Adjustment of Parameters of Static VAR Compensators in Permanent Regime using Salp Swarm Algorithm

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Abstract *– This work presents a proposal for the adjustment of parameters of Static VAR Compensators (SVC) in permanent regime that contemplates the remote voltage control. In the work, an application was developed that used the Salp Swarm Algorithm (SSA) metaheuristic as an optimization algorithm to find the best parameter setting of a set of SVCs existing in a system. The SSA was applied to the power flow algorithm based on the Newton-Raphson power flow method, in which the Jacobian matrix was modified for the inclusion of the SVC model that considers remote voltage control. For the resolution of the problem, the adjustment of the reference voltage and the limits of reactive generation of the SVCs were taken into account, minimizing the financial investment in reactive compensation, the voltage deviation and the electrical losses of the power system.*

Keywords – Active Power, EPS, NRPF, Reactive Power, SSA.

I. Introduction

Voltage stability today represents a main issue in the planning and operation of Electric Power Systems (EPS) and its deficiency could lead to limiting power transfers, thus how to cause load disconnections. Stress stability is related to the ability of an EPS to maintain acceptable stress levels in all the bars of the system, under normal conditions and after being subjected to a disturbance. An EPS is said to have entered a state of stress instability when a disturbance results in a progressive and uncontrollable decrease in stress [1, 2].

The reinforcement of the system, against voltage instability, can be carried out using SVCs, also known as SVCs, which consist of capacitors and reactors connected in shunt that, together with devices, Transformation systems and power switches form a reactive power compensation system, whose maneuvers are carried out through the use of power electronics [3].

The adjustment of the parameters of a set of SVCs must be carried out considering the entire interconnected system, mainly if we want to observe the influence of each SVC on the reactive power compensation, and consequently on the control of voltage, which is given by adjusting the slope of the characteristic curve of each device [4].

A. Exploration of the Importance of the Problem

The optimal adjustment of the SVC parameters can be approached as a non-linear optimization problem that, depending on the EPS analyzed, can represent a major problem. This problem could be solved by minimizing the reactive power capacity of the set of compensators installed in the

EPS. On the other hand, this problem requires a complete analysis of the network, since it must consider it both in normal operating conditions and in a contingency regime, where each contingency generates a different network topology [1].
In the literature there are several works focused on the optimal adjustment of SVC parameters [3] [4] [5]. However, these studies did not consider remote voltage control, so taking it into account for the study of voltage stability in EPS represents an advance in this line of research.

B. Objectives

The general objective of this work is to develop an application for the optimal adjustment of the parameters of a set of SVCs, for the remote control of voltage, in permanent regime of an EPS using the salp swarm algorithm metaheuristic.

Specific Objectives:

- Computationally implement the SVC model for power flow studies, which includes remote voltage control of an EPS;
- Develop an algorithm that minimizes the financial investment in reactive compensation, the voltage deviation and the electrical losses of the power system, optimizing the setting of reactive generation limits and SVC reference stress.
- Validate the algorithm by comparing the results obtained with those provided by other power flow algorithms, by simulating several cases of permanent regime of some IEEE standard EPSs.

C. Hypothesis

The computationally implemented SVC model satisfactorily corrects the voltage levels, considering small and large disturbances, such as load variations and disconnections of transmission lines.

II. Proposed Methodology

This technical research work is based on the development of an algorithm that finds the optimal adjustment of the parameters of static reactive compensators to achieve remote control of voltage at a point of the system in r Permanent regime, through the implementation of the salp swarm algorithm metaheuristic. Due to this nature of the problem, this investigation is quantitative.

Scope of Quantitative Research: The adjustment of the parameters of a set of SVCs must be carried out considering the entire interconnected system, allowing to observe the influence of each SVC on the reactive power compensation, and consequently on the voltage control. This is a non-linear optimization problem that, depending on the EPS analyzed, can mean a problem of great importance, where the problem requires a complete analysis of the network, since it must consider it both under normal operating conditions as in contingency regime.

A. Design of the Investigation

This work proposes a methodology for the optimal adjustment of the SVC parameters, in permanent regime, with the aim of finding the best reference voltage values and the limits of reactive power, which are able to minimize the active power losses of the entire EPS, the voltage deviations and the financial investment for the acquisition of these devices (which is given in function of the capacity of reactive power injection). To achieve this objective, with the methodology used it is proposed to use the metaheuristic SSA in this search procedure.

B. Process

At work, the aim is to control the voltage of a bar remotely, which is achieved by injecting reactive power into a bar of the system to control the voltage level of another bar, which it is desired to control. This fact is usually a common practice in substations due to physical space restrictions and constitutes an advance with respect to the SVC model presented in [6].

The methodology of this research seeks to minimize the financial investment in reactive compensation, the voltage deviation and the electrical losses of the power system by optimizing the setting of generation limits. Reactive and reference voltage of SVCs, where the search method for these parameters used is the Salp Swarm metaheuristic.

1. SVC Model Adopted

In this work, the SVC model is adopted as a variable derivation susceptance for voltage control, associated with the low voltage bus of the coupling transformer. In Eq. 1 the expressions for the power injected into the SVC are shown operating within the control zone and passing its limits respectively.

$$Q_{SVC} = b_{SVC} \cdot V_k^2$$

$$Q_{SVC}^{max} = b_{SVC}^{max} \cdot V_k^2$$

$$Q_{SVC}^{min} = b_{SVC}^{min} \cdot V_k^2 \tag{1}$$

When the SVC operates in the control zone, it injects the EPS with the appropriate amount of reagents in order to maintain an adequate voltage profile in some group of sensitive bars [6]. In the controlled bar k, the stress value depends on the following control function:

$$V_k = V_{ref} - r_{SVC} \cdot Q_{SVC} \tag{2}$$

Where r_{SVC} represents the inclination of the linear part of the SVC characteristic curve.

2. SVC Implementation in Newton-Raphson Power Flow (NRPF) Method

To represent the SVC model in the power flow problem, the reactive power injected into the SVC bus is considered as an additional state variable. In order for the system of equations to remain consistent, a control equation representing the behaviour of the SVC is added to the system. This equation is modified during the iterative process, being a function of the operating point of the equipment and the model adopted to represent it, let be a SVC connected to the bar k, controlling the modulus of the voltage of the bar m. The generic voltage control structure is shown in the following equation:

$$\begin{bmatrix} \Delta P_k \\ \Delta Q_k \\ \Delta P_m \\ \Delta Q_m \\ \Delta y \end{bmatrix} = \begin{bmatrix} \frac{\partial P_k}{\partial \theta_k} & \frac{\partial P_k}{\partial V_k} & \frac{\partial P_k}{\partial \theta_m} & \frac{\partial P_k}{\partial V_m} & \frac{\partial P_k}{\partial x} \\ \frac{\partial Q_k}{\partial \theta_k} & \frac{\partial Q_k}{\partial V_k} & \frac{\partial Q_k}{\partial \theta_m} & \frac{\partial Q_k}{\partial V_m} & \frac{\partial Q_k}{\partial x} \\ \frac{\partial P_m}{\partial \theta_k} & \frac{\partial P_m}{\partial V_k} & \frac{\partial P_m}{\partial \theta_m} & \frac{\partial P_m}{\partial V_m} & \frac{\partial P_m}{\partial x} \\ \frac{\partial Q_m}{\partial \theta_k} & \frac{\partial Q_m}{\partial V_k} & \frac{\partial Q_m}{\partial \theta_m} & \frac{\partial Q_m}{\partial V_m} & \frac{\partial Q_m}{\partial x} \\ \frac{\partial y}{\partial \theta_k} & \frac{\partial y}{\partial V_k} & \frac{\partial y}{\partial \theta_m} & \frac{\partial y}{\partial V_m} & \frac{\partial y}{\partial x} \end{bmatrix} \cdot \begin{bmatrix} \Delta \theta_k \\ \Delta V_k \\ \Delta \theta_m \\ \Delta V_m \\ \Delta x \end{bmatrix} \tag{3}$$

The new variable in this case is then:

$$\Delta x = \Delta Q_{G_k} \tag{4}$$

Since the control equations vary according to the region of operation of the SVC, their derivatives also depend on the region of operation of the SVC. These expressions are the following according to the region in which the SVC is operating [6].

Capacitive Region:

$$\begin{gathered} f = \Delta x - b_{max} \cdot V_k^2 \\ \frac{\partial f}{\partial V_k} = -2 \cdot b_{max} \cdot V_k \\ \frac{\partial f}{\partial x} = 1 \\ \Delta y = b_{max} \cdot V_k^2 - \Delta x \end{gathered} \tag{5}$$

Control Region:

$$\begin{gathered} f = V_k - V_{ref} - r_{SVC} \cdot \Delta x \\ \frac{\partial f}{\partial V_k} = -1 \\ \frac{\partial f}{\partial x} = -r_{SVC} \\ \Delta y = V_{ref} + r_{SVC} \cdot \Delta x - V_k \end{gathered} \tag{6}$$

Inductive Region:

$$\begin{gathered} f = \Delta x - b_{min} \cdot V_k^2 \\ \frac{\partial f}{\partial V_k} = -2 \cdot b_{min} \cdot V_k \\ \frac{\partial f}{\partial x} = 1 \\ \Delta y = b_{min} \cdot V_k^2 - \Delta x \end{gathered} \tag{7}$$

3. Adjusting the SVC Parameters

The optimal adjustment of parameters of each SVC present in the system was considered as a multiple optimization problem, subject to restrictions on the generation capacity of each generator and the maximum tolerable voltage deviation in each bus, where there is interest in optimizing the following objectives:

- *Minimize the cost of SVCs by limiting the amount of power they can supply since their cost depends on their power supply capacity.*

$$F_1(X) = \sum_{i=1}^{p} \beta_i \cdot \left| Q_{max}^i - Q_{min}^i \right| \tag{8}$$

  Where β_i represents the monetary value used in reactive compensation, given by units of monetary value / MVAr, for each SVC.

- *Minimize Voltage Deviation:*

$$F_2(X) = \|\Delta V_1^{max} \dots \Delta V_{nos}^{max}\|_\infty \tag{9}$$

Each component of $F_2(X)$ is obtained according to:

$$\Delta V_{ii}^{max} = \|V^{exp} - V\|_\infty$$
$$ii \in \{1,2,\dots,nos\} \tag{10}$$

Where nos is the number of scenarios considered in the analysis (base case plus cases considering contingencies), V^{exp} is the vector that contains the expected modulus of voltage, and, V is the vector that contains the calculated modules of voltage.

- *Minimize Active Power Losses:*

$$F_3(X) = \left|P_1^{loss} \dots P_{nop}^{loss}\right| \tag{11}$$

Each component of $F_3(X)$ is obtained according to:

$$P_{jj}^{loss} = \left|\sum_{b\in\Omega G} PG_b - \sum_{b\in\Omega} PL_b\right| \tag{12}$$

Where ΩG is the group of bars with generation, Ω is the group of all the bars in the system, PG_b is the generated power, and PL_b is the power consumed by the load.

Then, the problem is posed as follows:

$$F(X) = [F_1(X) \quad F_2(X) \quad F_3(X)] \tag{13}$$

Subject to:

$$PG_i - PL_i - \sum\nolimits_{i\in\Omega} P_{ki} = 0$$
$$b \neq i$$
$$b \in \{1,2,\dots,nbs\} \tag{14}$$

$$QG_k + b_{SVC} \cdot V_k^2 - QL_k - \sum_{i\in\Omega k} Q_{ki} = 0 \tag{15}$$

$$V_{REF} - V_k + r_{SVC} \cdot b_{SVC} \cdot V_k^2 = 0 \tag{16}$$

Where Ωk is the group of bars with controlled voltage, PG_i, QG_i, PL_i, QL_i represent the active and reactive powers generated and demanded in the analysis bar, nbs is the number of bars in the system, and X is the vector that contains:

1. The bar where the SVC is installed, the controlled voltage bar,
2. Reference voltage, and,
3. The generation limits, for each SVC.

4. Objective Function

For this work, the objective function is adapted to the weighted sums method, according to the following equation:

$$F(x) = a_1 \cdot F_1(x) + a_2 \cdot F_2(x) + a_3 \cdot F_3(x) \tag{17}$$

Where the coefficients a_1, a_2 and a_3 are the weights of the objective functions in the optimization algorithm, which can be adjusted to avoid the predominance of one function over the others.

5. Salp Swarm Algorithm

Salps belong to the Salpidae family and have a transparent barrel-shaped body. Its texture is very similar to the texture of jellyfish. They also move forward by pumping water through their bodies, much like jellyfish [7]. Due to the difficulty of these creatures reaching their habitats and keeping them in a laboratory environment, biological research about these creatures is just at the starting point. The most interesting aspect of salps is herd behavior, which is the subject of this article. In the deep oceans, salps often form many, called salpa chains. The main reason for this behavior is not yet known, but some researchers believe that this is done to achieve better movement using quickly coordinated changes and food search methods [7].

A mathematical model of herd behavior displayed by salpa chains; it begins by dividing the population into two groups: a leader and a follower. The leader is always in front of the chain to control the herd, and the rest follow him. There is a targeted food source in the search space called TF which every herd targets. The position update equation for leader salp by target food source is as follows [7]:

$$x_j^1 = \begin{cases} TF_j + c_1\big(c_2(ub_j - lb_j) + lb_j\big) & c_3 \geq 0 \\ TF_j - c_1\big(c_2(ub_j - lb_j) + lb_j\big) & c_3 < 0 \end{cases} \tag{18}$$

Here, x_j^1 represents the leading salpine position in the j^{th} dimension, TF_j represents the target food source in the j^{th} dimension, the c_1, c_2 and c_3 are random numbers, ub_j and lb_j, respectively, the upper and lower boundaries in the j^{th} dimension. The coefficient c_1 balances the exploration (global search) and exploitation (local search) phases of the research space. Therefore, it is considered as the most important parameter of the SSA algorithm and is given in the following equation [7]:

$$c_1 = 2e^{-\left(\frac{4m}{M}\right)^2} \tag{19}$$

Here, m represents the current step, while M represents the total number of steps. Let the value of M is 100. Both are random numbers, coefficients produced uniformly in the range of c_1 and c_2 [0, 1]. Each follower salpin updates the position according to the track followed by the equation as follows [7]:

$$x_j^i = \frac{1}{2}\left(x_j^i + x_j^{i-1}\right) \qquad \forall i \geq 2 \tag{20}$$

Equation (20) shows that each follower salpin follows its leader to form a chain of salps. Here, x_j^i represents the j^{th} dimension i^{th} follower salpin site. The starting locations of all salps are randomly generated, as with other herd-based optimization algorithms [7].

III. SIMULATION RESULTS

The graphs below represent the results obtained:

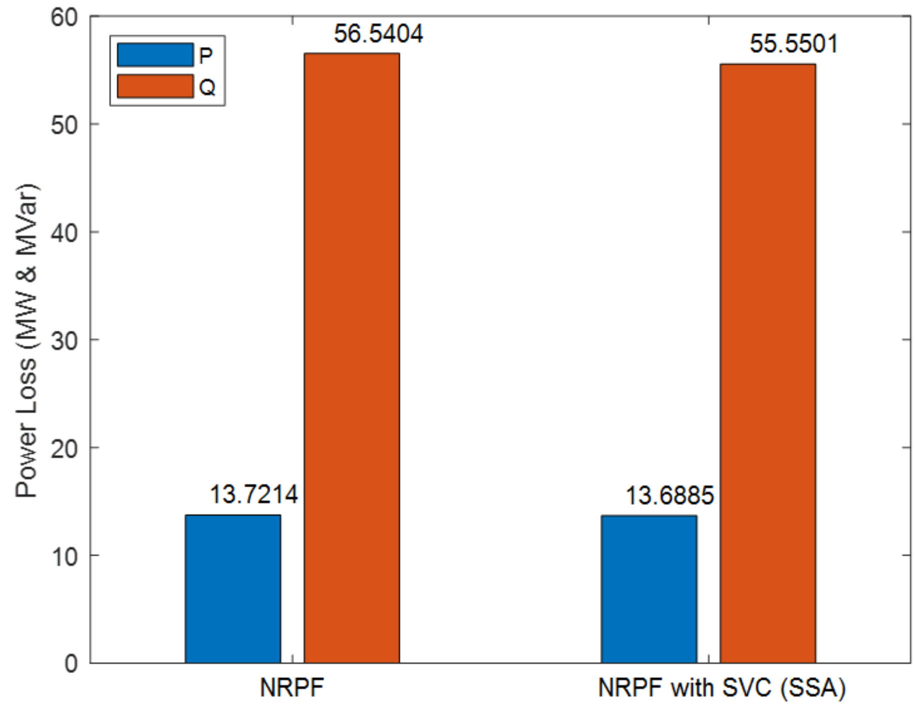

Figure 1: Active & Reactive power losses in IEEE-14 bus system using SSA

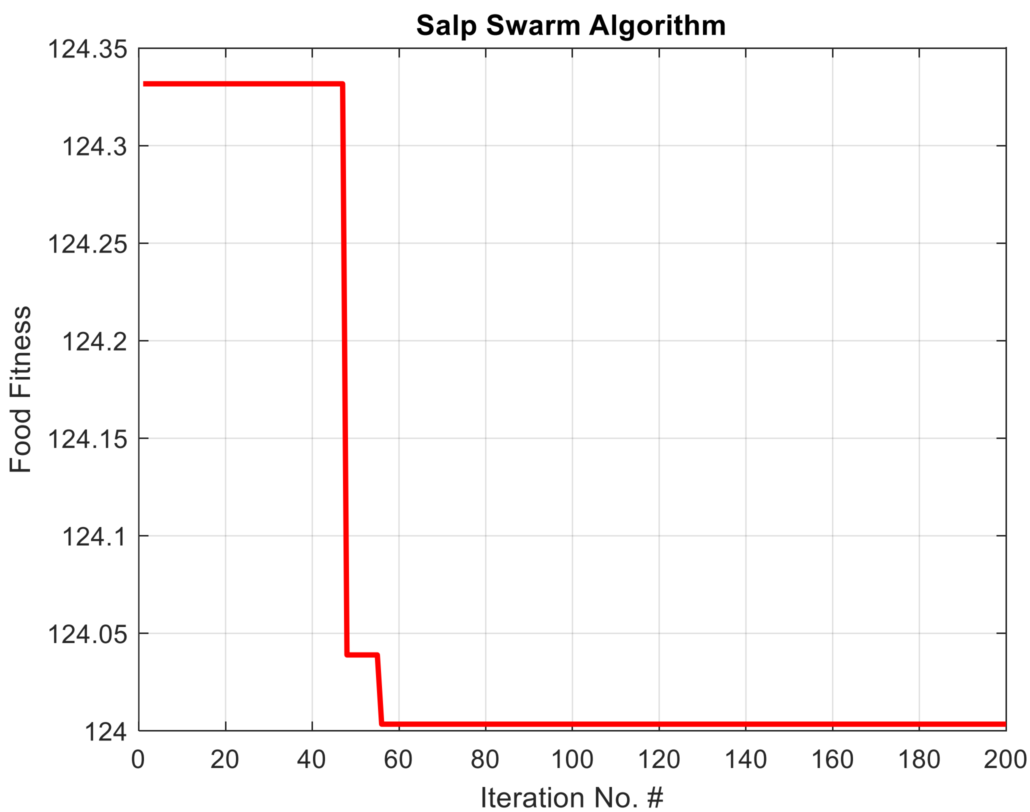

Figure 2: Salp swarm algorithm iteration graph

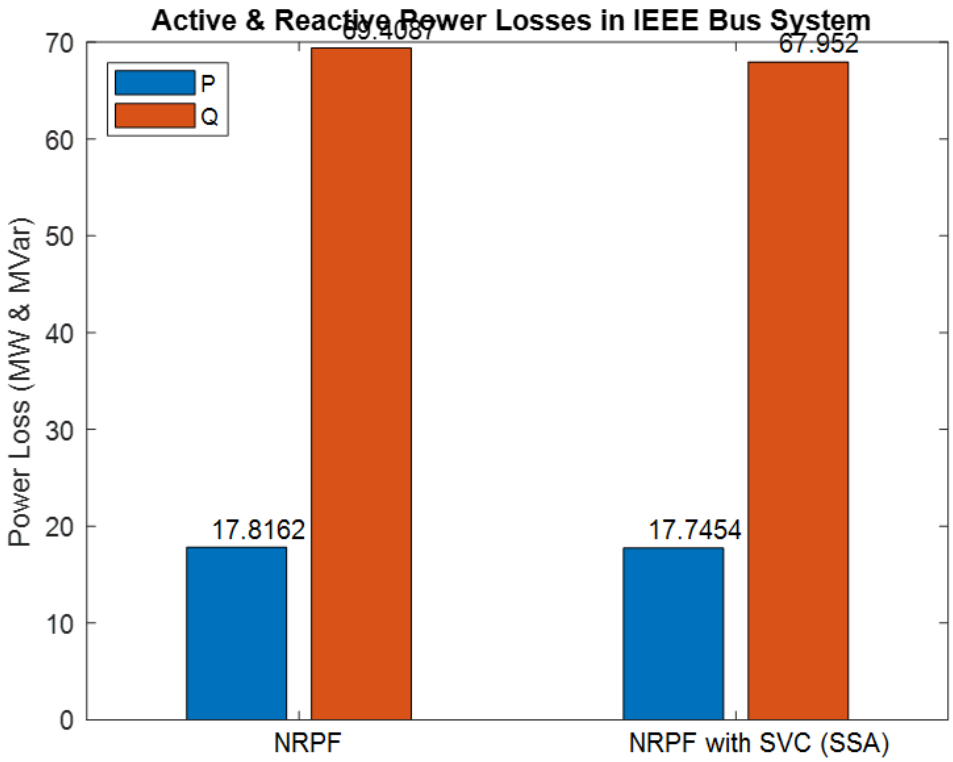

Figure 3: Active & Reactive power losses in IEEE-33 bus system using SSA

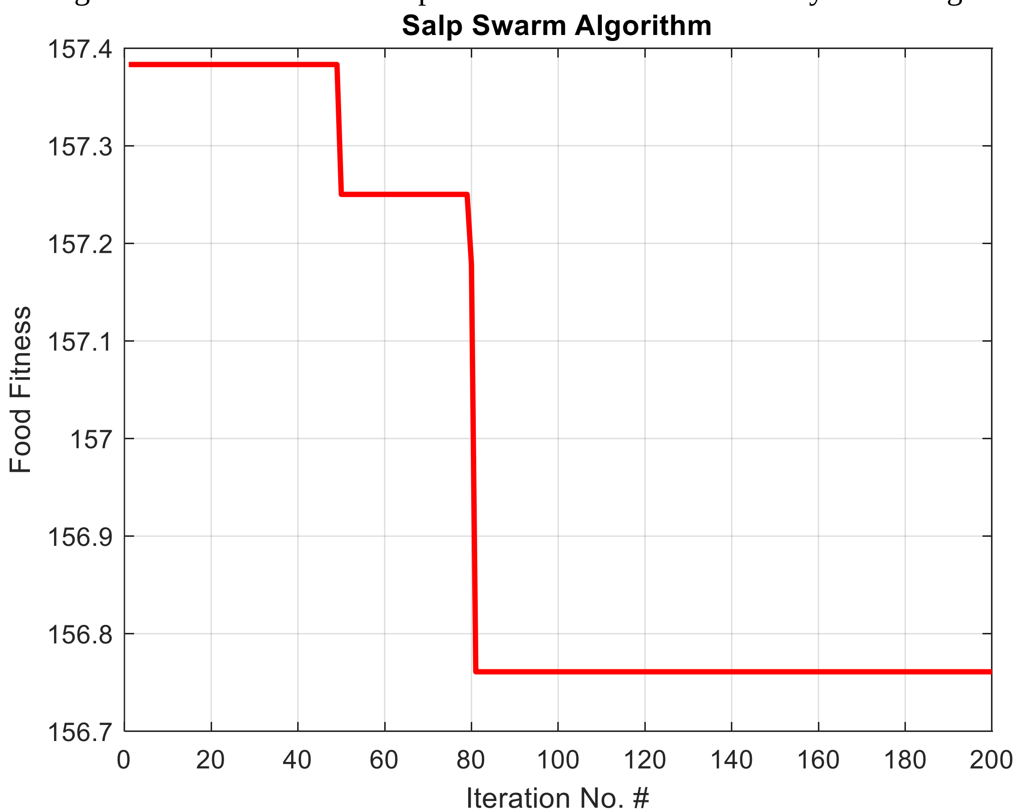

Figure 4: Salp swarm algorithm iteration graph

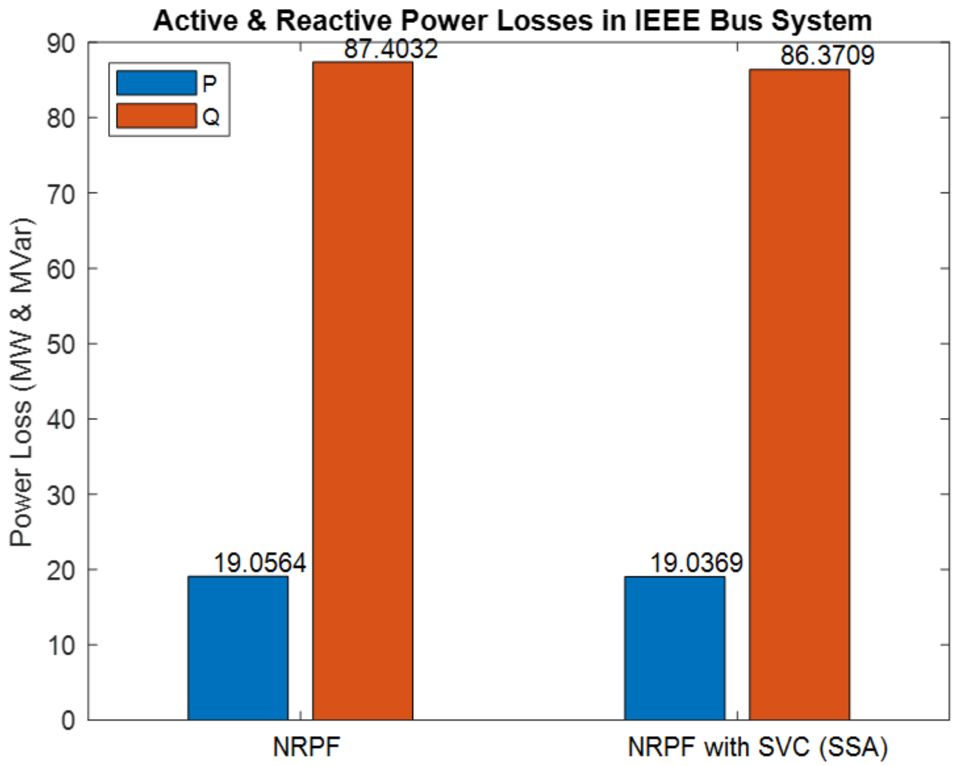

Figure 5: Active & Reactive power losses in IEEE-57 bus system using SSA

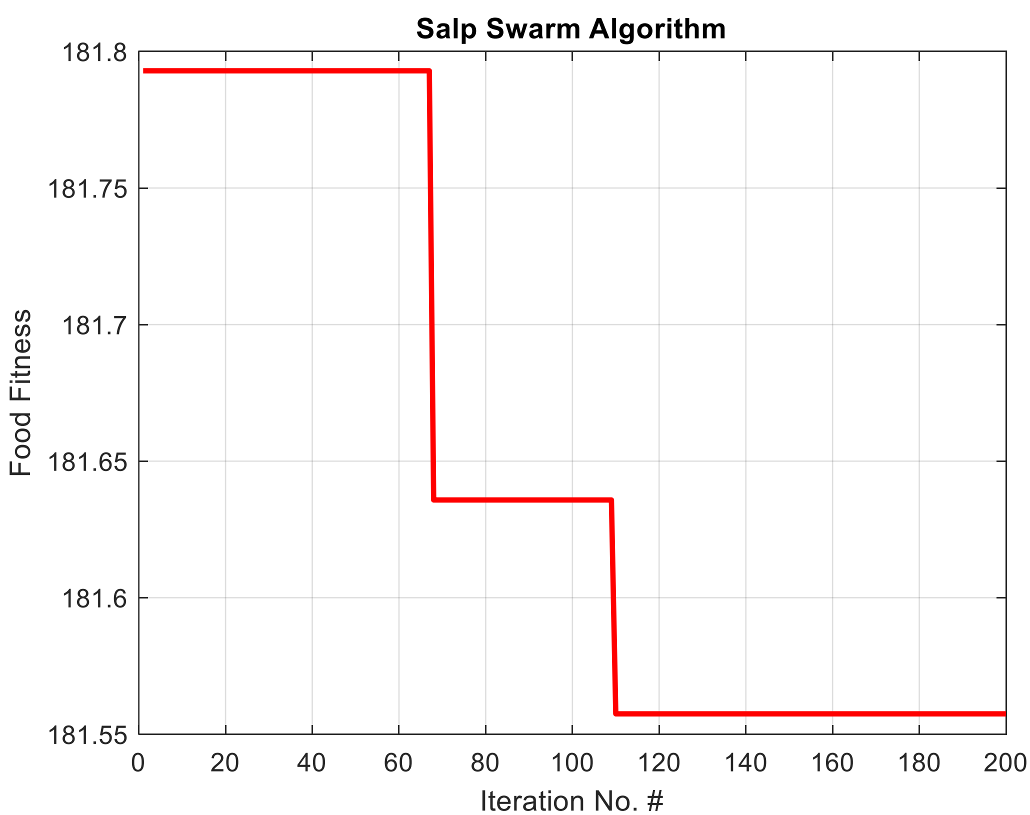

Figure 6: Salp swarm algorithm iteration graph

Table 1: Comparative analysis for active power loss and reactive power loss

Bus Test System	NRPF		NRPF-SVC-SSA	
	Active power (MW)	Reactive power (MVar)	Active power (MW)	Reactive power (MVar)
IEEE 14 bus test system	13.7214	56.5404	13.6885	55.5501
IEEE 33 bus test system	17.8162	69.4087	17.7454	67.952
IEEE 57 bus test system	19.0564	87.4032	19.0369	86.3709

IV. CONCLUSION

In carrying out this work, the main objective was to develop an application that finds the optimal setting of the parameters of a set of SVCs installed in an EPS, and that at the same time this application considers remote voltage control by SVCs. This objective was achieved by the proposed methodology, since with the application it is possible to find satisfactorily values to adjust the parameters of the SVCs, improving the performance of the EPS in which they are installed; by minimizing the active and reactive power losses. The SVC model has been implemented where it is represented as a variable susceptance considering the possibility of remote control of voltage. This model is widely used since with respect to others (e.g.: power injection model) it more faithfully represents the behavior of a SVC within the system. Another contribution of this work corresponds to considering a coupling transformer in the modeling of the SVC, a fact that makes it possible to represent the bus to which said device is connected. One aspect to be highlighted is the efficiency of the metaheuristic technique implemented in this methodology, the SSA, since the reduction in the execution time of the program in comparison with other similar works is notable like for example [8]. Another positive aspect of the present work is the performance achieved in the EPS when using SVCs adjusted by the methodology proposed in the dynamic regime, keeping the voltage of the system within normal values afterwards contingencies, even those that were not considered in the adjustment of SVCs, demonstrating the robustness and efficiency of the method.

REFERENCES

[1] Kothari, D.P. and Nagrath, I.J., 2019. *Power System Engineering, 3e*. McGraw-Hill Education.

[2] Sauer, P.W., Pai, M.A. and Chow, J.H., 2021. *Power system dynamics and stability: with synchrophasor measurement and power system toolbox*. John Wiley & Sons.

[3] Baadji, B., Bentarzi, H. and Bakdi, A., 2020. Comprehensive learning bat algorithm for optimal coordinated tuning of power system stabilizers and static VAR compensator in power systems. *Engineering Optimization*, *52*(10), pp.1761-1779.

[4] Teh, J., Lai, C.M. and Cheng, Y.H., 2018. Improving the penetration of wind power with dynamic thermal rating system, static VAR compensator and multi-objective genetic algorithm. *Energies*, *11*(4), p.815.

[5] Ćalasan, M., Konjić, T., Kecojević, K. and Nikitović, L., 2020. Optimal allocation of static var compensators in electric power systems. *Energies*, *13*(12), p.3219.

[6] Cardozo, R.K., Viveros, E.C. and Martínez, E.A., 2020, October. Parallel Evolutionary Algorithm for Coordinated Tuning of Exciter Controllers and a group of Static VAR Compensators. In *2020 IEEE ANDESCON* (pp. 1-6). IEEE.

[7] Mirjalili, S., Gandomi, A.H., Mirjalili, S.Z., Saremi, S., Faris, H. and Mirjalili, S.M., 2017. Salp Swarm Algorithm: A bio-inspired optimizer for engineering design problems. *Advances in Engineering Software*, *114*, pp.163-191.

[8] Chaparro, E.R. and Sosa, M.L., 2011, June. Coordinated tuning of a set of Static VAR Compensators using Evolutionary Algorithms. In *2011 IEEE Trondheim PowerTech* (pp. 1-6). IEEE.