

Article

Not peer-reviewed version

Network Reconfiguration for Loss Reduction using Tabu Search and a Voltage Drop

[Dionicio Zocimo Naupari Huatuco](#)^{*}, Luiz Filho, Franklin Simeon Pucuhuayla, [Yuri Percy M. Rodriguez](#)^{*}

Posted Date: 2 November 2023

doi: 10.20944/preprints202311.0077.v1

Keywords: network reconfiguration; distribution system; optimization; Tabu Search; minimization; distribution system loss; OpenDSS; Python



Preprints.org is a free multidiscipline platform providing preprint service that is dedicated to making early versions of research outputs permanently available and citable. Preprints posted at Preprints.org appear in Web of Science, Crossref, Google Scholar, Scilit, Europe PMC.

Copyright: This is an open access article distributed under the Creative Commons Attribution License which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Article

Network Reconfiguration for Loss Reduction using Tabu Search and a Voltage Drop

Dionicio Zocimo Ñaupari Huatuco ^{a,*}, Luiz Otávio Pinheiro Filho ^{b,*}, Franklin Jesus Simeon Pucuhuayla ^a and Yuri Percy Molina Rodriguez ^b

^a National University of Engineering, Faculty of Electrical Engineering, Lima, Peru

^b Center of Alternative and Renewable Energy, Federal University of Paraíba, João Pessoa, Paraíba, Brazil

* Correspondence: znaupari@uni.edu.pe

Abstract: This work presents a new algorithm to resolve the problem of distribution network reconfiguration using the Tabu Search metaheuristic and voltage drop. The proposed method presents a different way to obtain the initial solution using the voltage drop, as well as a new way to generate a neighborhood of candidate solutions, based on randomness and the voltage drop, to perform a smooth and steady descent execution of the algorithm. The proposed algorithm has the main objective to reduce the active power losses in distribution networks, but it also achieves an refinement in the voltage profile. The proposed method was tested in two distribution systems, the 33-Bus and 94-Bus systems, commonly found and tested in the literature. The results of the tests show that the proposed method presents a low computational cost, achieves good solutions, and is better than the other methods found in the literature.

Keywords: network reconfiguration; distribution system; optimization; Tabu Search; minimization; distribution system loss; OpenDSS; Python

1. Introduction

The relentless rise in global demand for electrical energy, as well as society's growing reliance on it, necessitates the development of an efficient, dependable, continuous, stable, and low-cost electrical system. The electrical power system is responsible for the generation, transmission, and distribution of energy in society. The distribution system is in charge of getting electricity to end-users. At this point, the most significant power losses [1] occur.

Conducting studies on the reconfiguration of the distribution system to reduce losses and improve the voltage profile, among other purposes, is one of the actions that energy firms can take to improve energy supply.

The traditional reconfiguration study seeks to find an optimal topology that generates the lowest possible losses in the system under study. The system topologies are generated by opening or closing the switches present in the system distribution. The reconfiguration problem does not involve the installation of new equipment or new power generation. The only costs of the reconfiguration are the ones associated with opening or closing switches, which are negligible [2].

The reconfiguration problem is combinatorial, as it depends on the number of switches existing in the system. In this way, as a switch can assume two states, open or closed, a system with n switches can have 2^n candidate solutions for the network topology.

Due to the combinatorial nature of the problem, as it depends on the number of switches existing in the system, a system with n switches can have 2^n candidate solutions for the network topology. This way, deterministic approaches become practically unfeasible [3]. Therefore, there is a need to use computational algorithms and tools that reduce substantially the amount of solutions to be tested and find a possible optimal or close to optimal solution with a substantially reduced and affordable computational cost.

The pioneers of the reconfiguration heuristic were Merlin and Back [4], who provided a heuristic that started with a meshed network and opened the switches progressively, considering the branch

whose removal would limit the power flow as little as feasible. One of their algorithm's shortcomings was that the power flow computation only took into account the real part of the current.

The Branch Exchange approach, suggested by Civanlar et al. [5], entails attempting to recombine related branches in order to minimize losses. They devised a criterion based on the terminal voltage of the typically opened switches to limit the search to only those configurations that result in loss reduction due to the high number of candidate configurations. However, the search space only contains a subset of the possible network configurations, which is still dependent on the initial system configuration.

Niknam and Farsani [6] proposed a hybrid evolutionary algorithm for solving the distribution feeder reconfiguration. Their algorithm is a combination of SAPSO (self-adaptive particle swarm optimization) and MSFLA (modified shuffled frog leaping algorithm). The main idea of integrating SAPSO and MSFLA was to use their advantages and avoid their disadvantages. The algorithm was tested in two distribution systems.

There has been an increase in the technical literature on the usage of heuristics based on biology or physics since the 2000s, highlighting the use of meta-heuristics. Meta-heuristics, according to Glover [7], guide and modify other heuristics, resulting in better results than conventional heuristics. The meta-heuristic Tabu Search is often applied in the Reconfiguration problem.

Jeon and Kim [8] presented a hybrid method that used tabu search and simulated annealing techniques to solve real-world problems. According to the authors, the tabu search strategy uses a descent algorithm to find a solution, but it cannot ensure convergence; simulated annealing, on the other hand, avoids local minima by accepting an increase in the optimization function, but at a high computational cost.

To diversify the search in unexplored regions, Abdelaziz *et al.* [9] presented an algorithm built with tabu search with a tabu list of an adaptable size conforming to the size of the system, as well as a new procedure of generating solutions called *constrained move*.

The article referenced as [10] presents a comparison between two well-known metaheuristic algorithms employed for solving combinatorial optimization problems, specifically focusing on network reconfiguration problems. The methods under investigation in this study are Simulated Annealing and Tabu Search. To assess the performance of Simulated Annealing and Tabu Search, the researchers applied these algorithms to address network reconfiguration problems in power systems, specifically focusing on the 16 and 33 buses systems. These systems serve as standard test cases widely employed in the field.

Bagheri *et al.* [11] proposed an algorithm with tabu search applied to reconfiguration capable of working in systems with distributed generation. The algorithm works out the problem of sizing, reconfiguration, operation and allocation of distributed generation considering the financial costs, losses and injected reactive power for distributed generation.

Sayed *et al.* [12] present a SHADE optimization algorithm to perform the reconfiguration problem along with the integration of distributed generation units and shunt capacitors in the system. Maximizing the hosting capacity (HC) of the distributed generation units and reducing network power losses in addition to improving the voltage profile have been considered optimization objectives. The authors used the 33-Bus and the 59-Bus systems.

The Tabu Search metaheuristic has consistently proven its effectiveness in solving various energy system problems. Building upon this, we propose a novel Tabu Search-based method designed to uncover high-quality solutions for two commonly encountered distribution systems in the literature: the 33-Bus and 94-Bus systems.

The main contributions of the proposed method are:

- A method for calculating the voltage drop between the component buses of the meshes in order to generate an initial solution. This approach allows the tabu search algorithm to begin with a good solution, which is necessary for tabu search techniques to be implemented successfully;

- The hybrid neighborhood-generating method leverages the voltage drop information, which is a critical factor in energy systems, to guide the search process. By considering the voltage drop, the algorithm can focus on areas where improvements are most needed, ensuring that the generated solutions adhere to voltage stability requirements. This approach enhances the algorithm's ability to explore promising regions of the solution space efficiently;
- The proposed method has demonstrated remarkable success in terms of achieving favorable conditions for initializing the initial solution and sustaining a productive neighborhood throughout the optimization process. This approach ensures that the algorithm starts from a promising point in the solution space, enhancing its chances of finding optimal solutions.

This work is organized as follows: Section 2 presents the theoretical foundation to be used in the work, such as the Reconfiguration problem, the classic Tabu Search algorithm and the concept of the ΔV used in this work; Section 3 presents the proposed method for the Tabu Search algorithm and its modifications; Section 4 brings the application of the proposed method to the Reconfiguration problem; Section 5 presents the results obtained from the simulations and discusses these results; and finally Section 6 brings the conclusions of the study and the achievements of the work.

2. Theoretical Foundation

In this section, the distribution network reconfiguration problem, the classic Tabu Search algorithm and the ΔV concept will be explained.

2.1. Distribution Network Reconfiguration Problem

In electrical power distribution systems, reconfiguration involves evaluating the status (open or closed) of each of the sectioning or connecting switches in the system.

The reconfiguration problem is a minimization problem with an objective function and constraints. There are different objective functions presented in the technical literature, including enhancing the voltage profile, rebalancing loads between feeders, and, most importantly, decreasing active losses in conductors. The latter is the objective function that will be employed in this project.

As a result, the goal of this research is to find a distribution network system architecture that minimizes conductor losses while also meeting operational constraints.

2.1.1. Objective Function

The fitness function of the reconfiguration problem is to minimize system losses given by:

$$f(s) = \sum_{l=1}^{N_l} r_l \cdot i_l^2 \quad (1)$$

Where $f(s)$ is the sum of all active losses in the distribution system conductors; N_l is the number of lines in the distribution system; r_l is the resistance of the l line; i_l is the electric current passing through the l line and s is the solution for the system with some switches closed and some switches open.

2.1.2. Constraints

- Voltage Constraints:

The voltage in the bus must satisfy the minimum and maximum limits, as follows:

$$E_{min} \leq \|E_k\| \leq E_{max} \quad (2)$$

Where E_{min} is the minimum and E_{max} is the maximum voltage values, allowed for a given bus k . Commonly adopted values are 0.95 pu and 1.05 pu. This condition is valid for all buses in the system.

- Current Constraints:

The current limit constraint on the branch is due to the technical characteristics of the branch used in the distribution system. The current passing through a line (i_l) cannot exceed the maximum current supported by that line (i_l^{max}), as in:

$$\|i_l\| \leq i_l^{max} \quad (3)$$

- Radiality Constraints:

The act of opening and closing switches in a distribution system must be done in such a way that the system's radiality is preserved. Radiality is defined as the lack of meshes in the system as well as the fulfillment of all related loads. The conditions for the imposition of radiality employed in this work are taken from Lavorato *et al.* [13] and given below:

1. Condition 1: the solution must have $A = n_b - n_{bs}$; where A is the number of active branches, n_b is the number of buses in the system and n_{bs} the number of substation buses in the system;
2. Condition 2: The system must be connected. This implies that, in addition to the system must be connected to some substation, all loads must be attended to.

2.2. Classic Tabu Search Algorithm

Tabu Search (TS) [7] is a metaheuristic procedure whose philosophy is to derive and exploit a collection of intelligent problem solving strategies, based on implicit and explicit learning procedures to exploit an adaptive memory framework, which is an important feature of the artificial intelligence [14].

The motions described above are carried out with the goal of arriving at a satisfactory solution while taking into account some function $f(s)$ that must be minimized or maximized [7].

Each solution s belonging to a search space S has a neighborhood $N(s) \subset S$ and each solution $s' \in N(s)$ is obtained by a movement mechanism [15]. Tabu Search Algorithms solve algorithms as follows:

$$\begin{aligned} & \underset{s}{\text{minimize}} && f(s) \\ & \text{subject to} && s \in S \end{aligned}$$

Where s is a possible solution, $f(s)$ is the objective function (fitness function) according to the solution s and S is the search space. Optimization problems commonly also have constraints to be met. Before explaining the algorithm itself, it is interesting to define the basic concepts, as seen in [16] and [17]:

- Initial solution: a feasible solution from the problem, namely, Initial solution, which is generally obtained by using the heuristic rule.
- Current solution: a possible solution to the problem;
- Movement: mechanism for generating a new solution applying a perturbation in the current solution;
- Neighborhood: A feasible solution is derived from the original feasible solutions by searching with the Movement Strategy by determining which conforms to the problem constraints;
- Tabu List: list of last performed moves prohibited from being performed again by T iterations. In practice, the presence of the tabu List prevents cycling in the algorithm;
- Aspiration Criteria: list of criteria for a solution containing movements from the tabu list to be adopted as the current solution. If a generated neighbor is the best solution ever found but has moves in the tabu list, it can be accepted as the current solution.

With the notions in mind, the algorithm can be described as follows: Begin with a solution that satisfies the constraints. A neighborhood with multiple surrounding solutions is produced from this

solution using the movement mechanism; verify that these neighbors meet the Constraints. This is the new current solution if the best neighbor (according to the minimization function) is not in the tabu list and fits the aspiration requirements. If such a neighbor is on the tabu list but does not match the aspiration requirements, repeat the test for the second-best neighbor and so on until you find a neighbor who is not on the tabu list. Add the moves of this solution to the tabu list after selecting the new current solution. The fitness of the current solution is then tested to find out if it is the best discovered; if it is, the solution is kept as *BestS*, the fitness as *BestFit*, and the iteration number as *BestIter*. When a preset amount of iterations without an update on *BestS* are completed, the Tabu Search algorithm stops.

An observation about the tabu list is that it has a predetermined size T and when it is filled, every set of new moves is added, and the oldest ones are removed and can be chosen again as the current solution.

2.3. The Kirchhoff's Circuit Laws and the Voltage Drop

Kirchhoff's Laws were first introduced in 1847 by the German physicist Gustav Robert Kirchhoff and are formally known as Kirchhoff's Law for Current (KCL, or Kirchhoff's point rule) and Kirchhoff's Law for Voltage (KVL, or Kirchhoff's mesh rule) [18].

- Kirchhoff's law for current says that the algebraic sum of currents entering into the bus is zero [18], i.e.:

$$\sum_{n=1}^N i_n = 0 \quad (4)$$

Where N is the number of branches connected to the bus and i_n is the n th current entering or leaving the bus.

- Kirchhoff's law for voltage says that the algebraic sum of all voltages around a closed path (or loop, or mesh) is zero [18], i.e.:

$$\sum_{m=1}^M v_m = 0 \quad (5)$$

Where M is the number of voltages in the loop (loads, sources, conductors, etc.) and v_m is the m -th voltage.

Ohm's Law, which states that a voltage v in a resistor is directly proportional to the current i through it, along with the concept presented by KVL, brings an important concept which is the voltage drop between two buses.

In this way, according to KVL, between two buses where there is an element connected, there is a voltage drop. And according to Ohm's Law, the greater the current over a resistive element, the greater the voltage in the element, which means that if there is a resistive element between two buses, a large current passing through that element will produce a large voltage drop between these buses.

In accordance with the electrical theory, which states that electrical power is directly proportional to the voltage drop and current, it can be inferred that in a resistive element where a large current is passing there will be a large dissipation of active power.

In order to better understand it, the power dissipation between two buses shown in Figure 1 can be analyzed. Thus, for a large current flowing through the conductor, there will be a large power dissipation in the conductor. This implies that the greater the voltage difference between two buses (ΔV), the greater the power dissipation between those two buses.

$$\Delta V = \|V_{bus1} - V_{bus2}\| \quad (6)$$

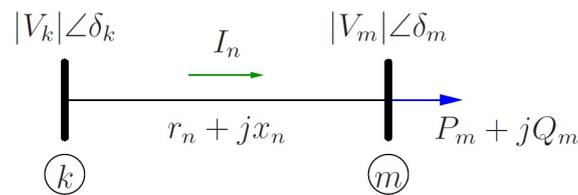


Figure 1. 2-Bus example system.

3. The Modified Tabu Search Algorithm

Before explaining the algorithm used in this work, it is interesting to comment on a few words about the *software* OpenDSS, used in this work. For the losses, voltages, and several other variables to be obtained from a distribution system, it is necessary to calculate the power flow. There are several algorithms capable of calculating a power flow, such as Newton-Raphson, Gauss-Seidel, Decoupled Newton, and several others. In this work, all data related to the power flow come from OpenDSS.

OpenDSS *software* is an embracing simulation tool for electrical systems that allows it to be controlled by various *software* platforms, such as C#, Python, MATLAB, Microsoft Office and others. OpenDSS uses two algorithms capable of solving the power flow: the current injection method (CIM) and the Newton method. The first one is faster and used by default. The second is mostly used for complex systems [19].

Having said these observations about the power flow and OpenDSS, it is possible to start exploring the algorithm proposed in this work, starting with the initial solution and then with the neighborhood generation method.

3.1. Initial Solution using the Voltage Drop ΔV

As explained in the subsection 2.3, a large voltage difference between two buses can indicate that a high current passes through the conductor that connects the two buses. Consequently, there would also be a large power dissipation in the conductor, which would produce many losses to the system.

Applying then to the distribution systems, it would be logical to open these switches that are between buses with large ΔV that probably have large power dissipation and large current passage, however, *this would lead to opening probable main feeders of the distribution system*, by where it *must* elapse a lot of energy. It is important, then, for the reconfiguration problem to minimize losses, to open the switches that possibly produce little loss, and that their opening will probably not cause problems for the system. Shirmohammadi and Hong [20] proposed something similar with currents, opening the switches that had the smallest chain within each mesh of the system.

The proposed algorithm for generating an initial solution starts with a radial system, opened with the tie switches used in the literature for the system. The algorithm closes the first switch (it can be any switch), getting a mesh in the system. Then the power flow is calculated and all the ΔV of the mesh that has just been formed are calculated, that is, all the ΔV between buses connected by a conductor in that mesh. The currently opened switch will be closed and the switch corresponding to the conductor with the lowest ΔV will be opened.

Then the power flow is recalculated and the radiality condition is tested. If the solution is not radial, the test with the switch which has the second smallest ΔV is performed, and so on until the solution becomes radial again. If the solution is radial and there is a decrease in active losses (in the fitness function), then this switch is saved as part of the solution. Then the algorithm closes the second tie switch, thus obtaining a second mesh different from the first one, already using the first switch obtained from the first mesh process to calculate the power flow. The ΔV of the second mesh is calculated and then the process for obtaining the new switch is the same process already explained for the first mesh. This process is repeated for all switches and loops in the distribution system. With all switches renewed, the new solution can be used as an initial solution for the Tabu Search algorithm. The algorithm flowchart is shown in Figure 2.

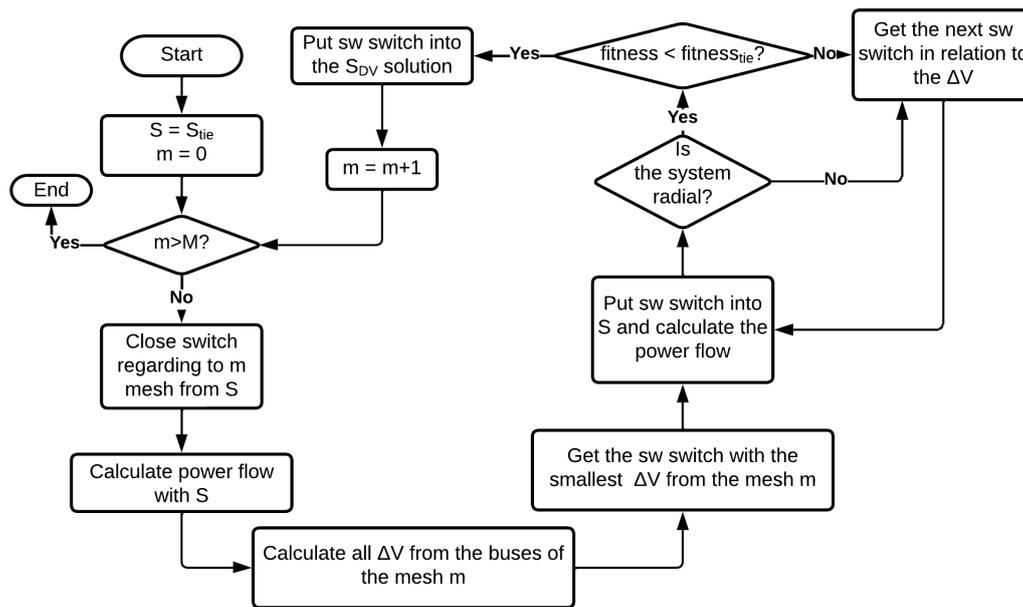


Figure 2. The initial solution flowchart.

3.2. The Hybrid Neighborhood Algorithm

A satisfying neighborhood is crucial for the progress of Tabu Search algorithm results. The neighborhood is generated by perturbing the current solution with a movement mechanism. Chiang and Jumeau [21] and several other authors [9,15,22], for example, employed a mechanism called *add/subtract* to generate neighbors.

In the first place, it is interesting to denote the variables to be used from now on. M is the number of switches that shall be opened in order for the system to be radial (but remember, this is not the only condition); M can also be called system dimension number. Ω_X is the set of switches belonging to mesh X , after closing all tie switches. For example, in a system with M meshes after closing all tie switches, the first mesh to be analyzed has a Ω_1 set of switches, the second mesh has a Ω_2 set and so on. The order of analysis of the meshes is not important. It is also interesting to note that each set of switches contains all the sectionalizing and tie switches belonging to that mesh X . In these sets the switches are ordered according to their geographic position, which means that physically neighboring branches are also neighbors in the set of switches.

The proposed algorithm presents a hybrid approach that incorporates two distinct methods to generate neighboring solutions. During even iterations, the algorithm employs a methodology that prioritizes randomness, while during odd iterations, the focus shifts to the differences in voltages (ΔV) within the system. Notably, the algorithms for both methods share a remarkable similarity, with the sole variation being the approach used to select the subsequent switch, also referred to as the moving mechanism.

Therefore, both algorithms start by analyzing the current solution S . The *index* of the first switch of S in the set Ω_1 is found. Right now there is a difference between the algorithms:

- For random algorithm: algorithm randomly chooses whether the new switch will be immediately to the left or right of the currently opened switch and then chooses the new switch;
- For the ΔV algorithm: all the ΔV between the buses that have conductors connecting them within that mesh are calculated and then the chosen switch is the one with the smallest ΔV .

With the new chosen switch opened and the old switch closed, the other switches of the other meshes are not modified and then the first neighbor is created.

For the second neighbor, the process is repeated, but now for the second mesh and the switch set Ω_2 . But notice that the first switch (from the first mesh) for the second neighbor is still the switch to

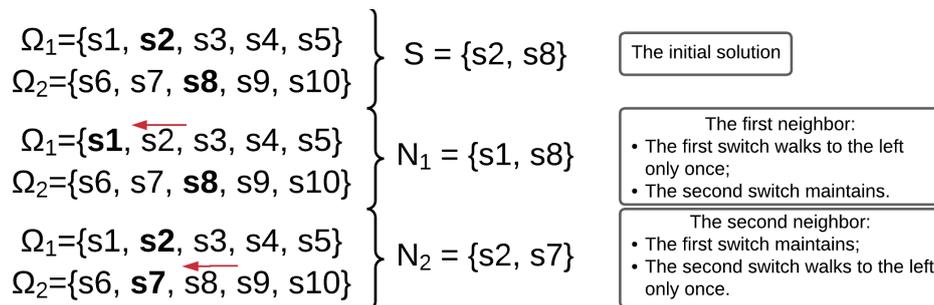
the current solution S . The algorithm will produce M neighbors since only one neighbor was created for each mesh of the system.

However, there is a manner to generate more than M neighbors, both for the ΔV algorithm and for the algorithm with emphasis on randomness:

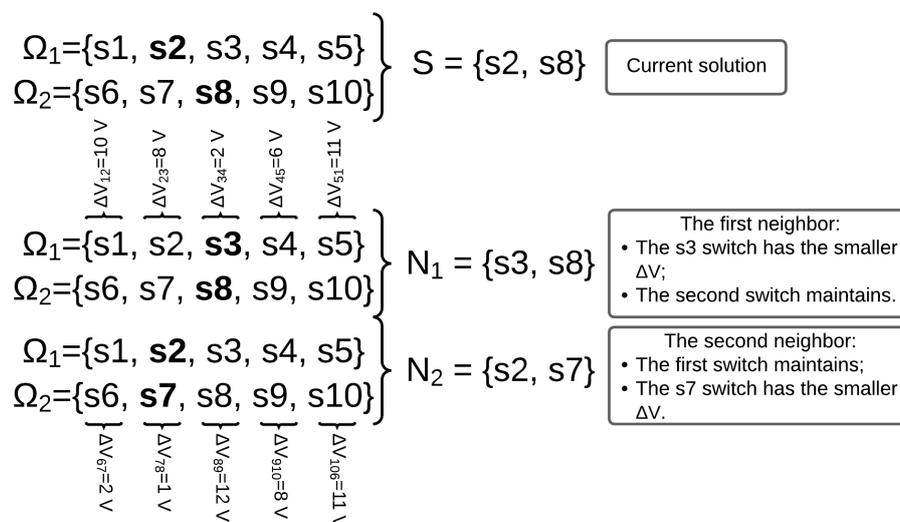
- For the algorithm with emphasis on randomness: after generating the M neighbors that were generated by choosing the switch immediately lateral to the switch of S , it is possible to obtain neighbors going further, selecting not only the immediately to the left or immediately to right but also the second switch to the left or right and so on. To avoid this, the method is also limited to "walking" only to the number of switches that the smallest mesh has to avoid having very distant neighbors;
- For the ΔV algorithm: after generating the M neighbors that were generated with the smallest ΔV of each mesh, it is possible to generate other M neighbors with the second smallest ΔV of each mesh and so on up to the size of the smallest mesh of the system as was done for the case of randomness.

Thus, the variable created to inform the number of neighbors to be generated by the algorithm is NNb (Number of Neighbors).

For example, consider a system with $M = 2$ meshes, $\Omega_1 = s1, s2, s3, s4, s5$ and $\Omega_2 = s6, s7, s8, s9, s10$. Consider the current solution $S = s2, s8$. In order to better illustrate the proposed structure the generated neighbors, it is considering that $NNb = 2$, in Figure 3 is shown the random algorithm and the ΔV algorithm. Consider that for the random one the algorithm chose the left movement.



(a) The random algorithm for even iterations.



(b) The ΔV algorithm for odd iterations.

Figure 3. Example of one iteration for the Hybrid Neighborhood Algorithm.

4. Application of the Modified Tabu Search

The Modified Tabu Search algorithm for the reconfiguration problem can be observed by following these steps:

1. In this step, the lines, switches, loads, and feeds are added, as well as the variables $BTMax$ (number of iterations without improvement), T (size of the tabu list), $MaxIter$ (maximum number of iterations) and NNb (number of neighbors to be generated at each iteration) are set;
2. Get the Initial Solution by ΔV method, as seen in the subsection 3.1;
3. The iterative loop begins. $Iter = Iter + 1$. If $Iter$ is even, neighbors with an emphasis on randomness are generated. If $Iter$ is odd, the neighbors of the voltage differences ΔV are generated. Each neighbor already tracks its active loss value for that topology;
4. The neighborhood is ordered according to the losses that each neighbor generates, in ascending order of losses, that is, the first neighbor will be the best, as it will have the lowest loss value. This neighbor is selected;
5. If this neighbor is the best solution found during this iteration, the new S will be this neighbor (by the aspiration criterion); if not, the neighbor will be checked if any switch is on the tabu list. If not, it will be the new S solution. If it is in the tabu list, the algorithm will select the second best neighbor and perform the described test again until it finds a neighbor that has no switches on the tabu list. With the new S chosen, the tabu list is updated;
6. If this new S solution is the best found, save it as $BestS$ (best solution ever found), save its losses as $BestFit$ (best fitness ever found), and save the iteration number as $BestIter$;
7. Check the stopping criteria: if $(Iter - BestIter)$ is greater than $BTMax$ or if $Iter$ reaches the value of $MaxIter$ the algorithm stops and goes to step 8. If none of the criteria are met, go to step 3;
8. Show the results: the best solution found, the losses of the best solution, and the minimum and maximum voltages of this solution.

5. Simulations and Results

In this section, the algorithm is executed for two distribution feeder systems used in the technical literature. The parameters for both systems are $BTMax$, T , NNb , and $MaxIter$. It is worth saying that the tests were conducted with Python, on an Intel[®] Core[™] i7-7500 CPU @ 2.70 GHz 8GB RAM.

5.1. Initial Solution Method Results

Before commenting on the results for the entire proposed modified algorithm, it is valid to comment on the results obtained only with the ΔV Initial Solution. The proposed method obtained a better solution than the *default* solutions with open tie switches proposed by the authors who presented the systems. The method presents good initial solutions for the 33-Bus by Baran and Wu [23] and 94-Bus by Su and Lee [24] systems, as can be seen in Table 1.

Table 1. Initial Solutions Using ΔV method

System	Default Initial Solution	Initial Solution using ΔV method	Reduction
33-Bus [23]	s33, s37, s35, s36, s34 202.27 kW	s6, s25, s11, s32, s14 163.22 kW	19.31%
94-Bus [24]	s96, s88, s91, s87, s89, s94, s95, s93, s92, s90, s84, s85, s86 532.8 kW	s96, s88, s82, s72, s89, s33, s42, s39, s92, s90, s84, s7, s86 485.41 kW	8.89%

With these reductions in system losses, the initial solution generation algorithm proves to be efficient for obtaining solutions with less active losses for the system using an algorithm with low computational cost.

5.2. Case 1: 33-Bus System

Baran and Wu's 33-Bus system [23] has 37 branches, 32 of which are normally closed switches (sectionalizing switches), and 5 switches are normally opened (tie switches). With all switches closed, the system forms 5 meshes. System voltage is 12.66 kV, total active loads is 3715 kW and reactive loads is 2300 kvar. The system is represented in Figure 4, where its sectionalizing switches, from s1 to s32, are represented by continuous lines, while the tie switches, from s33 to s37, by dashed lines. The system presents 202.63 kW of losses before the reconfiguration is performed.

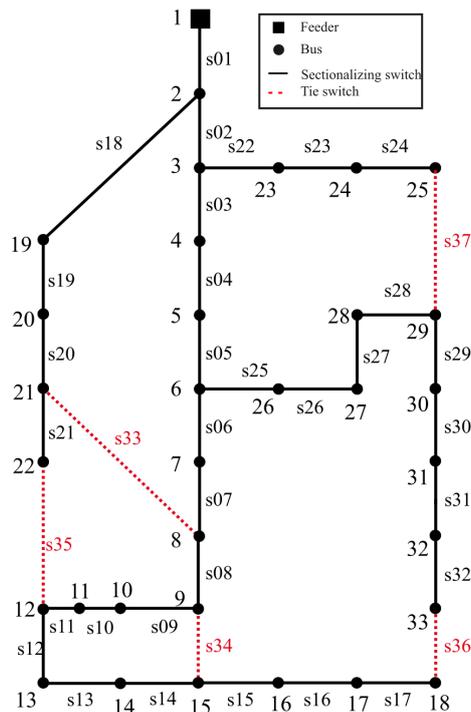


Figure 4. Single line diagram of IEEE-33 bus distribution system.

The best solution found by the proposed algorithm is to open switches s7, s9, s14, s32, and s37 and keep the other switches closed. The active losses of this solution are 139.56 kW and represent a reduction of 31.12% in comparison with the system before reconfiguration. The same solution was found by [1,15,22].

There was also a considerable upgrade in the voltage profile of the system. Before reconfiguration, the smallest voltage at a bus was 0.9174 p.u. and after reconfiguration, the minimum voltage was 0.9378 p.u.

For the proposed method to be validated, several tests were performed with different combinations of $BTMax$, T , and NNb . As can be seen in Table 2, the higher the $BTMax$ or NNb , the greater the chances of 100% success in 100 executions of the algorithm, however, according to many tests performed, for values greater than 5 for T the system efficiency starts to drop due to the 33-Bus system size which does not support large tabu list size values.

It is interesting to make comparisons with other reconfiguration methods with tabu search available in the technical literature. The proposed algorithm generates 100 optimal solutions for 100 executions, using the same values for the variables $BTMax$, T , and NNb for the proposed algorithm and the algorithms of other authors. The variables were: $BTMax = 15$, $T = 2$ and $NNb = 5$. Table 3 brings the results obtained for the proposed algorithm and other algorithms.

Table 2. Results varying BTMax, T and NNb in 100 trials for 33-Bus system.

BTMax	T	NNb	Loss average (kW)	Standard deviation (kW)	Worst Solution	Losses (kW)	No. of global solutions
10	2	5	139.62	0.2419	s7, s28, s10, s32, s14	140.72	91
10	2	10	139.57	0.1367	s7, s28, s10, s32, s14	140.72	98
10	5	5	139.81	1.2575	s7, s26, s10, s32, s14	147.98	90
10	5	10	139.58	0.1000	s7, s37, s10, s32, s14	140.29	96
20	2	5	139.56	0	-	-	100
20	2	10	139.56	0	-	-	100
20	5	5	139.56	0	-	-	100
20	5	10	139.56	0	-	-	100

Table 3. Comparison between the results of the 33-Bus system for different techniques in 100 tests.

Method	Loss average (kW)	Standard deviation	Worst solution	No. of global solutions
Proposed method	139.56	0	-	100
Abdelaziz et al. [9]	140.30	1.9496	s33, s27, s11, s31, s34 148.71 kW	68
Andrade and Ferreira [25]	139.75	0.9708	s33, s28, s11, s32, s34 143.52 kW	78
Jeon and Kim [8]	139.69	1.0410	s33, s28, s9, s32, s34 144.38 kW	85

5.3. Case 2: 94-Bus System

Su and Lee's 94-Bus system [24] is a real Taiwanese system, with a voltage of 11.4 kV, 11 feeders, and 83 normally closed switches (sectionalizing switches), s1 to s83, and 13 normally opened switches (tie switches), s84 to s96. Thirteen meshes are formed by closing the tie switches. Before reconfiguration, the system has 532 kW in active losses. The system can be seen in Figure 5. Normally closed switches are represented by solid black lines and normally opened switches are represented by red dashed lines.

The best solution delivered by the algorithm is to open switches s07, s13, s34, s39, s42, s55, s62, s72, s83, s86, s89, s90, and s92, keeping the other switches closed. The same configuration was obtained by [1,24]. This configuration produces losses of 470.67 kW, which means a reduction of 11.53% in comparison with the system before reconfiguration.

The 94-Bus system, as well as the 33-Bus, showed an improvement in the voltage profile. Before reconfiguration, the lowest voltage was 0.9283 p.u. and after reset, the lowest voltage became 0.9532 p.u.

To validate the proposed method using the 94-Bus system, several tests were performed with different combinations of *BTMax*, *T*, and *NNb*. As can be seen in Table 4, for different values of *BTMax*, *T* and *NNb* the system had 100% efficiency, delivering the best solution in 100 attempts every time. The authors admit that they tried different combinations of the variables to obtain one that would make the algorithm difficult, but a combination was not found. The most critical variable for the algorithm is *BTMax* (number of iterations without improvement), after all, it dictates the moment of the stop of the algorithm and, even with a value of 1, the algorithm did very well. It is believed that great success is due to the initial solution generation algorithm that generates a solution close to the ideal solution. Remember that the initial solution produces 485.41 kW, while the solution after reconfiguration produces 470.67 kW, which makes them relatively approximate and facilitates the work of the Tabu Search and Neighborhood algorithm.

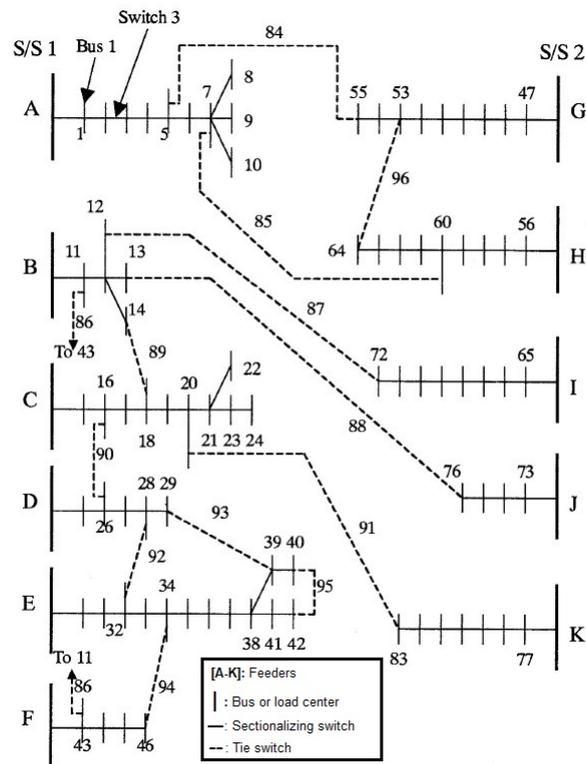


Figure 5. Single-line diagram of 94-Bus distribution system [24].

Table 4. Results varying BT_{Max} , T and NNb in 100 trials for 94-Bus system.

BT_{Max}	T	NNb	Loss average (kW)	Standard deviation (kW)	Worst Solution	Losses (kW)	No. of global solutions
1	5	13	470.67	0	-	-	100
1	5	26	470.67	0	-	-	100
1	10	13	470.67	0	-	-	100
1	10	26	470.67	0	-	-	100
10	5	13	470.67	0	-	-	100
10	5	26	470.67	0	-	-	100
10	10	13	470.67	0	-	-	100
10	10	26	470.67	0	-	-	100

As was done with the 33-Bus system, comparisons were also carried out with other methods available in the literature. The proposed algorithm again presented 100 optimal solutions for 100 executions of the algorithm, using the same values for BT_{Max} , T , and NNb for the proposed algorithm and the other authors' algorithms. The values used were: $BT_{Max} = 15$, $T = 8$ and $NNb = 13$. Comparative results are available in Table 5.

Table 5. Comparison between the results of the 94-Bus system for different techniques in 100 tests.

Method	Loss average (kW)	Standard deviation	Worst solution	No. of global solutions
Proposed method	470.67	0	-	100
Abdelaziz et al. [9]	471.55	4.6203	s96, s13, s83, s72, s89, s34, s42, s39, s92, s90, s84, s85, s86 503.42 kW	69
Andrade and Ferreira [25]	472.65	7.4419	s96, s88, s82, s87, s89, s34, s42, s39, s92, s90, s84, s85, s86 508.21 kW	52
Jeon and Kim [8]	471.78	5.5723	s96, s13, s83, s72, s89, s34, s42, s39, s92, s90, s84, s85, s86 503.42 kW	62

6. Conclusions

The tabu search metaheuristic was used to suggest a new strategy for solving the problem of Distribution Network Reconfiguration in this research. The voltage drop notion was employed to produce a suitable first solution, reducing the computing cost.

It's also notable for introducing a novel method for producing a neighborhood, based on shifting a single dimension of the current solution for each neighbor, using randomness and the voltage drop to perform a smooth and steady descent execution of the algorithm resulting in a neighborhood that has a strong probability of improving with each iteration.

The simulation results yielded positive findings, affirming the effectiveness of the proposed strategy and its ability to generate high-quality solutions for the problem at hand. The method was thoroughly tested using two different systems, both of which demonstrated a remarkable efficiency of 100 percent in producing the optimal solution reported in the technical literature. In comparison to other algorithms proposed and tested under identical conditions, the proposed algorithm not only achieved a standard deviation of zero but also outperformed them significantly by achieving a 100 percent success rate in finding global solutions.

References

- Pegado, R.; Ñaupari, Z.; Molina, Y.; Castillo, C. Radial distribution network reconfiguration for power losses reduction based on improved selective BPSO. *Electric Power Systems Research* **2019**, *169*, 206–213.
- Dias Santos, J.; Marques, F.; Garcés Negrete, L.P.; Andréa Brigatto, G.A.; López-Lezama, J.M.; Muñoz-Galeano, N. A Novel Solution Method for the Distribution Network Reconfiguration Problem Based on a Search Mechanism Enhancement of the Improved Harmony Search Algorithm. *Energies* **2022**, *15*, 2083.
- Gerez, C.; Coelho Marques Costa, E.; Sguarezi Filho, A.J. Distribution Network Reconfiguration Considering Voltage and Current Unbalance Indexes and Variable Demand Solved through a Selective Bio-Inspired Metaheuristic. *Energies* **2022**, *15*, 1686.
- Merlin, A. Search for a minimal-loss operating spanning tree configuration for an urban power distribution system. *Proc. of 5th PSCC, 1975* **1975**, *1*, 1–18.
- Civanlar, S.; Grainger, J.; Yin, H.; Lee, S. Distribution feeder reconfiguration for loss reduction. *IEEE Transactions on Power Delivery* **1988**, *3*, 1217–1223. <https://doi.org/10.1109/61.193906>.
- Niknam, T.; Farsani, E.A. A hybrid self-adaptive particle swarm optimization and modified shuffled frog leaping algorithm for distribution feeder reconfiguration. *Engineering Applications of Artificial Intelligence* **2010**, *23*, 1340–1349.
- Glover, F. Tabu search: A tutorial. *Interfaces* **1990**, *20*, 74–94.
- Jeon, Y.J.; Kim, J.C. Network reconfiguration in radial distribution system using simulated annealing and tabu search. In Proceedings of the 2000 IEEE Power Engineering Society Winter Meeting. Conference Proceedings (Cat. No. 00CH37077). IEEE, 2000, Vol. 4, pp. 2329–2333.

9. Abdelaziz, A.Y.; Mohamed, F.; Mekhamer, S.; Badr, M. Distribution system reconfiguration using a modified Tabu Search algorithm. *Electric Power Systems Research* **2010**, *80*, 943–953.
10. de Andrade, B.A.R.; Ferreira, N.R. Simulated annealing and tabu search applied on network reconfiguration in distribution systems. In Proceedings of the 2018 Simposio Brasileiro de Sistemas Eletricos (SBSE). IEEE, 2018, pp. 1–6.
11. Bagheri, A.; Bagheri, M.; Lorestani, A. Optimal reconfiguration and DG integration in distribution networks considering switching actions costs using tabu search algorithm. *Journal of Ambient Intelligence and Humanized Computing* **2020**, pp. 1–20.
12. Sayed, M.M.; Mahdy, M.Y.; Abdel Aleem, S.H.; Youssef, H.K.; Boghdady, T.A. Simultaneous Distribution Network Reconfiguration and Optimal Allocation of Renewable-Based Distributed Generators and Shunt Capacitors under Uncertain Conditions. *Energies* **2022**, *15*, 2299.
13. Lavorato, M.; Franco, J.F.; Rider, M.J.; Romero, R. Imposing radiality constraints in distribution system optimization problems. *IEEE Transactions on Power Systems* **2011**, *27*, 172–180.
14. Lalla-Ruiz, E.; Melián-Batista, B.; Moreno-Vega, J.M. Artificial intelligence hybrid heuristic based on tabu search for the dynamic berth allocation problem. *Engineering Applications of Artificial Intelligence* **2012**, *25*, 1132–1141.
15. Guimaraes, M.A.; Lorenzetti, J.F.; Castro, C.A. Reconfiguration of distribution systems for stability margin enhancement using tabu search. In Proceedings of the 2004 International Conference on Power System Technology, 2004. PowerCon 2004. IEEE, 2004, Vol. 2, pp. 1556–1561.
16. Pan, N.H.; Hsaio, P.W.; Chen, K.Y. A study of project scheduling optimization using Tabu Search algorithm. *Engineering Applications of Artificial Intelligence* **2008**, *21*, 1101–1112.
17. Al-Sultan, K.S. A tabu search approach to the clustering problem. *Pattern recognition* **1995**, *28*, 1443–1451.
18. Alexander, C.K.; Sadiku, M.N.; Sadiku, M. *Fundamentals of electric circuits*; McGraw-Hill Higher Education Boston, 2007; pp. 34–39.
19. Freitas, P.R.R.d. Impacto de funções inteligentes de inversores de sistemas fotovoltaicos na operação de redes de distribuição de energia elétrica. PhD thesis, Universidade de São Paulo, 2020.
20. Shirmohammadi, D.; Hong, H.W. Reconfiguration of electric distribution networks for resistive line losses reduction. *IEEE Transactions on Power Delivery* **1989**, *4*, 1492–1498.
21. Chiang, H.D.; Jean-Jumeau, R. Optimal network reconfigurations in distribution systems. II. Solution algorithms and numerical results. *IEEE transactions on Power delivery* **1990**, *5*, 1568–1574.
22. Goswami, S.K.; Basu, S.K. A new algorithm for the reconfiguration of distribution feeders for loss minimization. *IEEE Transactions on Power Delivery* **1992**, *7*, 1484–1491.
23. Baran, M.; Wu, F. Network reconfiguration in distribution systems for loss reduction and load balancing. *IEEE Transactions on Power Delivery* **1989**, *4*, 1401–1407. <https://doi.org/10.1109/61.25627>.
24. Su, C.T.; Lee, C.S. Network reconfiguration of distribution systems using improved mixed-integer hybrid differential evolution. *IEEE Transactions on Power Delivery* **2003**, *18*, 1022–1027.
25. de Andrade, B.A.R.; Ferreira, N.R. Simulated annealing and tabu search applied on network reconfiguration in distribution systems. In Proceedings of the 2018 Simposio Brasileiro de Sistemas Eletricos (SBSE). IEEE, 2018, pp. 1–6.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.