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Salp swarm algorithm for optimal load balancing in low voltage networks

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ABSTRACT

Distribution networks for low voltage (LV) are three-phase networks. It mostly serves single-phase end customers with a variety of load characteristics. Because each customer's load behavior differs, the current on the LV networks feeder is shared unequally, leading in an im-balance problem. This research investigates an efficient distribution of single-phase loads amongst three phase networks using the salp swarm algorithm (SSA) to phase swap consumers between phases. Customers are rearranged and their loads are switched from heavy to light to achieve phase shifting. Jordan's electricity distribution company (EDCO) has provided a full load feeder as a case study. The results of switching loads to a three-phase feeder show that the im-balance index and power losses can be decreased significantly.

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1. INTRODUCTION

Most of the low voltage (LV) networks are built with three phase, four wire radial networks connected to medium voltage feeders through three phase transformers. The majority of clients are serviced by a single-phase feeder. Each single-phase client has a different load profile than the others; the variance in load characteristics is assumed to be the root cause of the imbalanced situation. As a result, LV distribution networks have the highest losses when compared to other types of networks, such as medium or high voltage networks [1].

Due to the rapid growth of power demand in various sectors, the amount of current flowing through the network rapidly increases [2]. Upgrades to the existing network are critical to ensuring that energy is delivered to customers within acceptable limits and without outages. Jordan's energy and minerals regulatory commission (EMRC) establishes these limits. In an ideal world, three-phase balance is the primary objective for a power system's performance and the quality of delivered power [3]–[10].

Unbalanced behavior develops in three-phase LV networks as a result of uneven load distribution in each phase [10]–[16]. This issue has a detrimental effect on distribution networks. It increases the voltage drop between the feeders, resulting in an under-voltage condition at the feeder's end. Also, due to current flow in the neutral wire, it increases losses and raises the fraction of unbalanced voltage. Equipment life is shortened, resulting in a decrease in system efficiency. Finally, it results in a rise in in-vestment and operating expenses.

Unbalanced loads can occasionally restrict the quantity of electricity transmitted by the feeder. As a result of the imbalanced system, the current capability of the main feeder will be limited [16]– [20].

While unbalanced problems may be resolved by equitable load sharing on three phase networks, using the traditional way in Jordanian businesses requires time and effort with few returns [20]–[26]. To distribute loads evenly over the feeder, this paper proposes phase switching based on the salp swarm algorithm. The gathering of data on load behavior over time is critical for the load balancing process [3]–[6]. Neutral current generated by an imbalanced load is a danger; it presents safety issues and has the potential to start a fire. Additionally, it reduces the efficiency of the electrical power supply and may result in the failure of measuring equipment [3]. The radial distribution system examined in this paper is regarded the easiest network to configure from a configuration standpoint since it is easy to ride-through faults, has a cheap construction cost, and requires less security measures. However, it is fed by a single power supply, and in the event of an outage, there is no alternate source of power to serve the demand, as seen in Figure 1.

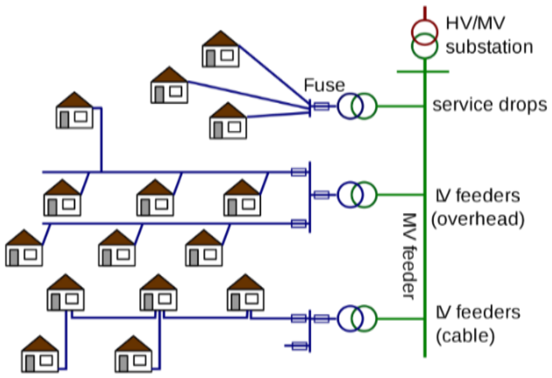

Figure 1. Radial LV network

2. UNBALANCED PROBLEM

Loads are spread equally over three phase networks under typical operating conditions. However, if the load is suddenly altered, there is a greater chance that feeders may be overloaded, leading to an unbalanced issue. Unbalance of the load is defined as a difference in the voltage or current's amplitude or phase angle. Non-linear loads over time that alter the drawn current per phase are the cause of this problem [1], [7].

Unbalanced loads can occur for a variety of causes, including single-phase overload, manual phase switching, insufficient single-phase load distribution, unbalanced three-phase loads, and asymmetrical transmission impedance. Accordingly, load unbalancing results in higher loss, current unbalance, and voltage issues in low voltage feeders [6]. Technical losses and non-technical losses are the two types of losses in low voltage networks. Energy loss is defined as the difference between the energy that was purchased and the energy that was sold. alternatively, the total of all losses, technological and otherwise. The low voltage distribution feeder's overall losses can be expressed as shown in (1) [7]:

$$P_{loss} = \sum_{i=1}^{n} r_i \frac{P_i^2 + Q_i^2}{|V_i|^2} \tag{1}$$

Where: n is the overall number of current bathes i, r_i is the feeder resistance, P_i is the active power, Q_i is the reactive power, and additionally, the voltage unbalance percentage equation developed by NEMA is used to derive the current unbalance percentage by simply substituting current for voltage as shown in (2) [8].

$$Unbalance\% = \frac{max.voltage - avg.voltage}{avg.Voltage}\% \tag{2}$$

In contrast, the average voltage is determined by taking one-third of the total voltage of all phases. Additionally, the maximum deviation is defined as the difference between the peak phase voltage and the average voltage value. The unbalanced occurrence has a negative impact on the power system, which lowers system stability and security [1], [9]. Increased feeder losses are one of the disadvantages. Increased voltage drops results in a higher percentage of unbalanced voltage. reducing the equipment's life span on the network. decrease in system performance and an increase in the features of imbalanced neutral current.

3. LOAD BALANCING

Keeping the load approximately equal between the three phase low voltage networks during the operating time is called load balancing [10]. The load balance analysis determines the best load distributing over different phases by swapping methods in order to minimize the losses across the feeder or to balance both current and load voltage. The best and most effective method for balancing low voltage networks is phase swapping. It reduces the unbalance index as a result. To maintain system security and lessen system load, phase swapping must include a limit on the number of times it can be performed. This study uses the salp swarm algorithm (SSA) to distribute heavy single-phase loads to light loads networks through selector switches connected at the customer, as illustrated in Figure 2, in order to achieve the best distribution for single-phase customers over three-phase feeder.

There are numerous devices connected for switching consumers between phases, and all of them have three separate inputs and a single-phase output, with essentially identical specs. The selector switch waits for the controller at the main sub-station to send a signal before deciding whether to do a swap or not in order to accomplish load balancing.

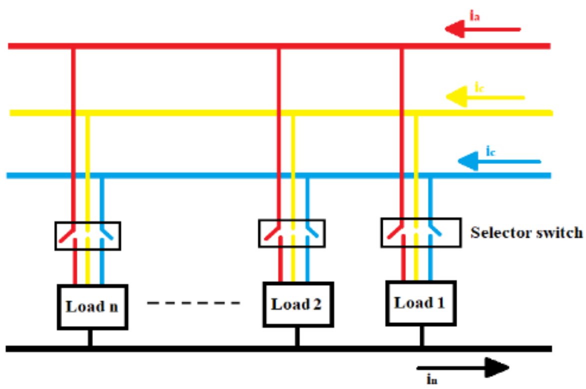

Figure 2. Phase swapping approach

4. PRESENTED SYSTEM

One radial feeder with the following specifications is chosen based on data from the electricity distribution company (EDCO): Aluminum with a cross sectional area of 95 mm^2, a length of 700 m, a rated transformer power of 250 kVA, and 19 consumers. The chosen feeder has been given the load balancing treatment based on SSA. Figure 3 illustrates the feeder that is being tested. Before balancing, the feeder serves 19 single-phase clients. As seen in Table 1, the consumers are spread among the three phases of the feeder.

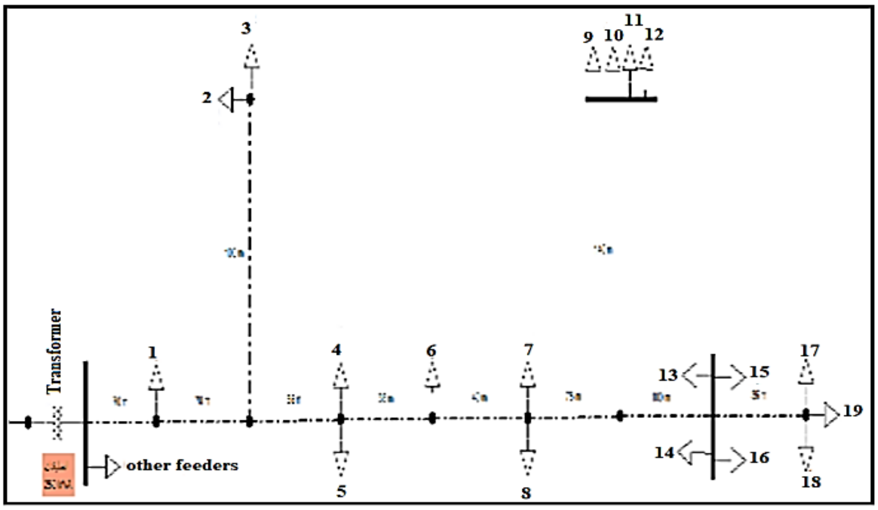

Figure 3. Tested feeder

Table 1. Studying the distribution of loads along the feeder

Phase	Customer Number (loads)
A	2, 3, 7, 10, 13, 15, 17, 18, 19
B	1, 4, 5, 9, 14
C	6, 8, 11, 12, 16

Smart meters record five measurements for the clients. Between June 27 and July 1, 2021, these meters are installed at each individual client within a five-day window. Figure 4 displays a summary of the measurements. Before load balancing, each measurement in Figure 4 was taken and recorded. The recorded data must then be contrasted with the recorded data following balancing. The following measurements are included in the comparison: i) The current at sending end of the feeder, ii) the neutral current, iii) unbalance voltage percentage, and iv) feeder losses.

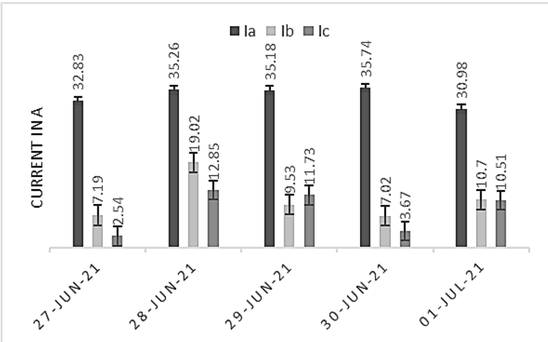

Figure 4. Total current among feeder

5. SLAP SWARM ALGORITHM

A unique optimization algorithm that relies on the salps swarming method is called the salp swarm algorithm (SSA) [14]. The behavior of salps, a type of marine creature, is imitated by SSA when maneuvering and foraging in the water. This algorithm was inspired by nature's common strategies, which include salps, which can prevent the optimum local, flexibility, simplicity, and behavior to find a workable solution to a problem in real life [15], [16].

Based on the slap swarm algorithm, it is expected that the load is distributed throughout the feeder in the best possible way to minimize current imbalance (neutral current), maintain it close to zero, balance voltage, balance current, and lower feeder losses. The voltage balance equation and the current balance equation are included in the multi-objective function, as shown in (3)-(5) [15].

$$obj\ fun\ 1 = \left(\frac{I_a}{I_m} - \frac{I_b}{I_m}\right)^2 + \left(\frac{I_c}{I_m} - \frac{I_b}{I_m}\right)^2 + \left(\frac{I_a}{I_m} - \frac{I_c}{I_m}\right)^2 \tag{3}$$

$$obj\ fun\ 2 = \left(\frac{V_a}{V_m} - \frac{V_b}{V_m}\right)^2 + \left(\frac{V_c}{V_m} - \frac{V_b}{V_m}\right)^2 + \left(\frac{V_a}{V_m} - \frac{V_c}{V_m}\right)^2 \tag{4}$$

$$obj\ fun = obj\ fun\ 1 + obj\ fun\ 2 \tag{5}$$

Where: $I_{a,}I_{b,}I_c$: Currents per phase a,b,c, I_m: Nominal/average value of current, $V_a, V_{b,}V_c$: Voltages per phase a,b,c and V_m: Maximum, normal or average value for secondary voltages of transformer.

When the negative value in the goal functions is removed using the square in (3)-(5), the outcome is zero without balancing. When utilizing the SSA algorithm to minimize the switch status numbers, some constraints must be taken into account. Making the least amount of loads switch is therefore advisable in order to lessen the feeder's present load and improve system security. The salps position in the n-dimensional search space, where n is the variable number for the problem, is accurately established, just like previous methods that rely on swarm-techniques. Then, a two-dimensional matrix called x is used to store the locations of all salps. The swarm's intended objective is also assumed to be a food source with the name *f* that is present in the search area. The following equation is suggested [14] as a means of updating the leader's position as (6).

$$x_d^1 = \begin{cases} f_d + c_1((ub_d - lb_d) \times c_2 + lb_d), c_3 \geq 0 \\ f_d - c_1((ub_d - lb_d) \times c_2 + lb_d), \ c_3 < 0 \end{cases} \tag{6}$$

Where x_d^1 defines the position of the food supply in the dth dimension, the upper bound of the dth dimension, and the lower bound of the dth dimension. fd is the position of the first salp (leader) in the dth dimension. In (6) suggests that the leader salps update their positions to follow the food source. Because it is the single parameter that controls the balance between exploration and exploitation and because it is time-varying, or dependent on the number of iterations, the coefficient C_1 is the most crucial parameter in the SSA. It is defined as shown in (7) [14]–[17].

$$c_1 = 2 \times e^{-\left(\frac{4t}{T}\right)^2} \tag{7}$$

Where T is the maximum iteration numbers and t is the current iteration.

The parameters C_2 and C_3 are evenly produced random values between 0 and 1. In reality, they specify the step size as well as whether the subsequent location in the dth-dimensional should go toward +∞ or -∞. The position of the followers is updated using as shown in (8) [14]–[17].

$$x_d^i = \frac{1}{2}(x_d^i - x_d^{i-1}) \tag{8}$$

Figure 5 provides a summary of the application of SSA for ideal voltage balance and current balance in the distribution system.

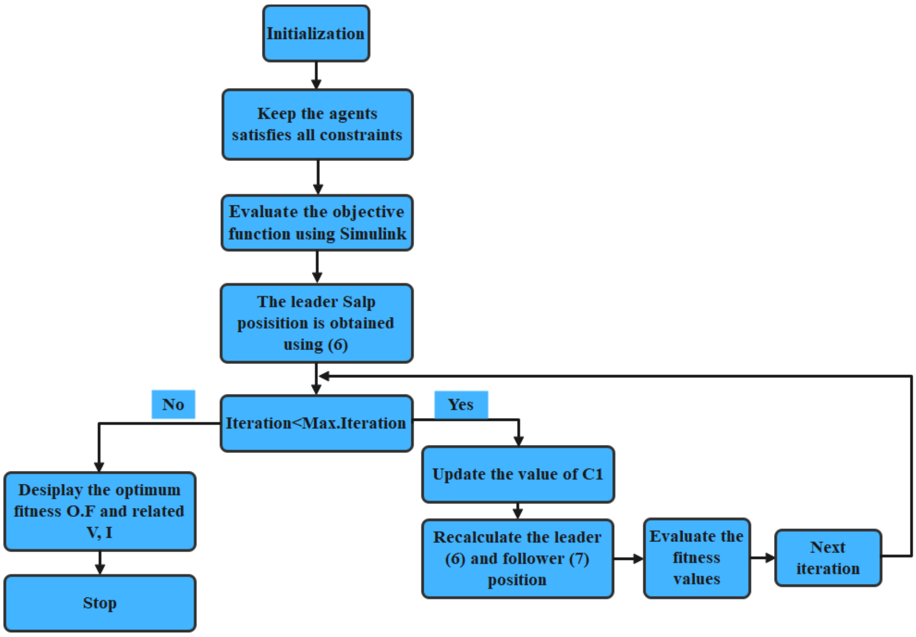

Figure 5. SSA utilized for best balance of voltage and current flow chart [13]

6. RESULTS AND DISCUSSION

The realization of SSA for the system being tested is established in this section. The SSA has used trial and error to run the algorithm up to 200 times to get the best load distribution. Implemented scenarios include; i) no load swapping and ii) the fewest possible load swaps. The following subsections include the experiment findings and comments.

6.1. Voltage magnitudes comparison

The energy and minerals regulatory commission (EMRC) regulates the magnitudes of the voltages prior to balancing. At the customer's end, a voltage imbalance could lead to home appliance failure. All voltage magnitudes fall within the two limitations after using SSA with the highest and lowest number of load swaps to obtain balanced loads. Figures 6 and 7 clearly display the three-phase voltage balance following SSA application. Figure 6 illustrates how the situation improves in three phase voltages compared to the first instance depicted in Figure 4 when only seven customers are switched between the phases. It is important to demonstrate how, when the customer's end voltages are lowering due to the voltage drop in the feeder.

The voltages have not altered in comparison to the prior example for maximum switching numbers to achieve balancing, as illustrated in Figure 7. Figures 6 and 7 are compared, and it is clear that there is no discernible difference in the values because, in both situations, all magnitudes after balancing are within acceptable bounds. It only takes a sample of seven consumers switching to bring the voltage magnitude within the acceptable range. As feeder end voltage magnitudes increase, the fraction of unbalanced voltage will decrease even further, as indicated in Table 2.

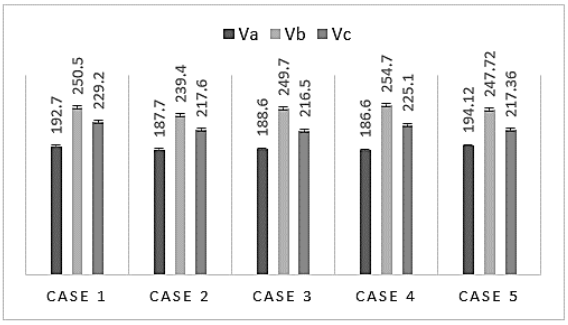

Figure 6. Voltage magnitudes for the last seven consumers that have switched

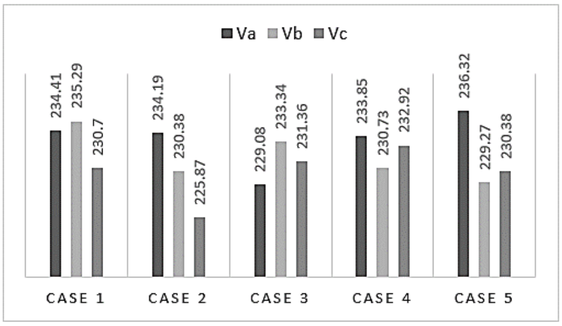

Figure 7. voltage levels following balancing for the greatest number of switches

Table 2. Percentage of unbalanced voltages

Unbalance %	Case 1	Case 2	Case 3	Case 4	Case 5
Before balancing	11.7%	11.4%	14.4%	14.6%	12.7%
After Balancing					
Min swapping	3%	2.73%	1.79%	2.12%	2.72%
Max swapping	0.78%	1.76%	0.9%	0.58%	1.87%

6.2. Currents magnitude comparison

Maintaining an equal current in each phase during the loading phase is referred to as a balanced state. Comparing the total currents in all phases in the two scenarios-before load balancing in Figure 4 and after in Figure 8 shows that SSA is capable of dispersing the current over the subject feeder, indicating that load balancing is almost complete. The currents after balancing for the greatest number of swapping are displayed in Figure 9 results. When it comes to the maximum and minimum number of customer swaps, it doesn't appear that there is much of a difference between phases. After balancing, current magnitudes in all phases are almost at the same peak regardless of the number of customers switching, which minimizes the neutral current flows into the neutral wire.

Table 3 makes it quite evident that the neutral current has decreased. Neutral current following balancing for the lowest swapping numbers can occasionally be preferable to balancing for the highest switching numbers. Therefore, achieving load balance may not always need using the maximum swapping numbers. To get a satisfactory outcome and lessen the strain on the distribution networks from voltage and current, it may be enough to exchange just the fewest number of end customers.

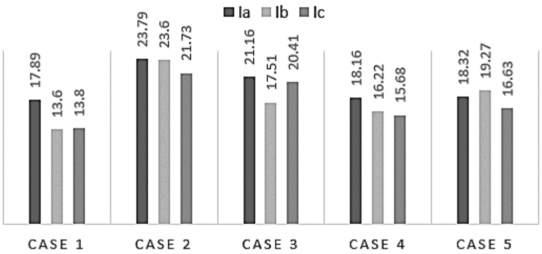

Figure 8. Currents magnitude for the past seven consumers who switched after balancing

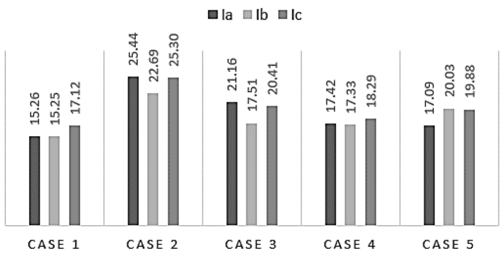

Figure 9. After balancing for up to seven consumers switching, current magnitude

Table 3. Comparison of neutral current

Neutral current	Case 1	Case 2	Case 3	Case 4	Case 5
Before balance	28.5	23.9	19.6	30	18.3
After Balancing					
min swapping	3.4	3.1	1.1	2.5	2.8
max swapping	2.5	1.4	4.2	1.4	2

6.3. Losses magnitude comparison

One of the most crucial indicators for the financial health of distribution companies is the amount of power lost in the system. Loss reduction is a challenging strategy. Loss minimization is achieved in this area through load balancing using the salp swarm algorithm (SSA). By achieving current balance among feeders, load balancing helps to reduce power losses, with the end result being total power losses as indicated in Table 4 with Figure 10. In two instances, the overall losses dropped, indicating that the present equilibrium was reached and that the number of swaps was crucial in cutting losses. Figure 10 demonstrates that by switching just seven customers, the power losses over the feeder under examination have been significantly decreased (solution A). Additionally, greater loss reduction is accomplished when the greatest number of customer switching occurs (solution B).

Table 4. Time consumed comparison

Time (minutes)	Case 1	Case 2	Case 3	Case 4	Case 5
Max. switching	16.72	7.78	7.71	17.24	16.89
Min. switching	4.45	4.57	4.38	4.39	4.35

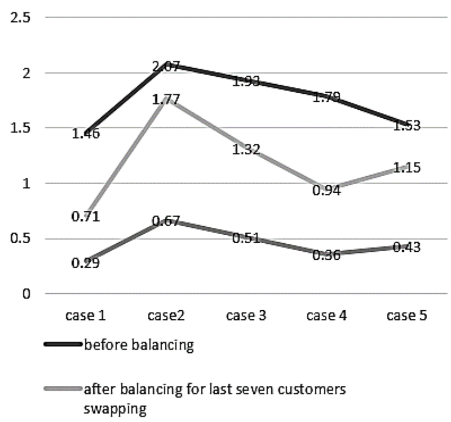

Figure 10. Power losses comparison

6.4. Time consumed comparison

The salp swarm algorithm (SSA) takes a varied amount of time to provide results in two instances. The amount of time spent for each example is shown in Table 4. According to Table 4, it appears that it takes less time to obtain results when only a small number of customers are swapped than when a large number of customers are swapped.

6.5. Discussion

The salp swarm algorithm (SSA) takes a varied amount of time to provide results in two instances. According to Table 4, it appears that it takes less time to obtain results when only a small number of customers are swapped than when a large number of customers are swapped. When compared to alternative algorithms with fewer iterations and a shorter calculation time, the SSA is quite effective in finding superior overall solutions. Selecting the case with the best values after running the algorithm numerous times is a useful method for choosing the algorithm's parameters.

The SSA demonstrates a practical method for switching the load over the feeder being investigated in order to accomplish load balancing. Regardless of how many consumers are switching, the total current magnitude among feeders is nearly identical in magnitude. As a result, the neutral current is minimized. As a result, there are instances where the neutral current for the lowest number of swaps is lower than the neutral current for the highest number of customer swaps.

After balancing, the three phase voltage magnitudes are also within acceptable bounds. It is noted that the results are virtually the same for lowest number of load swapping or highest number of load swapping for voltage unbalance percentage in all scenarios after balancing. Additionally, the overall losses among feeders prior to load switching are identical to the losses among feeders for the bare minimum of load switching.

7. CONCLUSION

In order to reduce voltage imbalance, current imbalance, current flow in neutral wire, and power losses by determining the best phase to connect customers, this paper examines the salp swarm algorithm (SSA), one of the newest artificial intelligence algorithms, on the low voltage feeder with 19 customers. The outcomes acquired from the highest and lowest numbers of switching clients are compared with the solutions employing SSA. The findings demonstrate that equilibrium is attained regardless of the number of swaps for various values, including voltages, currents, neutral currents, power losses, and voltage imbalance %. Additionally, the system's current level of stress is decreased. As a result, operating expenses in low voltage networks are decreased. The amount of electric current outages at the customers decreases once the ideal balance is achieved, maintaining the system's security and safety.

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