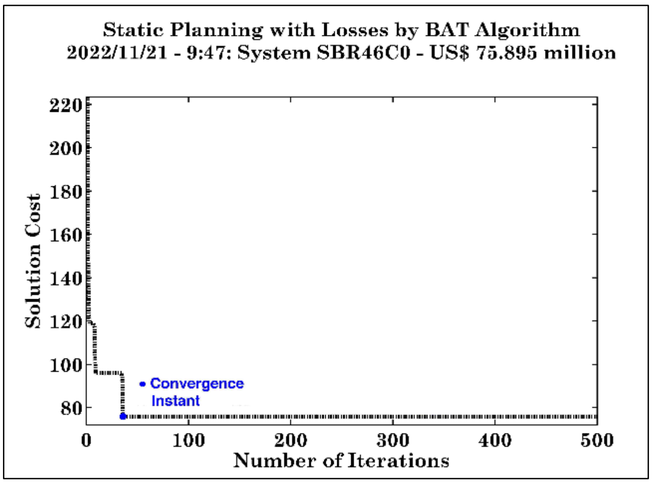

Figure 14: Case WR - SB-46/79 test system.
Cost convergence curve. Source: BATp optimizer, (2022).

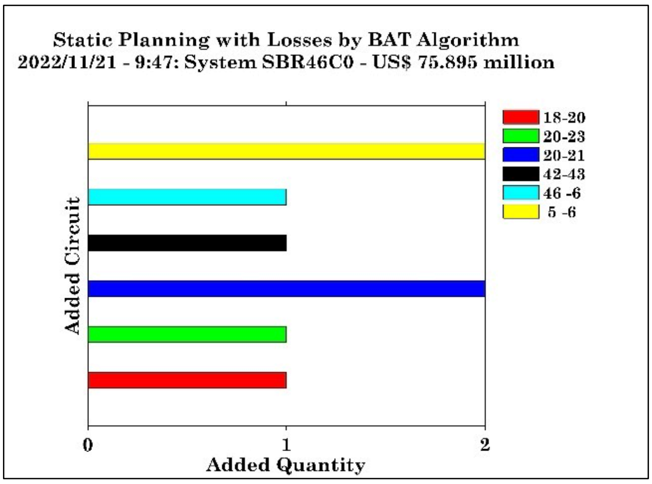

Figure 15: Case WR - SB-46/79 test system.
Planned circuits. Source: BATp optimizer, (2022).

V.2.3 Case Without Redispatch (WOR)

The characteristics of the optimal solution obtained by the BATp optimizer with less than 150 iterations (Figure 18) are as follows:

- Cost and number of circuits on the branches of the optimal solution: U$164.752 million and #20-21=2, #42-43=2, #46-6=1, #19-25=1, #31-32=1, #28-43=1, #24-25=2, #5-6=1 (Figure 19);
- Loading levels on the reinforced branches (Figure 20): #20-21 (92.05% of its capacity), #42-43 (99.94%), #46-6 (53.06%),

#19-25 (69.94%), #31-32 (15.49%), #28-43 (59.96%), #24-25 (80.06%), #5-6 (87.55%);

- Active power losses in the reinforced branches (Figure 21): 99.81 MW (35.18% of system loss). In the system, the active power loss is 283.68MW (3.83% of the load).

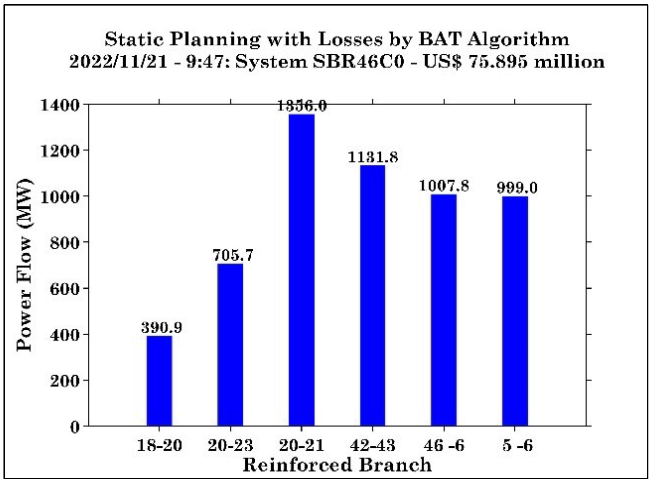

Figure 16: Case WR - SB-46/79 test system.
Flows in the branches. Source: BATp optimizer, (2022).

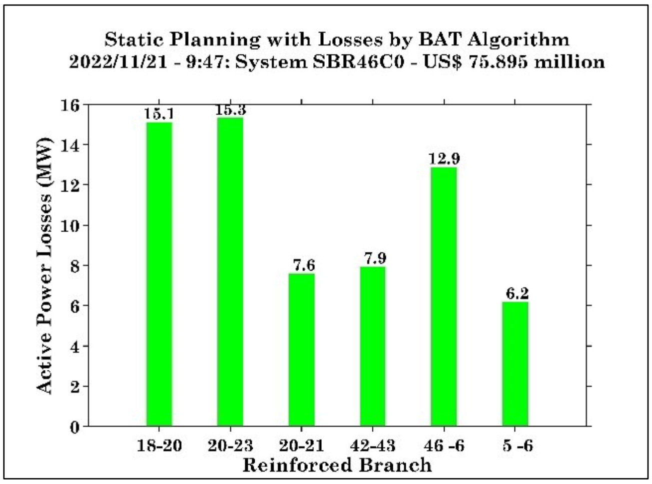

Figure 17: Case WR - SB-46/79 test system.
Losses in the branches. Source: BATp optimizer, (2022).

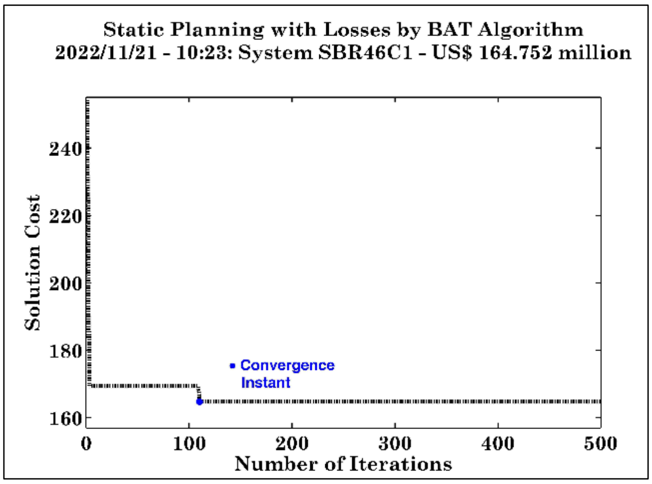

Figure 18: Case WOR - SB-46/79 test system.
Cost convergence curve, Source: BATp optimizer, (2022).

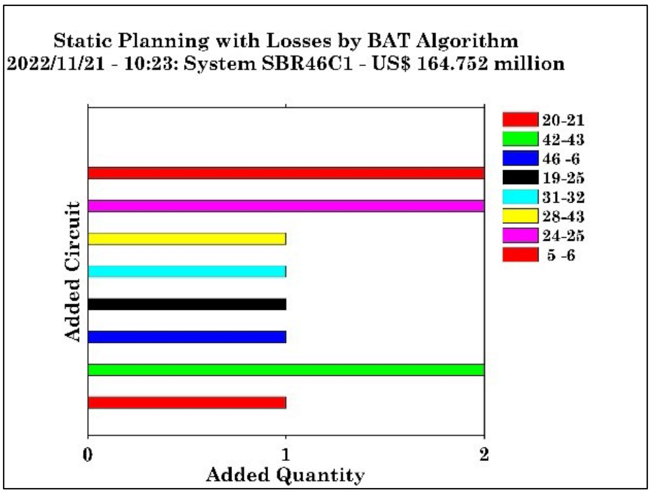

Figure 19: Case WOR - SB-46/79 test system.
Planned circuits. Source: BATp optimizer, (2022).

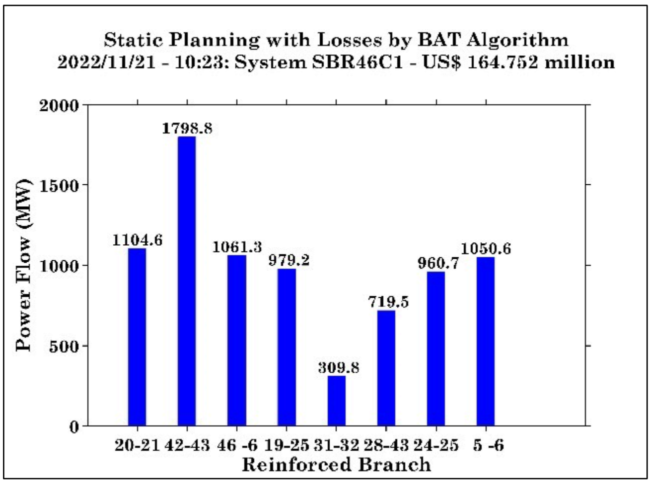

Figure 20: Case WOR - SB-46/79 test system.
Flows in the branches. Source: BATp optimizer, (2022).

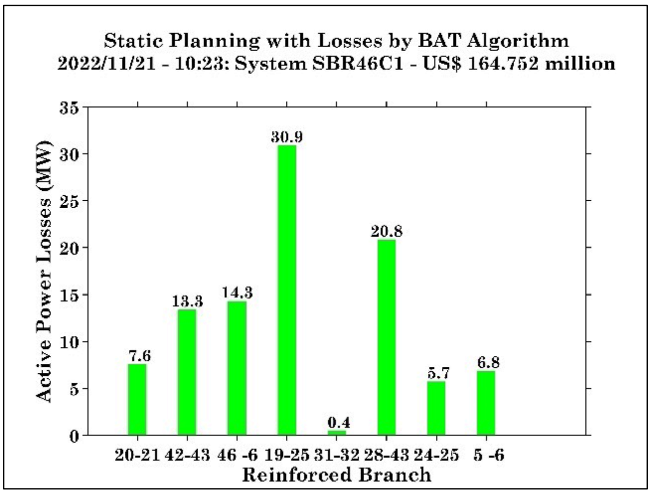

Figure 21: Case WOR - SB-46/79 Test System.
Losses in the branches. Source: BATp optimizer, (2022).

V.2.4 Summary of Results

The Table 6 shows the summary of the results, illustrated in Figures 15, 17 and 19, 21, where lower amounts of circuits added on the network branches, lower investment cost (US$ million) and lower active power loss (MW) are observed when considering generation redispatch.

Table 6: SB-46/79 test system - Comparison of the cases.

Case	Number Circuits	Added Circuits	Cost	Loss
WR	11	20-21=2, #42-43=2, #46-6=1, #19-25=1, #31-32=1, #28-43=1, #24-25=2, #5-6=1	75.895 (46.07%)	70.90 (71.03%)
WOR	8	18-20=1, #20-23=1, #20-21=2, #42-43=1, #46-6=1, #5-6=2	164.752 (100%)	99.81 (100%)

Source: Authors, (2022).

VI. CONCLUSIONS

This paper presents an optimization algorithm capable of solving the complex problem of planning the static expansion of transmission systems considering the effect of active power losses in circuits, which was represented in the equality constraints of the mathematical model. The choice of branches to perform circuit additions was made with the help of the bat algorithm, which was modified to intensify the search around the global optimal solution in each iteration. The modified bat algorithm used in the proposed algorithm belongs to the swarm intelligence paradigm and combines aspects of diversification and search intensification. Procedures for cost reduction of expensive solutions and elimination of discards of infeasible solutions were used together with a search intensification operator around the global optimal solution and with a rule that defines the population size as a function of the number of branches of the analyzed system. Given the complexity of the planning problem, the good quality results obtained with relatively low computational effort demonstrate the efficiency of the proposed optimization algorithm in all the analyzed systems, under various assumptions of generation redispatch and power balancing buses.

VII. AUTHOR'S CONTRIBUTION

Conceptualization: João Ricardo Paes de Barros.
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Investigation: João Ricardo Paes de Barros.
Discussion of results: João Ricardo Paes de Barros.
Writing – Original Draft: João Ricardo Paes de Barros.
Writing – Review and Editing: João Ricardo Paes de Barros and Dimitri Albuquerque de Barros.
Resources: João Ricardo Paes de Barros.
Supervision: João Ricardo Paes de Barros.
Approval of the final text: João Ricardo Paes de Barros and Dimitri Albuquerque de Barros.

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