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# OPTIMIZATION OF POWER SYSTEMS THROUGH AN ARTIFICIAL BEE COLONY ALGORITHM

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**ABSTRACT**

The integration of optimization methods in the different processes involved in an electric power system in the search for energetic efficiency has generated satisfying results in the reduction of energy consumption, technical losses, increasing security and system reliability. The purpose of this article is to implement the artificial bee colony optimization algorithm in a 15-node IEEE power system set at 13.2 kV, in order to find the possible values of the reactive compensation that optimize the system power flow. In first place, the results of the voltage profiles of a 15-node IEEE power distribution system are shown with the Newton Raphson method. Then, said system is optimized using an adapted version of the artificial bee colony algorithm which was developed in MATLAB. After the execution of the algorithm, it was concluded that the nodal voltage values have a significant increase in all 15 nodes of the system. This translates into a reduction of the losses in the interconnection lines of the nodes through the optimization of the power system. The application of the artificial bee colony algorithm offers an optimization alternative driven to reduce the energy losses in the power system.

**Keywords:** algorithm, optimization, power flow, power system.

## INTRODUCTION

The study of load flows and power systems are important to carry out the design, control and operation of power distribution and transmission systems [1]. The purpose of calculating the power flow is to determine the values of nodal voltages, and hence, determine the values of power generation and demand in the system nodes [2]. The traditional methods used to solve and calculate power flows are Newton-Raphson (NR) and Gauss-Siedel [3]. However, these methods have deficiencies in terms of the memory and computational resources required for the execution of the algorithm.

The current technological development and specifically the improvement in the processing speeds of computing equipment has facilitated the blooming progress of the research and creation of numerical methods and optimization algorithms, where it is required to perform a large number of calculations in the least time possible.

In this article, an implementation of the optimization algorithm based on the natural behavior of bees (artificial bee colony algorithm or ABC for short) is studied in a power system. The importance of this type of study lies in the large size of some power distribution systems and the need to search for alternatives that give more stability and profitability.

The ABC algorithm is based on the processes of search and exploitation of food sources that a bee colony carries out. The bees organize themselves in different groups where each one has a specific function and their goal is to find the best source of food (possible solution). Candidate food sources are selected considering their aptitude or quality, and, if possible, better food sources are found as the cycles or iterations of the algorithm increase. It is noteworthy to mention that, although food selection depends on their quality, the final decision is made based on the probability of each solution to be chosen [4] [5]. In [6], the ABC method is used with the purpose of optimizing different types of functions over discrete and continuous domains and their analysis with other optimization methods based on swarm intelligence. In [7], the solution to the problem of transmission expansion is presented for electric power systems (EPS) using the DC model. In [8], the ABC algorithm is used to design a PID controller for wind energy generators and control the frequency and power caused by changes in wind speed. In [9], the artificial bee colony strategy is used to measure the wind speeds to determine the maximum operation point in power generation. In [10], the six-phase design of an engine is optimized with the ABC algorithm and it is compared with classic design methods. In [11], the ABC method is used to assign an optimal power distribution to improve voltage stability and cut losses in radial distribution systems.

In section II, the electric power system under study is described and the procedure for the application of the ABC algorithm is stated in detail. The starting point is the initial result of the obtained power flow with the Newton Raphson method. In section III, the obtained results are assessed with a comparison of the power flow before and after applying the optimization algorithm. Finally, section IV discusses the results and section V presents a set of conclusions.

## METHODOLOGY

### Description of the power system to be optimized

The starting point to determine the data required to solve a power flow problem is the one-line diagram of the power system. The input data is comprised of node information, transmission lines, transformers and generators.

The values in the transmission lines, from transformers and generators are used to build the bar admittance matrix of the power system. To determine this matrix, the equivalent circuit of the power system must be

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simplified, so that a single admittance remains between two nodes, and also admittance between each node and the ground.

The single-line diagram used in this exercise is taken from regulation IEEE 15-bus radial distribution system, which represents a general use power system in rural distribution networks of medium voltage in Colombia. This power system is comprised of 15 nodes, where three of them are generator nodes.

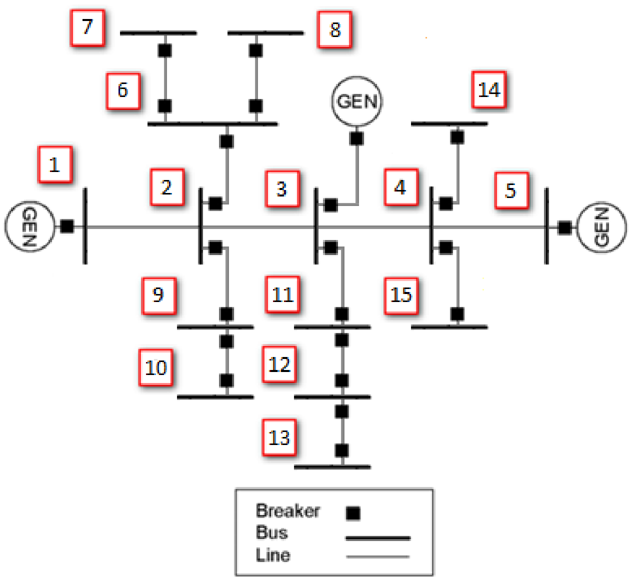


**Figure-1.** Node transmission system[12].

Figure-1 presents the single-line diagram of power system to be optimized. The nodes of the power system are the points in which two or more electric elements are interconnected [13] keeping the same level of voltage. In Table-1, the types of nodes of the power system are defined.

**Table-1.** Definition of the nodes of the distribution system.

| NODE | TYPEOF NODE |
|---|---|
| **1** | SLACK |
| 2 | PQ |
| 3 | PV |
| 4 | PQ |
| 5 | PV |
| 6 | PQ |
| 7 | PQ |
| 8 | PQ |
| 9 | PQ |
| 10 | PQ |
| 11 | PQ |
| 12 | PQ |
| 13 | PQ |
| 14 | PQ |
| 15 | PQ |

The load nodes or PQ nodes are those which have specified active and reactive powers, while the magnitude of the voltage and its angle are unknown.

The stable voltage nodes or PV nodes are the nodes in which the devices capable of controlling voltage magnitude are located. They generate or absorb reactive power through synchronous generators. In this case, the voltage magnitude in the bar and the net active power are specified while the net reactive power and the voltage angle are not specified.

In the compensation nodes or SLACK nodes, the known variables are the voltage magnitude in the bar and its angle, which is used as a reference for the angle in the other bars. Usually, the angle is set at 0°.

The distribution lines are the elements in charge of interconnecting nodes and carrying the energy from the generation points up to the load connection points for their end use. The distribution lines in middle voltage are generally comprised of ACSR (Aluminum Conductors Steel Reinforced) conductors which are bare conductors with a steel core designed for 13.2 kV voltage level. The Quail conductor meets the required characteristics for energy distribution and is used for simulation [14]. Table-2 shows the electric parameters of the conductor.

**Table-2.** Characteristics of the conductor.

| Conductor | AWG Caliber | DMG | RMG | AC Resistance to 75°C |
|---|---|---|---|---|
| Quail | 2/0 | 11.35 | 3.65 | 0.584 |

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The structure that supports the distribution network is the LA204 regulation from the public service company Codensa. Figure-2 shows the common usage structure in rural distribution networks used as a base to perform modelling calculations of the lines.

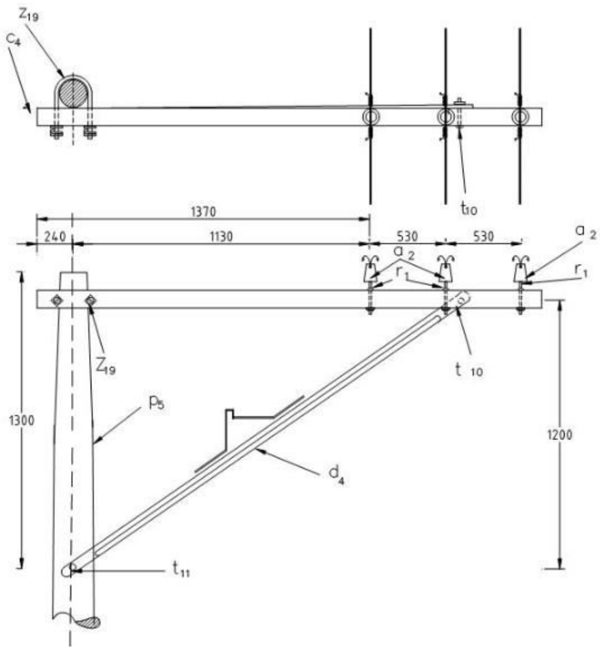


**Figure-2.** Circuit structure of the LA 204 regulation [15].

The data in Table-2 and Figure-2 show the calculation of impedances for the distribution line. Figure-3 presents the module developed to determine the results for the modelled line.

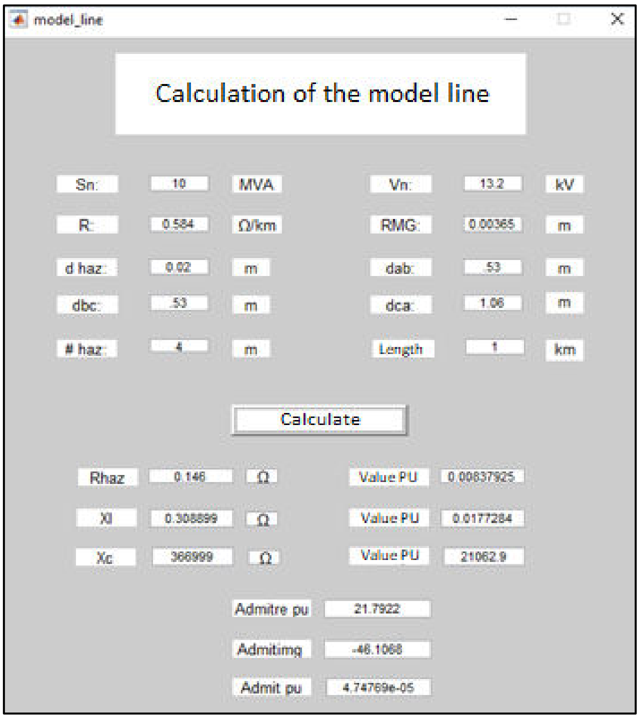


**Figure-3.** Model line.

Table-3 shows the length and impedances of the lines that interconnect the nodes.

**Table-3.** Distance between nodes and line impedances.

| N. I. | N. F. | Length (km) | R (km) | L (k) | C (km) |
|---|---|---|---|---|---|
| 1 | 2 | 10 | 0,083792 | 0,177283 | 0,000474 |
| 2 | 3 | 15 | 0,125688 | 0,265925 | 0,000712 |
| 2 | 6 | 6 | 0,050275 | 0,106370 | 0,000284 |
| 2 | 9 | 5 | 0,041896 | 0,088641 | 0,000237 |
| 3 | 4 | 8 | 0,067033 | 0,141826 | 0,000379 |
| 3 | 11 | 13 | 0,108930 | 0,230468 | 0,000617 |
| 4 | 5 | 7 | 0,058654 | 0,124098 | 0,000332 |
| 4 | 14 | 5 | 0,041896 | 0,088641 | 0,000237 |
| 4 | 15 | 7 | 0,058654 | 0,124098 | 0,000332 |
| 6 | 7 | 2 | 0,016758 | 0,035456 | 0,000094 |
| 6 | 8 | 3 | 0,025137 | 0,053185 | 0,000142 |
| 9 | 10 | 4 | 0,033516 | 0,070913 | 0,000189 |
| 11 | 12 | 4 | 0,033516 | 0,070913 | 0,000189 |
| 12 | 13 | 4 | 0,033516 | 0,070913 | 0,000189 |

The loads are the elements of the system that consume energy for purposed end use. All the loads that are connected to the PQ nodes are modelled in the same manner. For this power system, the loads are defined with a delayed power factor of 0.6. The consumed active and reactive powers per unit (p.u.) are defined in Table-4.

**Table-4.** Load powers in the PQ nodes.

| Active Power (P) | Reactive Power (Q) | Power Factor |
|---|---|---|
| 0.1 | 0.13 | 0.61 |

Traditional methods are used to solve the flow of power systems and determine the values of nodal voltages that comprise them. As the sum of the nodal voltages grows higher, the energy losses are reduced in the power system. Equation (1) represents the sum of nodal voltages in the system.

$$y = \sum_{i=1}^{i=n} V_i \tag{1}$$

Where $V$ represents the voltage value in each node of the system and $n$ is the number of the nodes of the power system.

The purpose of implementing the ABC method is to maximize the sum of nodal voltages of the entire power system and thereby reduce the system losses.

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**Construction of the algorithm**

The Artificial Bee Colony (ABC) algorithm is based on the natural process of bees searching for food, where there are specific tasks for each individual according to their location in the hierarchic structure [16]. It can be seen as an optimization process in which four elements intervene:

**Food sources:** They represent the possible solutions within the algorithm to which can be attributed a numerical value according to their viability.

**Worker bees:** They are a group of bees that exploit food sources and inform the scout bees of the potential of said sources. The natural method used to inform is a dance, which lasts longer when the source has more probability to be chosen by a scout bee [4].

**Scout bees:** They remain in the hive until they receive a notification to visit a detected food source.

**Foraging bees:** They seek new food sources.

In general, the number of worker bees is equal to the number of candidate solutions, i.e., each possible solution involves a single worker bee. The number of scout bees is equal to the number of worker bees.

The purpose of the algorithm is to find the best food sources with a growing number of iterations. When the worker bees are located in their food source, they find a new source nearby and remain in the source with the most aptitude [17]. When a candidate solution does not improve by increasing the number of attempts, it is discarded and replaced by a new random solution found by the scout bee. [18-20].

The ABC algorithm was adapted to study a possible optimization form of a power system. In this case, the food sources (possible solutions) are the reactive power values used to control the PQ-type nodal voltage values (injected net power).

The initial parameters of the algorithm are the following:

- **SN:** Number of food sources (or population).
- **D:** Number of variables of the problem (in this case this value is always 1).
- **L:** Limit of the number of attempts in which a solution is maintained with no improvement before being replaced with a new solution coming from a foraging bee. This parameter can be calculated with the formula L = SN×D.

Figure-4 shows the diagram of the implemented algorithm and then explained in detail.

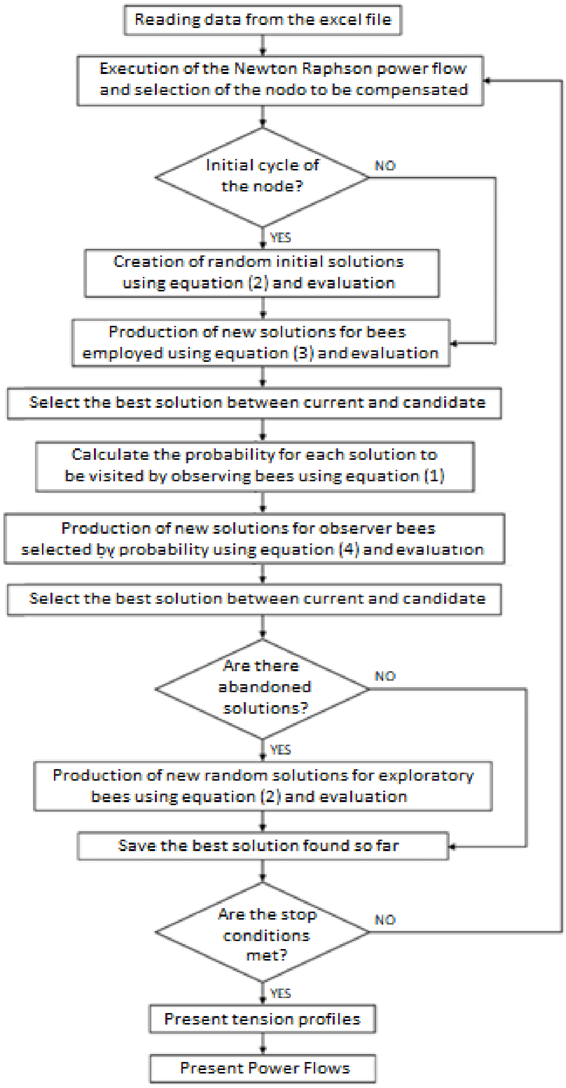


**Figure-4.** Flow diagram of the ABC algorithm applied to a power system.

**Execution of the power flow through Newton-Raphson and selection of the node to be compensated**

After executing the first power flow with the Newton Raphson method, a PQ type node is chosen (injected net power) that has a load. The selection is based on giving a probability value to each node depending on its voltage. For each node, a fitness value *fit* is determined based on its voltage magnitude $V_i$ as seen in Equation (2).

$$\mathrm{fit} = \frac{1}{1 + \mathrm{Vi}} \qquad (2)$$

It can be stated that the nodes with lower magnitudes have a higher fitness value and vice versa. Then, Equation (3) is used to assign a probability value to each node that determines in which one is carried out the compensation.

$$\mathrm{P_i} = \frac{\mathrm{fit_i}}{\sum_{n=1}^{SN} \mathrm{fit_n}} \qquad (3)$$

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**Creation and assessment of initial solutions**

When the node to be compensated is chosen, random initial solutions (reactive power values) are generated by using Equation (4):

$$Q_i = Q_{min} + rand(0, FC * Q_{max}) * (Q_{max} - Q_{min}) \quad (4)$$

The possible solutions are assessed so that each value of $Q_i$ corresponds to a value of voltage $V_i$. The convergence factor FC determines how fast a system can converge as it grows higher, while reducing the accuracy of the algorithm. The resulting reactive powers can become considerably lower than the maximum reactive power. It is recommended that this factor is set between 1.5 and 3.5.

**Generation and assessment of new solutions coming from worker bees**

Among these possible initial solutions, the first worker bees are located to calculate new candidate solutions $v_{i,g}$ with Equation (5):

$$v_{i,g} = x_{i,g} + \emptyset(x_{i,g} - x_{k,g}) \quad (5)$$

Where:

- The subscript $i$ represents the position of the possible solution (food source)
- The subscript $g$ represents the current cycle.
- The subscript $k$ is a random number between 1 and SN.
- $x_{i,g}$ represents the food source where the worker bee is located at that moment.
- $x_{k,g}$ represents a randomly chosen food source and diferent from $x_{i,g}$.
- $\emptyset$ is a real number between -1 and 1.

The objective is to choose the best solution between the new candidate and the previous candidate, so that the solution with the highest nodal voltage is chosen.

**Calculation of the probability that each solution is visited by scout bees**

In a selection process similar to the one performed for the compensation node, a fitness value is chosen for each possible solution depending on its reactive power value $Qi$. This fitness value is computed with Equation (6). The solutions with higher values have a higher fitness value and vice versa.

$$fit = \frac{1}{1 + \mathrm{Qi}} \quad (6)$$

Equation (7) is used to assign a probability value to each solution which determines which ones will be visited by the scout bees [5]:

$$P_i = \frac{fit_i}{\sum_{n=1}^{SN} fit_n} \quad (7)$$

**Generation and assessment of new solutions for scout bees**

When the solution visited by the scout bees is chosen, new candidate solutions $v_{i,g}$ are computed similarly to the process for worker bees with Equation (8):

$$v_{i,g} = x_{i,g} + \emptyset(x_{i,g} - x_{k,g}) \quad (8)$$

Where:

- The subscript $i$ represents the position of the possible solution to be visited by a scout bee.
- The subscript $g$ represents the current cycle.
- The subscript $k$ is a random number between 1 and SN.
- $x_{i,g}$ represents the food source where the scout bee is located at that moment.
- $x_{k,g}$ represents a randomly chosen food source different from $x_{i,g}$.
- $\emptyset$ is a real number between -1 and 1.

The objective is to choose the best solution between the new candidate and the previous candidate, so that the solution with the highest nodal voltage is chosen.

**Discarded solutions**

When a solution shows no improvement after a specific number of cycles (set by limit *L*), said solution is discarded and a new randomly chosen solution is created by a foraging bee with Equation (9):

$$Q_i = Q_{min} + rand(0, FC * Q_{max}) * (Q_{max} - Q_{min}) \quad (9)$$

Following the previous procedure, all the nodes to be compensated are travelled during various cycles until the stop condition is fulfilled. This condition can be set as a target voltage value or a constraint in the injected reactive power.

## RESULTS

In this section, the values of nodal voltages are presented after the execution of the first power flow with the Newton-Raphson and ABC methods. Afterwards, the error is computed for the ABC algorithm using the Newton-Raphson data as a base. The results are discussed in the end.

**Execution of the Newton Raphson method**

With the purpose of comparing the execution of the ABC algorithm, the power flow is computed with the Newton Raphson method, serving as a base for comparison. The voltage profiles obtained with the Newton Raphson simulation are presented in Table-5 where it is detected that nodes 1, 6, 7, 8, 9, 10, 11, 12, 13, 14 and 15 are under the 95% threshold.

The ABC algorithm was programmed so that the execution results of the Newton Raphson method serve as input parameters. Hence, this defines the nodes in which the optimization is performed. Each PQ node is chosen based on its fitness and probability with the previously stated strategy. The reactive power is determined for each node which sets an increase in the voltage magnitude due to compensation.

**Table-5.** Nodal voltages with the Newton Raphson method.

| Node | Voltage magnitude [p.u.] | Voltage angle [°] |
|---|---|---|
| 1 | 1,000 | 0,000 |
| 2 | 0,851 | -6,900 |
| 3 | 1,000 | -13,075 |
| 4 | 0,963 | -13,186 |
| 5 | 1,000 | -12,423 |
| 6 | 0,777 | -7,968 |
| 7 | 0,769 | -8,100 |
| 8 | 0,765 | -8,166 |
| 9 | 0,811 | -7,469 |
| 10 | 0,796 | -7,712 |
| 11 | 0,851 | -14,878 |
| 12 | 0,820 | -15,328 |
| 13 | 0,804 | -15,565 |
| 14 | 0,946 | -13,402 |
| 15 | 0,940 | -13,490 |

After travelling all nodes, a new itinerary is started to find better reactive power values until the stop condition is fulfilled.

**Execution of the ABC algorithm**

In Table-7, the results are shown after 26 iterations of the algorithm. The voltage levels are increased in nodes 2, 4, 6, 7, 8, 9, 10, 11, 12, 13, 14 and 15.

Nodal voltage values increase since each iteration involves a compensation in the reactive power of each node. Table-6 exhibits the corrections of $Q$ generated in the nodes after 26 iterations of the algorithm.

**Table-6.** Reactive compensation of the nodes.

| Bus_i | Type of node | PWg | PQg | PWd | PQd |
|---|---|---|---|---|---|
| 1 | 1 | 0,600 | 0,000 | 0,000 | 0,000 |
| 2 | 3 | 0,000 | 0,083 | 0,100 | 0,130 |
| 3 | 2 | 0,400 | 0,000 | 0,000 | 0,000 |
| 4 | 3 | 0,000 | 0,079 | 0,100 | 0,130 |
| 5 | 2 | 0,200 | 0,000 | 0,000 | 0,000 |
| 6 | 3 | 0,000 | 0,076 | 0,100 | 0,130 |
| 7 | 3 | 0,000 | 0,092 | 0,100 | 0,130 |
| 8 | 3 | 0,000 | 0,102 | 0,100 | 0,130 |
| 9 | 3 | 0,000 | 0,117 | 0,100 | 0,130 |
| 10 | 3 | 0,000 | 0,087 | 0,100 | 0,130 |
| 11 | 3 | 0,000 | 0,093 | 0,100 | 0,130 |
| 12 | 3 | 0,000 | 0,052 | 0,100 | 0,130 |
| 13 | 3 | 0,000 | 0,112 | 0,100 | 0,130 |
| 14 | 3 | 0,000 | 0,116 | 0,100 | 0,130 |
| 15 | 3 | 0,000 | 0,094 | 0,100 | 0,130 |

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**Table-7.** Correction of the nodal voltages for the ABC algorithm.

| V1 | V2 | V3 | V4 | V5 | V6 | V7 | V8 | V9 | V10 | V11 | V12 | V13 | V14 | V15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1,000 | 0,851 | 1,000 | 0,963 | 1,000 | 0,777 | 0,769 | 0,765 | 0,811 | 0,796 | 0,851 | 0,820 | 0,804 | 0,946 | 0,940 |
| 1,000 | 0,851 | 1,000 | 0,970 | 1,000 | 0,777 | 0,769 | 0,765 | 0,812 | 0,796 | 0,851 | 0,820 | 0,804 | 0,953 | 0,959 |
| 1,000 | 0,861 | 1,000 | 0,970 | 1,000 | 0,789 | 0,781 | 0,777 | 0,823 | 0,807 | 0,851 | 0,820 | 0,804 | 0,953 | 0,959 |
| 1,000 | 0,861 | 1,000 | 0,975 | 1,000 | 0,789 | 0,781 | 0,777 | 0,823 | 0,807 | 0,851 | 0,820 | 0,804 | 0,959 | 0,965 |
| 1,000 | 0,875 | 1,000 | 0,975 | 1,000 | 0,815 | 0,807 | 0,803 | 0,837 | 0,822 | 0,851 | 0,820 | 0,804 | 0,959 | 0,965 |
| 1,000 | 0,887 | 1,000 | 0,975 | 1,000 | 0,838 | 0,834 | 0,827 | 0,850 | 0,835 | 0,851 | 0,820 | 0,804 | 0,959 | 0,965 |
| 1,000 | 0,902 | 1,000 | 0,975 | 1,000 | 0,868 | 0,864 | 0,863 | 0,866 | 0,851 | 0,851 | 0,820 | 0,804 | 0,959 | 0,965 |
| 1,000 | 0,918 | 1,000 | 0,975 | 1,000 | 0,884 | 0,879 | 0,879 | 0,893 | 0,879 | 0,851 | 0,820 | 0,804 | 0,959 | 0,965 |
| 1,000 | 0,927 | 1,000 | 0,975 | 1,000 | 0,894 | 0,889 | 0,889 | 0,910 | 0,902 | 0,851 | 0,820 | 0,804 | 0,959 | 0,965 |
| 1,000 | 0,927 | 1,000 | 0,975 | 1,000 | 0,894 | 0,890 | 0,889 | 0,910 | 0,902 | 0,870 | 0,839 | 0,824 | 0,959 | 0,965 |
| 1,000 | 0,928 | 1,000 | 0,975 | 1,000 | 0,894 | 0,890 | 0,890 | 0,911 | 0,902 | 0,905 | 0,885 | 0,880 | 0,959 | 0,965 |
| 1,000 | 0,928 | 1,000 | 0,975 | 1,000 | 0,894 | 0,890 | 0,890 | 0,911 | 0,903 | 0,920 | 0,904 | 0,899 | 0,959 | 0,965 |
| 1,000 | 0,928 | 1,000 | 0,982 | 1,000 | 0,894 | 0,890 | 0,890 | 0,911 | 0,903 | 0,920 | 0,904 | 0,899 | 0,974 | 0,971 |
| 1,000 | 0,928 | 1,000 | 0,982 | 1,000 | 0,894 | 0,890 | 0,890 | 0,911 | 0,903 | 0,920 | 0,904 | 0,899 | 0,974 | 0,971 |
| 1,000 | 0,928 | 1,000 | 0,982 | 1,000 | 0,894 | 0,890 | 0,890 | 0,911 | 0,903 | 0,920 | 0,904 | 0,899 | 0,974 | 0,971 |
| 1,000 | 0,928 | 1,000 | 0,982 | 1,000 | 0,894 | 0,890 | 0,890 | 0,911 | 0,903 | 0,920 | 0,904 | 0,899 | 0,974 | 0,971 |
| 1,000 | 0,928 | 1,000 | 0,982 | 1,000 | 0,894 | 0,890 | 0,890 | 0,911 | 0,903 | 0,920 | 0,904 | 0,899 | 0,974 | 0,971 |
| 1,000 | 0,930 | 1,000 | 0,982 | 1,000 | 0,896 | 0,892 | 0,892 | 0,913 | 0,905 | 0,920 | 0,904 | 0,899 | 0,974 | 0,971 |
| 1,000 | 0,930 | 1,000 | 0,982 | 1,000 | 0,896 | 0,892 | 0,892 | 0,913 | 0,905 | 0,929 | 0,914 | 0,909 | 0,974 | 0,971 |
| 1,000 | 0,932 | 1,000 | 0,982 | 1,000 | 0,898 | 0,894 | 0,894 | 0,916 | 0,909 | 0,929 | 0,914 | 0,909 | 0,974 | 0,971 |
| 1,000 | 0,934 | 1,000 | 0,982 | 1,000 | 0,903 | 0,899 | 0,898 | 0,918 | 0,911 | 0,929 | 0,914 | 0,909 | 0,974 | 0,971 |
| 1,000 | 0,935 | 1,000 | 0,982 | 1,000 | 0,904 | 0,900 | 0,899 | 0,920 | 0,913 | 0,929 | 0,914 | 0,909 | 0,974 | 0,971 |
| 1,000 | 0,935 | 1,000 | 0,982 | 1,000 | 0,904 | 0,900 | 0,899 | 0,920 | 0,913 | 0,929 | 0,914 | 0,909 | 0,974 | 0,971 |
| 1,000 | 0,935 | 1,000 | 0,982 | 1,000 | 0,904 | 0,900 | 0,899 | 0,920 | 0,913 | 0,929 | 0,914 | 0,909 | 0,975 | 0,971 |
| 1,000 | 0,935 | 1,000 | 0,982 | 1,000 | 0,904 | 0,900 | 0,899 | 0,920 | 0,913 | 0,929 | 0,914 | 0,909 | 0,975 | 0,971 |
| 1,000 | 0,935 | 1,000 | 0,983 | 1,000 | 0,904 | 0,900 | 0,899 | 0,920 | 0,913 | 0,929 | 0,914 | 0,909 | 0,978 | 0,973 |
| 1,000 | 0,935 | 1,000 | 0,983 | 1,000 | 0,904 | 0,900 | 0,899 | 0,920 | 0,913 | 0,929 | 0,914 | 0,909 | 0,978 | 0,973 |

## COMPARISON OF THE RESULTS

To determine which algorithm offers the best optimization, the obtained voltage magnitudes are shown in Table-8. There is an increase in the voltage in each node thanks to the implementation of the ABC algorithm compared to the original power flow with Newton Raphson.

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**Table-8.** Nodal voltages with Newton Raphson and ABC.

| Node | Voltage magnitude [PU]Newton Raphson | Voltage magnitude [PU] ABC algorithm |
|---|---|---|
| 1 | 1,000 | 1,000 |
| 2 | 0,851 | 0,935 |
| 3 | 1,000 | 1,000 |
| 4 | 0,963 | 0,983 |
| 5 | 1,000 | 1,000 |
| 6 | 0,777 | 0,904 |
| 7 | 0,769 | 0,900 |
| 8 | 0,765 | 0,899 |
| 9 | 0,811 | 0,920 |
| 10 | 0,796 | 0,913 |
| 11 | 0,851 | 0,929 |
| 12 | 0,820 | 0,914 |
| 13 | 0,804 | 0,909 |
| 14 | 0,946 | 0,978 |
| 15 | 0,940 | 0,973 |
| Total | 13,093 | 14,157 |

Furthermore, the sum of nodal voltages given by Equation (1) is 8.13% higher with ABC than with Newton Raphson.

Table-9 shows the percentage error after the execution of ABC algorithm, where significant increases of up to 17.573% can be seen in some nodal voltages.

**Table-9.** Percentage error after the optimization of the ABC algorithm.

| Node | Percentage error ABC [%] |
|---|---|
| 1 | 0,000 |
| 2 | 9,915 |
| 3 | 0,000 |
| 4 | 2,123 |
| 5 | 0,000 |
| 6 | 16,282 |
| 7 | 17,081 |
| 8 | 17,573 |
| 9 | 13,394 |
| 10 | 14,759 |
| 11 | 9,161 |
| 12 | 11,466 |
| 13 | 12,992 |
| 14 | 3,327 |
| 15 | 3,535 |

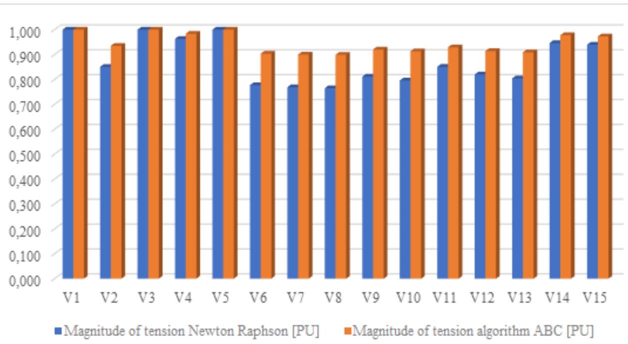


**Figure-5.** Nodal voltages with Newton Raphson and ABC algorithm.

Figure-5 establishes a relation between the power flow before and after the optimization with the ABC algorithm. The bars colored in blue correspond to the first power flow obtained with the Newton Raphson algorithm and the bars colored in orange correspond to the power flow obtained with the ABC algorithm. An improvement can be clearly appreciated in the nodal voltages.

**Execution times of the algorithms**

In Table-10, the execution times for each algorithm are shown. The ABC algorithm is executed in 137.8487 seconds, while the first power flow with the Newton Raphson method takes 6.5115 seconds.

**Table-10.** Execution times of the algorithms.

| Execution time (s) Newton Raphson | Execution time (s) ABC algorithm |
|---|---|
| 6.5115 | 137.8487 |

**Number of iterations of the algorithms**

Table-11 shows the number of iterations required for the program to converge. The ABC algorithm converges after 26 iterations while the first power flow with the Newton Raphson method converges after 5 iterations.

**Table-11.** Number of iterations of the algorithms.

| Number of iterations Newton Raphson | Number of iterations ABC Algorithm |
|---|---|
| 5 | 26 |

## ANALYSIS OF THE RESULTS

The starting point to perform the analysis is the first result of the power flow obtained with the Newton Raphson method, where very low nodal voltages were obtained. The minimum voltage was obtained in node 8 with a value of 0.765 p.u. After applying the ABC algorithm, a significant increase was detected for all nodal voltages, with a maximum increase of 17.573% in the same node 8. The resulting voltage was 0.9 p.u. (minimum voltage of the ABC algorithm).

In the same manner, the algorithm shows a higher voltage increase in the nodes with the lowest voltages and vice versa. A slighter increase in voltage is seen in the nodes that originally had lower voltage. In nodes 4, 14 and 15, the increase did not surpass 3.6% since their voltage values were not much lower in the first power flow. Said nodes had voltages of 0.963 p.u., 0.946 p.u. and 0.940 p.u. respectively.

Furthermore, the algorithm was effective since it did not surpass the reactive power value of the load, which is a stop condition per se. However, the algorithm requires considerable computational resources as expected and, therefore, needs a higher execution time. This is explained by the fact that it must execute various power flows to choose the best solution among randomly defined solutions.

## CONCLUSIONS

The ABC algorithm applied to power systems, offers as a result a considerable improvement in the nodal voltages. Said improvement is more notorious in the nodes with the initial lowest voltages. This is reflected in the reduction of the electric potential difference between the lines which translates into a considerable reduction of the system losses.

Although the optimization offered by the ABC algorithm is superior than the one offered by the Newton Raphson method, the computational resources and execution times required for convergence should be considered. It is possible to modify the original ABC algorithm to deliver better results with lower execution times to be applied in different electric processes.

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