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Electrical Engineering and Technology
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Optimal Location and Sizing of Thyristor Controlled Series Capacitor in Nigerian Transmission System Using Hippopotamus Optimization Algorithm

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Received: 17 April 2025; **Revised:** 20 May 2025; **Accepted:** 7 June 2025; **Published:** 13 June 2025

Abstract: Optimal power transmission plays a pivotal role in ensuring the stability and viability of the power grid, and such a need is further exacerbated by the rising power demands that developing power grids face. In this paper, a novel approach is presented to implement the Hippopotamus Optimization Algorithm (HOA) to ensure optimal Thyristor-Controlled Series Capacitor (TCSC) placement and size to reduce power transmission losses and improve voltage profile. A Newton-Raphson load flow study is developed to incorporate TCSC models, aiming to reduce active power losses and costs of generation. The results obtained on the IEEE 14-bus test network indicate the effectiveness of the proposed HOA method over the existing and manual methods. On the IEEE 14-bus test system, the proposed method was effective in reducing active power loss substantially from 13.599 MW to 4.101 MW and lowering the costs of the systems from $6799 to $2788. On the Nigerian 28-bus power grid, the HOA method successfully reduced the active power loss to 732.05 MW, compared to the value of 802.37 MW of active power loss on the base case. It was also successful in lowering the reactive power loss to 1655.58 Mvar, and the cost of operation was reduced to $372,541, outperforming the results obtained through the manual method. These results indicate that the HOA is a powerful strategy that can be employed to reduce active power loss substantially and improve the voltage stability without the need to develop extensive infrastructure.

Keywords: Thyristor; Capacitor; Current; Transmission; Hippopotamus; Algorithm

1. Introduction

The electric power industry is the backbone of the growth of societies, as well as the operation of industries worldwide. With the increase in the population, the size of the cities keeps growing, while industries also increase the scope of their activities, leading to an increase in the demand for electrical power. Power stations are usually located away from areas where electrical power is consumed due to economic and environmental factors, leading to high power losses in long distances over huge loads carried by the transmission lines, making them approach their limits, with losses arising primarily due to resistance in the lines and reactive power flow, as well as a threat to voltage stability in these lines. In developing countries such as Nigeria, maintaining the stability of the power grid is a matter of urgent concern [1].

Instead of constructing new transmission lines, research now emphasizes the cost-effective nature of Flexible AC Transmission Systems (FACTS). FACTS are designed to alter voltage levels, phase angles, and impedance through the use of power electronics to increase transmission capacity and stability. In the field of FACTS, the Thyristor-Controlled Series Capacitor (TCSC) is a type of compensation that is particularly useful for series compensation and provides dynamic control of the reactance of a transmission line to control the active power flow and to suppress subsynchronous resonance. However, the effectiveness of TCSC can be largely affected by its size and site, and may even create instabilities and ineffective reduction of losses. A recent article emphasizes the need to optimize the use of FACTS [2].

Identifying the optimal location and scale of the TCSC devices is an arduous, nonlinear, and non-convex optimization problem. The large solution spaces of power systems make it difficult to solve using conventional optimization approaches. As such, there has been growing interest in applying metaheuristics such as Genetic Algorithms and Particle Swarm Optimization to FACTS devices. While these methodologies are effective, they have difficulties with early convergence or sensitive parameters in the complex solution spaces of contemporary power systems. More recent approaches, such as the Whale Optimization Algorithm and models of politics-based optimization methods, are currently being investigated [3].

To escape the problem of premature convergence and increase the efficiency of the solutions, a new approach considered within this paper is the Hippopotamus Optimization Algorithm (HOA). The HOA approach revolves around a novel heuristic technique inspired by the nature of hippopotamuses, where exploration can be described as position renovation, diversity as defense mechanisms, and escaping as escape mechanisms. Thus, the proposed HOA algorithm can more efficiently explore a complex solution space, especially when the global optima of the TCSC problem lie within a vast solution space. In this study, we implement HOA to solve for optimal sizing and placement of TCSC devices on the Nigerian 28-bus transmission network. We modify the Newton-Raphson load flow model to incorporate firing angles for TCSC devices for comparison with the result provided by HOA. The significance of this research is to make available quantifiable active power losses with improved voltage profiles while also verifying the superior convergence properties provided by HOA [4].

1.1. Growing Electricity Demand and Transmission Challenges

Due to the continuous growth in population, rapid urbanization, industrialization, and the development of electricity-powered technologies, there has been an intensified demand for electricity. In an attempt to meet this increased demand, major production units for electricity are often built far from regions of consumption owing to certain economic, resource, or environmental constraints [5]. As such, electricity has had to be transmitted over long distances.

The world's electricity output has maintained an upward trend over the years and currently stands at about 22,200 TWh per year, and the scale of electricity that is distributed over power grids indicates the severity of the issue of electricity transmission that the world is facing as a whole [6]. The issue of transmission has been made worse due to the development that is taking place in the world, due to the rising electricity output.

However, the development in the world due to the rise in electricity output can pose serious threats to the future of the electricity sector. The biggest threat is terrorism, which is on the rise in many nations through organizations

1.2. Power Losses and Voltage Stability in Transmission Systems

During the transmission of power, a large amount of generated energy is wasted along the way before it reaches the consumer. These losses can be broadly categorized into technical losses, which occur owing to resistance in the transmission line, transformer losses, reactive power flow, and corona discharges, and non-technical losses, which occur owing to theft of electricity, meter reading errors, and administrative reasons [7].

Apart from minimum loss, voltage profile improvement is one of the most challenging modes of functioning for a power system. Poor voltage control may cause a decrease in the quality of the power, equipment malfunctions, or, in extreme cases, a voltage collapse, leading to a blackout [8]. The conditioning of the bus voltage is a prerequisite to ensure the secure functioning of the power system.

1.3. Load Flow Analysis and System Performance Evaluation

In order to analyze and optimize the performance parameters of the power system, several analytical and numerical methods have been established. Load Flow Studies: This is an essential technique used to calculate the steady-state solution of the power system, including the bus voltage magnitude, power, and network losses. Among the several numerical algorithms, the Newton-Raphson method is the most commonly used method in power system analysis, especially for larger power systems, due to its superior robustness and fast convergence properties.

Load flow studies are the basis of transmission planning, contour analysis, voltage management, and optimal placement of any control device in a power system. However, the complexity of the modern power system environment requires better management control methods to adjust system parameters dynamically according to different operating conditions [9].

1.4. Flexible AC Transmission Systems (FACTS)

The introduction of Flexible AC Transmission Systems (FACTS) has brought substantial improvements to the controllability and flexibility levels of modern power systems. In this context, the main functions controlled using power electronic control systems in FACTS components include voltage magnitude, line impedance, phase angle, and power flow. The fast and continuous control offered by the use of FACTS technology has been known to stabilize voltages, extend transmission capacity, reduce transmission losses, and provide overall security [10].

Among the many FACTS controllers that have been developed, the Thyristor-Controlled Series Capacitor (TCSC) has also made its presence felt for its efficiency in series Compensation applications. The TCSC provides dynamic control of the transmission line reactance by switching thyristors for the control of active power and prevention of subsynchronous resonance effects [11].

1.5. Importance of Optimal Placement and Sizing of TCSC

Even though FACTS devices have immense operational advantages, they remain highly sensitive to their location and size in the transmission network. They might not always have positive effects on power systems or might even cause instability if they are not appropriately located [12]. This means that finding the optimal location and size of TCSC devices in the transmission network is indeed complex and one of the nonlinear optimization problems involving power flow equations [13].

1.6. Metaheuristic Optimization Methods for Power Systems

Conventional optimization methods have difficulty in efficiently tackling large-scale, nonlinear, and nonconvex optimization problems in the area of power system optimization. As such, metaheuristic and nature-inspired algorithms have found broad acceptance in dealing with search spaces in identifying near-optimal solutions within a reasonable amount of time computationally required [14].

A number of metaheuristic algorithms, such as Genetic Algorithms, Particle Swarm Optimization, Differential Evolution, and Ant Colony Optimization have already been effectively used for the placement of FACTS devices [15]. But the ever-increasing search for better algorithms is a continuous process.

1.7. Introduction of Hippopotamus Optimization Algorithm (HOA)

Hippopotamus Optimization Algorithm (HOA): It is a newly developed nature-inspired metaheuristic search technique. It is based on the survival behavior of hippos in their natural habitat. It simulates three major behavior phases. These phases include (i) position renovation in water reservoirs to increase exploration, (ii) defense strategies against predators to ensure diversity in population, and (iii) escape strategies to increase exploitation in promising areas.

Through this balance of exploration and exploitation, the HOA is able to efficiently handle complex optimization problems that are high-dimensional and nonlinear. Various recent studies have demonstrated the efficiency of the HOA over other competitive approaches for solving different optimization problems that arise in various engineering areas [16].

1.8. Motivation and Contribution of This Study

The Nigerian power grid, like many power systems in developing nations, suffers from large transmission loss and voltage instability. The driving reason for this work is the imperative of developing an effective optimization solution for the application of a cost-effective Flexible AC Transmission System solution like the Thyristor-Controlled Series Capacitor. The key contributions of this work include:

i. To the best of our knowledge, this is the first use of the Hippopotamus Optimization Algorithm (HOA) in optimal location and sizing of TCSC in a realistic transmission system.
ii. Development of a novel Newton-Raphson load flow solution framework that integrates the firing angle modeling of the TCSC with the HOA Optimizer.
iii. Detailed examination of both the standard IEEE benchmark case of 14-bus systems and real-world applications involving the 28-bus systems in Nigeria.
iv. A comparative analysis to show how superior the HOA approach is to the base cases and manual placement methods with respect to loss reduction, economic savings, and voltage profile improvements [17–19].

2. Methodology

2.1. Data Collection

The data set (line data, bus data, generator data, and load data) for this study was sourced online from the IEEE Distribution System Analysis Subcommittee website (https://sites.ieee.org/pes-testfeeders) in July 2024.

2.2. Problem Formulation

The purpose of this research work is to minimize the active transmission power loss P_{loss} within the transmission network by obtaining the optimal location and sizing of Thyristor-Controlled Series Capacitor devices. The objective is to minimize P_{loss} as follows:

$$\min F = P_{loss} = \sum_{k=1}^{N_l} G_k \left(V_i^2 + V_j^2 - 2V_iV_j\cos(\delta_i - \delta_j)\right) \tag{1}$$

In the above expressions, the symbol N_l is the number of transmission lines, and the value of G_k is the conductance value for the transmission line k. The values V_i and V_j are the magnitudes of the voltages at the ith and jth buses, whereas the angles δ_i and δ_j show the angles associated with the buses.

The optimization problem is under the following constraints:

A. Power Flow Equality Constraints
The conventional load flow equations for a Newton-Raphson solution are applied to meet the power balance conditions at each bus:

$$P_{Gi} - P_{Di} - V_i \sum_{j=1}^{N} V_j \left(G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij}\right) = 0 \tag{2}$$

$$Q_{Gi} - Q_{Di} - V_i \sum_{j=1}^{N} V_j \left(G_{ij}\sin\theta_{ij} - B_{ij}\cos\theta_{ij}\right) = 0 \tag{3}$$

B. Operational Constraints
The bus voltage limits as:

$$V_i^{\min} \le V_i \le V_i^{\max}, \forall i \in N_{bus} \tag{4}$$

The reactive power limits of a generator as:

$$Q_{Gi}^{\min} \le Q_{Gi} \le Q_{Gi}^{\max} \tag{5}$$

The TCSC reactance limits as:

$$X_{TCSC}^{\min} \le X_{TCSC} \le X_{TCSC}^{\max} \tag{6}$$

Here, X_{TCSC} denotes the variable series reactance due to the TCSC.
The thermal limits for transmission line are also given as:

$$S_l \le S_l^{\max}, \forall l \in N_{lines} \tag{7}$$

2.3. TCSC Modelling in Load Flow Analysis

The model of the TCSC is represented by a controllable series reactance. The reactance of the compensated line after compensation is given by the expression:

$$X_{line}^{eff} = X_{line} + X_{TCSC} \tag{8}$$

This change affects the susceptance of the line and hence the system's admittance matrix Y_{bus}. The control of the TCSC based on the firing angle is inherently included in the model through the variation of X_{TCSC} within the range of variation. For every iteration of the process of optimization, the relevant entries of the Y_{bus} matrix will be adjusted accordingly, and a modified Newton-Raphson load flow will be implemented with the objective of calculating the steady state of the solution considered by the HOA [20].

2.4. Application of Hippopotamus Optimization Algorithm

Hippopotamus Optimization Algorithm (HOA) is a population-based metaheuristic algorithm inspired by the society and survival behaviors of hippos, such as water mobility, collaborative defense, and escape methods [17].

Each hippo here represents a deployment configuration for a candidate TCSC given by:

$$X_i = [L_1, X_{TCSC,1}, L_2, X_{TCSC,2}, \dots, L_n, X_{TCSC,n}] \tag{9}$$

where L_k refers to the transmission line that has been chosen for the installation of the corresponding TCSC, while $X_{TCSC,k}$ stands for the series reactance.

The implementation process of the HOA consists of the following steps:

i. Initialization
A starting population of N hippos is randomly created within a feasible search space that considers line selections and reactances.

ii. Fitness Assessment
The modified Newton-Raphson procedure is applied to every hippo, and the sum of the active losses is determined as the value of the fitness.

iii. Position Renovation (Exploration)
This phase encourages global exploration by moving hippos towards new regions of the search space:

$$X_{new} = X_{rand} + \mathrm{R} \odot (X_{best} - X_{rand}) \tag{10}$$

where R is a random vector in [1].

iv. Defense Strategy (Population Diversity)
Weaker solutions are steered towards stronger ones, while simultaneously ensuring diversity as well as the stability of convergence.

v. Escape Strategy (Exploitation)
The local search methods are used around the best-performing solutions in order to focus exploitation on these regions.

vi. Termination
The process continues until reaching the maximum number of generations $G_{\max}$, then the solution with the minimum value of power loss is selected.

The parameters used in the Hippopotamus Optimization Algorithm (HOA) are presented in **Table 1**. The parameters were used based on sensitivity analyses to reach appropriate levels that are consistent with the mathematical formulation described by Malachi and Singer [21]. The size of the population and number of generations were selected to provide stable results without requiring high computational processing, while TCSC's parameter upper and lower limits are based on its realistic operating capabilities, as typically reported in power system reconfiguration in the literature.

Table 1. Hippopotamus Optimization Algorithm (HOA) Parameter Settings.

Parameter	Value
Population size ($\boldsymbol{N}$)	50
Maximum generations $\boldsymbol{G_{max}}$	100
Number of TCSCs	3
$\boldsymbol{X_{TCSC}}$ search bounds	([−0.8, 0.8]) pu

2.5. Integrated Optimization Procedure

The solution strategy was incorporated as shown in **Figure 1**, and summarized as follows:

i. Reads the system data (bus, line, gen, load).
ii. Carry out base-case Newton-Raphson load flow, and record P_{loss0}.
iii. Initialize HOA Population.
iv. For each generation:
   - Update Y_{bus} with candidate TCSC parameters.
   - Run modified load flow.
   - Calculate the value of the fitness function
   - Apply HOA Update operators.

v. Store the best solution found so far.
vi. Output the optimal locations and capacities of the TCSCs and the minimum power loss.

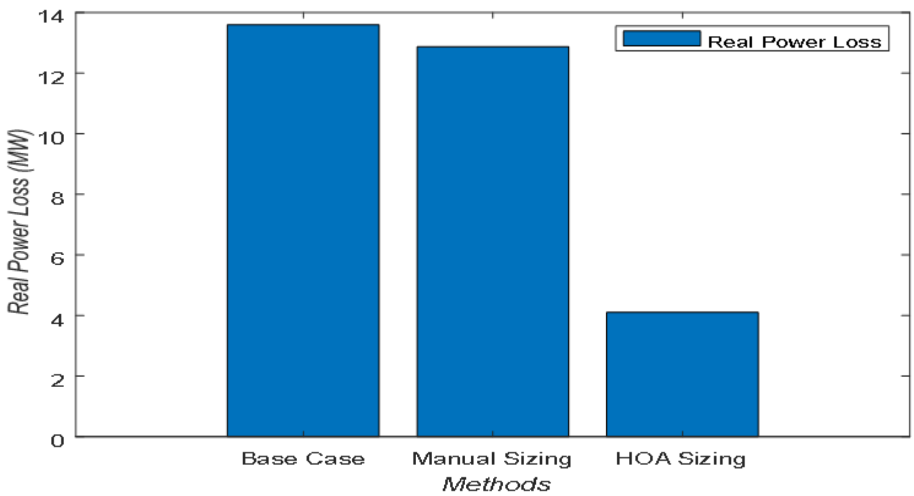

Figure 1. 14-Bus System Real Power Loss.

2.6. Test Systems

The proposed framework is validated using the IEEE 14-Bus Test System. It is a standard benchmark system widely utilized for the validation of power system optimization methods. Also, the Nigerian 28-Bus Transmission Network is a realistic model of the Nigerian 330 kV grid. Grid data were collected from the Transmission Company of Nigeria (TCN) and cross-checked with existing literature sources [22–25].

3. Results

3.1. The Result Gotten from the Performance of the Power Flow Analysis on Longitudinal Transmission System Using Newton-Raphson (NR) Method

Both test systems were modeled using the bus and line information. A power flow study was performed on test systems using the Newton-Raphson method. Test systems were studied for three different cases. Case one shows the steady state of the network, whereas case two describes the manual position of the Thyristor Controlled Series Compensator device in the network, and the third case describes the optimum position of the TCSC device in test systems using Hippopotamus Optimization Algorithm. Voltage magnitude, voltage improvement index, line flows, line losses, and generation cost for each case were recorded for analysis. Parameters for the HOA algorithm adopted for the optimization process are shown in **Table 2**, which presents data related to bus system information with voltage, angle, load, generation, and power information for 14 bus systems. Each bus contains information on voltage magnitude and angle in degrees, load in megawatts (MW) and megavolt-amperes reactive (Mvar), generation in MW and Mvar, and power in MW and Mvar. Total load is 259 MW and 73.5 Mvar, whereas total generation is 272.599 MW and 104.517 Mvar, with a net power of 13.599 MW and 31.017 Mvar, respectively.

Table 2. The Parameters of the HOA Used for the Optimization Process for the 14 Bus System.

Bus Data								
Bus No.	**Voltage Mag.**	**Angle Degree**	**Load**		**Generation**		**Power**	
			MW	**Mvar**	**MW**	**Mvar**	**MW**	**Mvar**
1	1.060	0.000	0.000	0.000	232.599	−15.262	232.599	−15.262
2	1.045	−4.991	21.700	12.700	40.000	47.956	18.300	35.256
3	1.010	−12.752	94.200	19.000	0.000	27.971	−94.200	8.971
4	1.013	−10.244	47.800	−3.900	0.000	0.000	−47.800	−3.900
5	1.017	−8.762	7.600	1.600	0.000	0.000	−7.600	−1.600
6	1.070	−14.448	11.200	7.500	0.000	23.422	−11.200	15.922
7	1.046	−13.238	0.000	0.000	0.000	0.000	0.000	0.000
8	1.080	−13.238	0.000	0.000	0.000	21.031	0.000	21.031
9	1.031	−14.822	29.500	16.600	0.000	0.000	−29.500	−16.600
10	1.030	−15.037	9.000	5.800	0.000	0.000	−9.000	−5.800
11	1.046	−14.859	3.500	1.800	0.000	0.000	−3.500	−1.800
12	1.053	−15.299	6.100	1.600	0.000	0.000	−6.100	−1.600
13	1.047	−15.333	13.500	5.800	0.000	0.000	−13.500	−5.800
14	1.019	−16.073	14.900	5.000	0.000	0.000	−14.900	−5.000
	Total		259.000	73.500	272.599	104.517	13.599	31.017

Additionally, it includes the line losses for each connection. The data provides insights into the efficiency and performance of the network's power distribution.

Table 3 presents line data for an electrical network, detailing power flow between various nodes. Each row contains information about power transfer from one node to another, including both real power (MW) and reactive power (Mvar) in both directions.

Table 3. Line Data for an Electrical Network for the 14 Bus System.

Line Data							
Line from to		**From»To**		**To»From**		**Power**	
		MW	**Mvar**	**MW**	**Mvar**	**MW**	**Mvar**
1	2	157.061	−17.515	−152.748	30.674	4.312	13.159
1	5	75.539	7.984	−72.766	3.468	2.773	11.451
2	3	73.387	5.934	−71.054	3.895	2.333	9.829
2	4	55.945	2.944	−54.276	2.123	1.670	5.067
2	5	41.716	4.724	−40.796	−1.917	0.920	2.807
3	4	−23.146	7.763	23.538	−6.764	0.391	0.999
4	5	−59.590	11.596	60.071	−10.084	0.481	1.511
4	7	26.470	−3.767	−26.470	5.184	0.000	1.418
4	9	14.983	3.535	−14.983	−2.298	0.000	1.237
5	6	42.770	12.681	−42.770	−8.344	0.000	4.337
6	11	8.288	8.899	−8.165	−8.642	0.123	0.257
6	12	8.066	3.177	−7.985	−3.010	0.081	0.168
6	13	18.337	9.980	−18.085	−9.484	0.252	0.496
7	8	0.000	−20.363	−0.000	21.031	0.000	0.668
7	9	27.066	14.797	−27.066	−13.840	0.000	0.957
9	10	4.392	−0.906	−4.386	0.922	0.006	0.016
9	14	8.636	0.322	−8.547	−0.131	0.086	0.190
10	11	−4.614	−6.722	4.665	6.842	0.051	0.120
12	13	1.885	1.410	−1.874	−1.400	0.011	0.010
13	14	6.459	5.083	−6.353	−4.869	0.105	0.215
			Total			13.599	54.912

It is apparent from **Table 4** that voltage magnitude, angle, load in megawatts (MW) and megavars (Mvar), as well as generation in MW and Mvar, for each bus are given in **Table 3**. The maximum generation is with Bus 1 and is 232.530 MW, whereas other buses, such as Bus 3, Bus 8, etc., are having considerable loads without any generation. The total load is 259.000 MW and 73.500 Mvar, whereas total generation is 272.530 MW and 103.396 Mvar, resulting in a power output of 13.530 MW and 29.896 Mvar.

Table 4. Load Analysis Result for Manual Sizing for14 Bus System.

Bus Data								
Bus No.	Voltage Mag.	Angle Degree	Load		Generation		Power	
			MW	Mvar	MW	Mvar	MW	Mvar
1	1.060	0.000	0.000	0.000	232.599	−15.420	232.599	−15.420
2	1.045	−5.017	21.700	12.700	40.000	47.787	18.300	35.087
3	1.010	−12.142	94.200	19.000	0.000	26.712	−94.200	7.712
4	1.013	−10.065	47.800	−3.900	0.000	0.000	−47.800	3.900
5	1.017	−8.658	7.600	1.600	0.000	0.000	−7.600	−1.600
6	1.070	−14.463	11.200	7.500	0.000	22.997	−11.200	15.497
7	1.045	−13.254	0.000	0.000	0.000	0.000	−0.000	−0.000
8	1.080	−13.254	0.000	0.000	0.000	21.320	−0.000	21.320
9	1.030	−14.942	29.500	16.600	0.000	0.000	−29.500	−16.600
10	1.029	−15.139	9.000	5.800	0.000	0.000	−9.000	−5.800
11	1.046	−14.917	3.500	1.800	0.000	0.000	−3.500	−1.800
12	1.055	−15.045	6.100	1.600	0.000	0.000	−6.100	−1.600
13	1.047	−15.276	13.500	5.800	0.000	0.000	−13.500	−5.800
14	1.019	−16.117	14.900	5.000	0.000	0.000	−14.900	−5.000
	Total		259.000	73.500	272.530	103.396	13.530	29.896

The total power loss is summed at the bottom, with 12.875 MW and 52.967 Mvar in total line losses shown in **Table 5**.

Table 5. Line Data Analysis Result for Manual Sizing for 14 Bus System.

Line Data							
Line from to		From»To		To»From		Power	
		MW	Mvar	MW	Mvar	MW	Mvar
1	2	157.845	−17.698	−153.489	30.990	4.356	13.292
1	5	74.685	8.008	−71.974	3.189	2.712	11.198
2	3	67.663	6.527	−65.675	1.852	1.989	8.378
2	4	53.931	3.279	−52.378	1.434	1.553	4.713
2	5	40.426	4.994	−39.560	−2.352	0.866	2.642
3	4	−19.359	5.962	19.628	−5.274	0.269	0.688
4	5	−56.646	10.880	57.080	−9.517	0.434	1.364
4	7	28.180	−3.332	−28.180	4.929	−0.000	1.597
4	9	15.947	3.838	−15.947	−2.434	0.000	1.404
5	6	43.668	12.817	−43.668	−8.298	0.000	4.519
6	11	8.726	8.937	−8.596	−8.666	0.129	0.271
6	12	6.054	3.270	−6.003	−3.164	0.051	0.106
6	13	17.459	10.372	−17.220	−9.903	0.238	0.469
7	8	−0.000	−20.633	0.000	21.320	0.000	0.687
7	9	28.814	15.329	−28.814	−14.256	0.000	1.073
9	10	3.964	−0.924	−3.959	0.937	0.005	0.013
9	14	8.131	0.380	−8.052	−0.210	0.079	0.169
10	11	−5.041	−6.737	5.096	6.866	0.055	0.128
12	13	3.266	0.942	−3.243	−0.921	0.023	0.021
13	14	6.963	5.024	−6.848	−4.790	0.115	0.234
			Total			12.875	52.967

3.2. Simulation Results Summary for 14 Bus Test System

In the base case, the active power loss was 13.5992 MW, with a reactive power loss of 54.9117 Mvar and a system cost due to losses of $6799.577. In the case of manual sizing, the active power loss reduced to 12.8749 MW, the reactive power loss decreased to 52.9665 Mvar, and the system cost lowered to $6454.7354. In the case of optimal sizing by using HOA, it drastically improved, with an active power loss of 4.1014 MW, a reactive power loss of 22.1501 Mvar, and a system cost drastically reduced to $2788.4383. The best solution provided by HOA for the objective function F1 was given by the values 0.19138, 0.17356, 0.037318, 2.1928, 3.5, and 7.4146, while the optimal value of the objective function was 4.5228. The bar chart depicts the real power loss in MW for three different methods, namely Base Case, Manual Sizing, and HOA Sizing. The HOA Sizing method gives significantly lower power loss as compared to other methods, indicating that HOA Sizing is the most effective method presented among all three (**Figure 1**). The bar graph shows a comparison of reactive power loss in Mvar. Base Case and Manual Sizing show approximately the same but higher reactive power loss, while HOA Sizing gives a significantly lower loss (**Figure 2**). Similarly, **Figure 3** shows a comparison in system cost, in which HOA Sizing gives a significantly lower cost. This indicates that HOA Sizing is the most cost-effective method presented among the three figures. **Figure 3** is the System Cost Accounted to Losses, shows the impact of transmission losses on total operating cost, highlighting that loss reduction improves economic efficiency. **Figure 4** is the Voltage Profile, displays bus voltage magnitudes across the network, indicating improved voltage stability and compliance with operating limits. **Figure 5** is the Convergence of Objective Function, illustrates the iterative decline of the objective function, confirming fast convergence and computational efficiency.

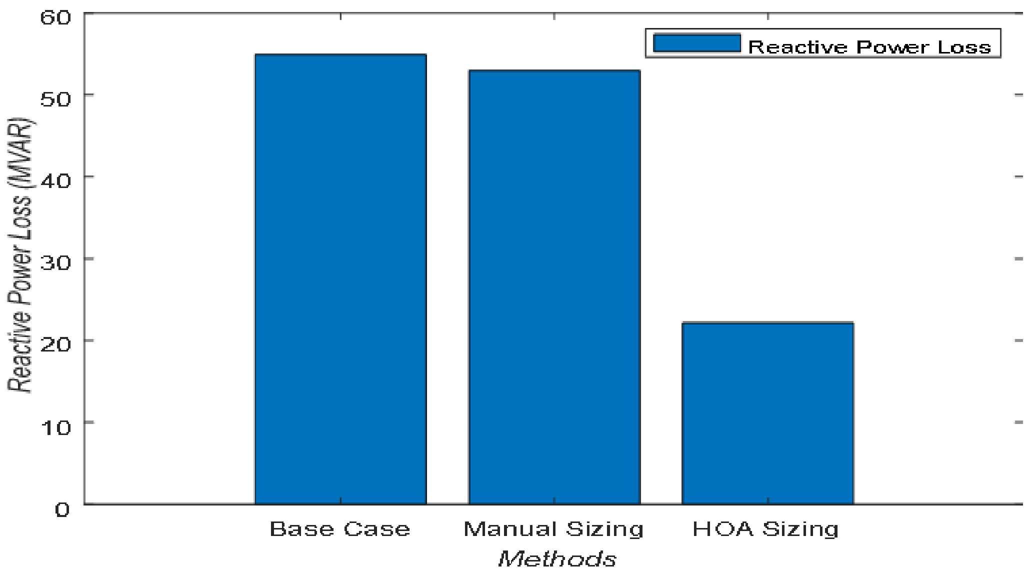

Figure 2. 14-Bus System Reactive Power Loss.

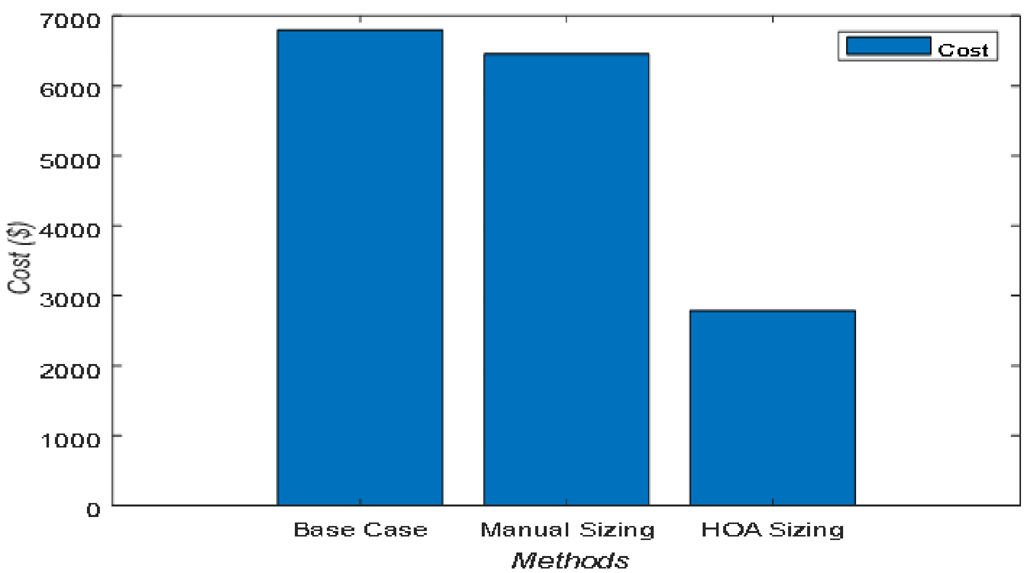

Figure 3. 14-Bus System Cost Accounted to Losses.

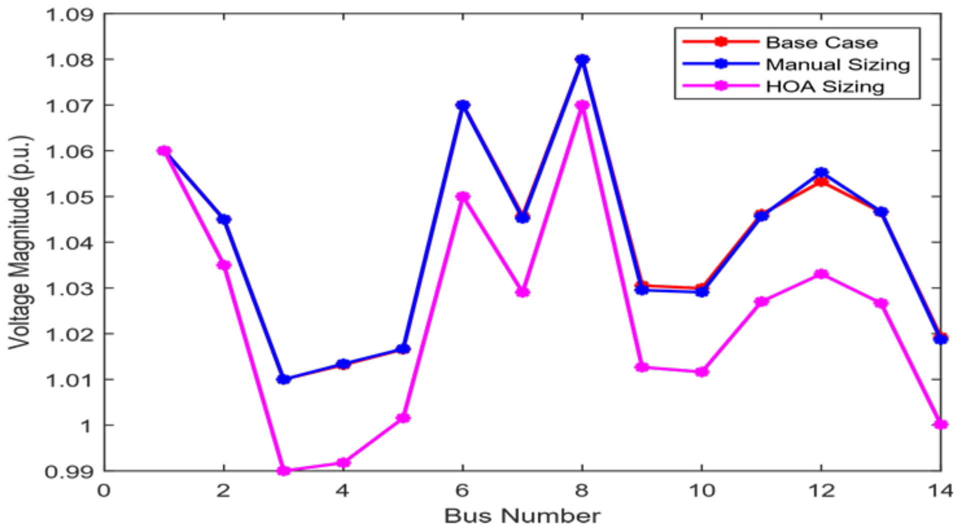

Figure 4. 14-Bus System Voltage Profile.

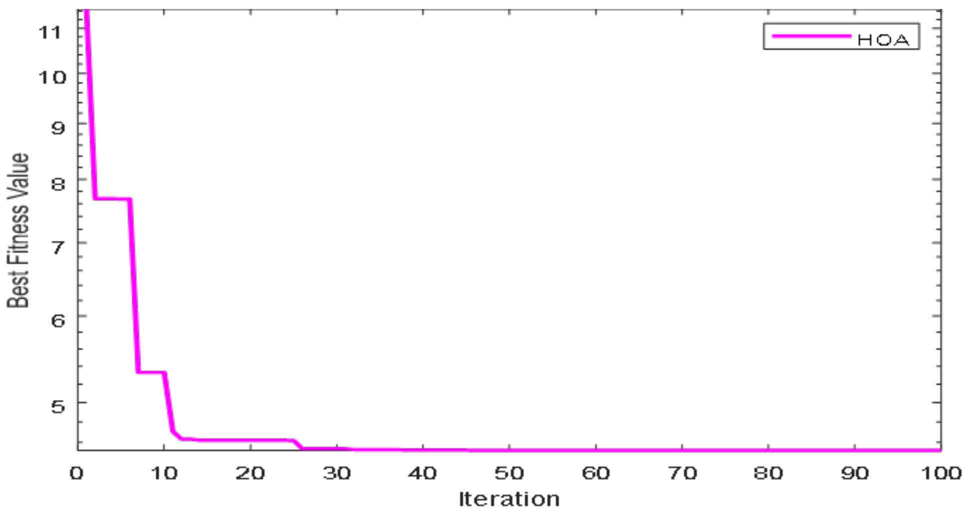

Figure 5. 14-Bus System Convergence of Objective Function.

3.3. Result Gotten from Hippopotamus-Optimized Newton–Raphson Method Incorporating TCSC Firing Angle Model

Table 6 is a structured tabular form of the bus data relevant to the power system being analyzed. It provides a systematic outlook of the electrical quantities at each bus. Parameters such as voltage magnitude, voltage angle, active power (in MW), and Mvar, as well as active power (in MW) and Mvar for power generation, are taken into consideration for each bus in the table. This detailed information facilitates analysis of the electrical values for the 14 buses in the power system. From the detailed result, it is evident that the total power load is given by 259 MW for active power and 73.5 Mvar for reactive power, whereas the total active and reactive power generated is 276.379 MW and 75.805 Mvar, respectively. This yields a positive power balance of 17.379 MW for active power and 2.305 Mvar in the power system.

Table 7 presents the power flow characteristics of the transmission network in active and reactive power components in megawatts (MW) and megavolt-amperes reactive (Mvar). In this table, for each transmission line, the power flow values are given in both directions-that is, the path “From → To” and “To → From”-thus indicating the bidirectional nature of power transfer in the system. Besides the directional power flow values, the table also gives the amount of line losses at every transmission segment. At the bottom of the table, the cumulative sum of these losses is shown, indicating the total line losses to be 4.101 MW in active power and 22.150 Mvar in reactive power, thus giving a clear measure of the transmission loss within the network.

Table 6. Load Analysis for Optimal Sizing for a 14 Bus System using HOA.

Bus Data								
Bus No.	**Voltage Mag.**	**Angle Degree**	**Load**		**Generation**		**Power**	
			MW	**Mvar**	**MW**	**Mvar**	**MW**	**Mvar**
1	1.060	0.000	0.000	0.000	236.379	−22.161	236.379	−22.161
2	1.035	−2.965	21.700	12.700	40.000	41.992	18.300	29.292
3	0.990	−4.025	94.200	19.000	−0.000	9.594	−94.200	−9.406
4	0.992	−3.674	47.800	−3.900	0.000	0.000	−47.800	3.900
5	1.002	−3.674	7.600	1.600	0.000	0.000	−7.600	−1.600
6	1.050	−3.215	11.200	7.500	0.000	21.504	−11.200	14.004
7	1.029	−8.757	0.000	0.000	0.000	0.000	0.000	−0.000
8	1.070	−6.980	0.000	0.000	0.000	24.875	−0.000	24.875
9	1.013	−8.720	29.500	16.600	0.000	0.000	−29.500	−16.600
10	1.012	−9.021	9.000	5.800	0.000	0.000	−9.000	−5.800
11	1.027	−9.010	3.500	1.800	0.000	0.000	−3.500	−1.800
12	1.033	−9.610	6.100	1.600	0.000	0.000	−6.100	−1.600
13	1.027	−9.617	13.500	5.800	0.000	0.000	−13.500	−5.800
14	1.000	−10.180	14.900	5.000	0.000	0.000	−14.900	−5.000
	Total		259.000	73.500	276.379	75.805	17.379	2.305

Table 7. Line Data Analysis for Optimal Sizing for a 14 Bus System using HOA.

Line Data							
Line from to		**From»To**		**To»From**		**Power**	
		MW	**Mvar**	**MW**	**Mvar**	**MW**	**Mvar**
1	2	100.557	14.292	−98.775	−8.857	1.781	5.435
1	5	31.747	20.846	−31.054	−17.983	0.693	2.863
2	3	14.361	20.202	−14.091	−19.067	0.270	1.136
2	4	14.051	20.780	−13.710	−19.744	0.341	1.036
2	5	8.239	17.214	−8.045	−16.623	0.194	0.591
3	4	−3.392	0.302	3.400	−0.282	0.008	0.020
4	5	−23.794	−15.336	23.903	15.679	0.109	0.343
4	7	28.142	−6.034	−28.142	7.749	0.000	1.716
4	9	15.882	2.815	−15.882	−1.396	0.000	1.418
5	6	40.300	13.856	−40.300	−9.782	−0.000	4.073
6	11	6.669	8.948	−6.562	−8.723	0.107	0.225
6	12	7.860	3.221	−7.780	−3.054	0.080	0.167
6	13	17.511	10.002	−17.267	−9.522	0.244	0.481
7	8	0.000	−23.923	−0.000	24.875	0.000	0.952
7	9	28.775	15.743	−28.775	−14.625	0.000	1.118
9	10	5.994	−0.989	−5.983	1.019	0.011	0.030
9	14	9.671	0.266	−9.555	−0.020	0.116	0.247
10	11	−3.017	−6.819	3.062	6.923	0.045	0.104
12	13	1.680	1.454	−1.669	−1.444	0.010	0.009
13	14	5.436	5.166	−5.345	−4.980	0.091	0.186
			Total			4.101	22.150

Table 8 compares TCSC placement and reactance values obtained using the Manual Method and HOA, showing that HOA identifies different optimal locations (2, 4, 7) with refined reactance sizes that potentially enhance system performance more effectively than the manual approach.

Table 8. TCSC Sizes and Locations for IEEE 14 Bus System.

TCSC Specification	Manual Method	HOA
Location	3, 9, 12	2, 4, 7
Reactance Size	0.026, −0.16, 0.1	0.19138, 0.17356, 0.037318

3.4. Validation and Performance Evaluation of Modified NR on IEEE 14-Bus and Nigerian 28-Bus Systems

Since the power system in consideration does not include a Thyristor Controlled Series Compensator, the results shown are those of the base case load flow study of the Nigerian 28-bus test system. **Table 9** shows in detail the electrical parameters at each bus of the network, including voltage magnitude and voltage angle, load demand, power generation, and net power in MW and Mvar. All 28 buses are represented in the table, each with its specific load and generation contributing to its net power. The values summarized at the end of the table are the system totals, depicting the total load demand and the total power generation to give an overview of the net power distribution in the network.

Table 9. Load Flow Analysis of the Nigerian 28 Bus Test System without TCSC for the 28 Bus System.

Bus Data								
Bus No.	Voltage Mag.	Angle Degree	Load		Generation		Power	
			MW	Mvar	MW	Mvar	MW	Mvar
1	1.000	0.000	150.000	105.200	−3540.228	1563.199	−3540.228	1563.199
2	1.000	18.379	200.000	300.000	882.000	−213.130	682.000	−513.130
3	1.050	14.335	0.000	0.000	760.000	−279.958	760.000	−279.958
4	1.050	16.318	0.000	0.000	600.000	−1173.363	600.000	−1173.363
5	1.050	13.406	0.000	0.000	1020.000	−645.443	1020.000	−645.443
6	1.010	14.868	0.000	0.000	578.000	−986.499	578.000	−986.499
7	1.020	34.828	0.000	0.000	931.600	−430.4777	931.600	−430.477
8	1.000	0.074	0.000	0.000	302.000	−85.254	302.000	−85.254
9	1.000	25.788	0.000	0.000	480.000	−80.478	480.000	−80.478
10	1.050	41.431	0.000	0.000	600.000	−427.797	600.000	−427.797
11	1.197	11.569	0.000	0.000	0.000	0.000	0.000	−0.000
12	1.013	14.684	130.000	80.000	0.000	0.000	−130.000	−80.000
13	1.192	11.848	220.000	154.800	0.000	0.000	−220.000	−154.800
14	1.047	15.420	114.000	90.000	0.000	0.000	−114.000	−90.000
15	1.007	7.737	110.000	80.000	0.000	0.000	−110.000	−80.000
16	1.026	9.585	104.000	70.000	0.000	0.000	−104.000	−70.000
17	1.061	12.023	36.000	25.000	0.000	0.000	−36.000	−25.000
18	1.075	11.211	72.000	45.000	0.000	0.000	−72.000	−45.000
19	0.973	5.596	136.000	84.000	0.000	0.000	−136.000	−84.000
20	0.977	6.043	72.000	45.000	0.000	0.000	−72.000	−45.000
21	0.999	24.034	39.000	27.400	0.000	0.000	−39.000	−27.400
22	1.008	27.257	84.000	50.000	0.000	0.000	−84.000	−50.000
23	1.011	33.875	146.000	84.500	0.000	0.000	−146.000	−84.500
24	1.026	15.764	32.000	17.800	0.000	0.000	−32.000	−17.800
25	0.995	−0.332	110.000	80.000	0.000	0.000	−110.000	−80.000
26	1.089	12.490	100.000	58.400	0.000	0.000	−100.000	−58.400
27	1.122	14.281	80.000	49.600	0.000	0.000	−80.000	−49.600
28	1.147	13.874	26.000	15.500	0.000	0.000	−26.000	−15.300
	Total		1961.000	1462.000	2613.372	−2759.201	802.372	−4116.001

The total line losses mentioned in the table at the end are indicative of the accumulated active and reactive power losses occurring along the transmission lines in the network, thereby indicating the inefficiency levels of the entire system. These accumulated loss values indicate the combined influence of the power losses occurring along various individual line sections of the power transmission system, taking into account factors like the line impedance values along with the power levels of the flows. Therefore, the information given in **Table 10** helps indicate the power distribution phenomena along with the loss factors of the network.

Table 11 is a detailed representation of the operating conditions of the 28 bus power system, with each bus represented by voltage magnitude, voltage angle in degrees, load demand, power generation, and net power in megawatts (MW) and megavolt-amperes reactive (Mvar). This table is detailed enough to provide information about the distribution of electrical power among the 28 bus power systems, represented by their respective active and reactive power demands. From the results, it can be observed that the total system power is 1961 MW with a total of 1462 Mvar, whereas the total power developed is 2581.448 MW with a total of −2804.196 Mvar. This implies that the total net power is 770.448 MW with a total of −4160.596 Mvar, signifying that the system harvests more active power but consumes more reactive power.

Table 12 below shows the detailed information about the performance of the transmission lines in the network, with each row representing the performance of a line between two buses. This information is given for each line, with power flow information given for both "From → To" and "To → From" paths, representing the bidirectional power transmission through the network. These values are accompanied by their respective active and reactive power components, which represent an entire representation of power transmission through the line. Furthermore, this information also provides specifics about the losses that occur through each transmission line. These results are then summarized for each line, with information given for the total active power loss of 769.164 MW for the line, accompanied by a total reactive power loss of 1701.814 Mvar.

Table 10. Line Data of NIGERIAN 28 Bus Test System without TCSC for 28 Bus System.

Line Data							
Line from to		**From»To**		**To»From**		**Power**	
		MW	**Mvar**	**MW**	**Mvar**	**MW**	**Mvar**
1	8	−302.903	75.682	302.000	−75.294	0.097	0.387
1	20	−3348.447	1439.534	3401.585	−1054.287	53.137	358.246
1	25	110.123	73.364	−110.000	−72.366	0.123	0.998
3	17	680.161	−263.427	−676.300	293.828	3.860	30.401
2	24	682.000	−477.280	−676.457	520.934	5.543	43.654
3	26	101.195	147.986	−100.000	156.848	1.195	8.862
3	12	−21.356	472.789	23.388	−456.129	2.032	16.659
4	27	339.947	−810.086	−332.247	877.991	7.701	67.905
4	12	144.053	152.987	−143.172	−143.615	0.881	9.372
4	14	115.999	−105.053	−114.000	106.542	1.999	1.488
5	17	1659.666	−1003.755	−1652.842	1054.939	6.825	51.184
5	24	−639.666	501.030	644.457	−463.305	4.791	37.726
6	12	578.000	−976.339	−576.738	981.387	1.262	5.048
7	23	931.600	−398.017	−916.803	409.854	14.797	11.837
9	21	480.000	−44.628	−478.141	59.269	1.859	14.641
10	23	600.000	−341.141	−529.570	401.633	70.430	60.492
11	13	0.000	217.031	1.052	−216.143	1.052	0.888
12	16	566.523	−127.821	−560.309	173.819	6.214	51.998
13	27	−221.052	448.734	225.807	−413.161	4.755	35.573
15	16	−350.998	−137.660	352.820	151.675	1.822	14.015
15	20	240.998	200.229	−239.450	−187.259	1.549	12.970
16	17	−196.215	−116.865	197.702	129.453	1.487	12.589
16	20	299.704	185.288	−295.811	−158.508	3.893	26.780
17	18	72.242	−81.441	−72.000	83.524	0.242	2.083
17	20	3517.869	−1522.664	−3074.478	1731.319	443.391	208.654
17	21	−1494.670	812.961	1535.779	−455.832	41.108	357.129
19	20	−136.000	−47.482	136.153	48.731	0.153	1.249
21	22	−584.169	−3.287	587.927	36.427	3.758	33.140
21	23	−512.469	619.473	617.945	−528.880	105.477	90.593
22	23	−671.927	110.401	682.428	−32.333	10.500	78.069
27	28	26.440	−140.703	−26.000	143.992	0.440	3.289
			Total			802.372	1674.919

Table 11. Load Analysis Result for Manual Sizing for 28 Bus System.

Bus Data								
Bus No.	**Voltage Mag.**	**Angle Degree**	**Load**		**Generation**		**Power**	
			MW	**Mvar**	**MW**	**Mvar**	**MW**	**Mvar**
1	1.000	0.000	150.000	105.200	−3572.152	1563.199	−3572.152	1509.703
2	1.000	18.286	200.000	300.000	882.000	−213.130	682.000	−513.130
3	1.050	14.103	0.000	0.000	760.000	−279.958	760.000	−278.301
4	1.050	15.882	0.000	0.000	600.000	−1173.363	600.000	−1197.008
5	1.050	13.314	0.000	0.000	1020.000	−645.443	1020.000	−636.092
6	1.010	14.443	0.000	0.000	578.000	−986.499	578.000	−964.741
7	1.020	33.730	0.000	0.000	931.600	−430.4777	931.600	−396.383
8	1.000	0.074	0.000	0.000	302.000	−85.254	302.000	−85.254
9	1.000	25.811	0.000	0.000	480.000	−80.478	480.000	−117.875
10	1.050	40.340	0.000	0.000	600.000	−427.797	600.000	−425.114
11	1.244	10.251	0.000	0.000	0.000	0.000	0.000	−0.000
12	1.013	14.260	130.000	80.000	0.000	0.000	−130.000	−80.000
13	1.239	10.530	220.000	154.800	0.000	0.000	−220.000	−154.800
14	1.047	14.984	114.000	90.000	0.000	0.000	−114.000	−90.000
15	1.016	8.923	110.000	80.000	0.000	0.000	−110.000	−80.000
16	1.023	8.794	104.000	70.000	0.000	0.000	−104.000	−70.000
17	1.061	11.120	36.000	25.000	0.000	0.000	−36.000	−25.000
18	1.075	11.120	72.000	45.000	0.000	0.000	−72.000	−45.000
19	0.975	5.629	136.000	84.000	0.000	0.000	−136.000	−84.000
20	0.979	6.074	72.000	45.000	0.000	0.000	−72.000	−45.000
21	1.002	24.044	39.000	27.400	0.000	0.000	−39.000	−27.400
22	1.009	25.430	84.000	50.000	0.000	0.000	−84.000	−50.000
23	1.011	32.805	146.000	84.500	0.000	0.000	−146.000	−84.500
24	1.026	15.672	32.000	17.800	0.000	0.000	−32.000	−17.800
25	0.995	−0.332	110.000	80.000	0.000	0.000	−110.000	−80.000
26	1.089	12.258	100.000	58.400	0.000	0.000	−100.000	−58.400
27	1.124	13.832	80.000	49.600	0.000	0.000	−80.000	−49.600
28	1.149	13.425	26.000	15.500	0.000	0.000	−26.000	−15.300
	Total		1961.000	1462.000	2581.488	−2804.196	770.448	4160.996

Table 12. Line Data Analysis Result for Manual Sizing for 28 Bus System.

Line Data							
Line from to		**From»To**		**To»From**		**Power**	
		MW	**Mvar**	**MW**	**Mvar**	**MW**	**Mvar**
1	8	−301.903	75.682	302.000	−75.294	0.097	0.387
1	20	−3380.371	1386.038	3433.763	−998.946	53.392	387.092
1	25	110.123	73.364	−110.000	−72.366	0.123	0.998
3	17	637.364	−257.461	−633.918	284.461	3.429	27.000
2	24	682.000	−477.280	−676.457	520.934	5.543	43.654
3	26	101.195	−147.986	−100.000	156.848	1.195	8.862
3	12	21.459	468.986	−19.464	−452.122	1.995	16.358
4	27	340.886	−834.179	−332.784	905.626	8.102	71.446
4	12	143.115	153.434	−142.236	−144.091	0.878	9.344
4	14	115.999	−105.053	−114.000	106.542	1.999	1.488
5	17	1659.666	−994.404	−1652.875	1045.333	6.791	50.930
5	24	−639.666	501.030	644.457	−463.305	4.791	37.726
6	12	578.000	−954.581	−576.779	959.464	1.221	4.883
7	23	931.600	−363.923	−917.178	375.461	14.422	11.538
9	21	480.000	−82.025	−478.103	96.964	1.897	14.939
10	23	600.000	−338.458	−529.839	398.719	70.161	60.261
11	13	0.000	234.358	1.136	−233.399	1.136	0.959
12	16	608.479	−103.487	−601.429	162.490	7.051	59.003
13	27	−296.384	752.972	307.907	−666.764	11.523	86.209
15	16	−14.550	−67.949	−14.490	68.417	0.061	0.468
15	20	398.135	245.024	−394.749	−216.664	3.386	28.360
16	17	−248.115	−119.942	250.293	138.386	2.178	18.444
16	20	233.751	168.642	−231.130	−150.611	2.621	18.031
17	18	72.242	−81.408	−72.000	83.491	0.242	2.082
17	20	3441.301	−1499.018	−3016.038	1699.141	425.263	200.124
17	21	−1513.043	799.142	1554.630	−437.853	41.587	361.289
19	20	−136.000	−47.350	136.153	48.593	0.153	1.243
21	22	−256.766	−42.294	257.508	48.839	0.742	6.545
21	23	−457.463	553.256	541.165	−481.365	83.702	71.891
22	23	−746.811	139.767	759.852	−42.811	13.041	96.956
27	28	26.442	−141.325	−26.000	144.629	0.442	3.304
			Total			769.164	1701.814

In a nutshell, the data organized in **Table 13** signifies the information for individual buses, while each line of the table belongs to a single bus within the whole power system network. In each bus, the table presents complete electric measurements, active and reactive power values in MW-Mvar. These values segregate the contributions from load demands and power generation. Therefore, it is very distinct and elaborate for defining the operating characteristics of each bus under consideration.

Table 13. Load Analysis for Optimal Sizing Using HOA for 28 Bus System.

Bus Data								
Bus No.	**Voltage Mag.**	**Angle Degree**	**Load**		**Generation**		**Power**	
			MW	**Mvar**	**MW**	**Mvar**	**MW**	**Mvar**
1	1.000	0.000	150.000	105.200	−3587.588	1610.994	−3587.588	1613.994
2	1.000	18.562	200.000	300.000	882.000	−213.130	682.000	−513.130
3	1.050	14.452	0.000	0.000	760.000	−745.090	760.000	−745.090
4	1.050	16.768	0.000	0.000	600.000	−1165.541	600.000	−1165.541
5	1.050	13.590	0.000	0.000	1020.000	−634.813	1020.000	−634.813
6	1.010	15.300	0.000	0.000	578.000	−545.655	578.000	−545.655
7	1.020	28.889	0.000	0.000	931.600	−634.813	931.600	−386.226
8	1.000	0.074	0.000	0.000	302.000	−85.254	302.000	−85.254
9	1.000	26.555	0.000	0.000	480.000	−207.279	480.000	−207.279
10	1.050	36.025	0.000	0.000	600.000	−490.152	600.000	−490.152
11	1.197	12.019	0.000	0.000	0.000	0.000	0.000	−0.000
12	1.013	15.141	130.000	80.000	0.000	0.000	−130.000	−80.000
13	1.192	12.298	220.000	154.800	0.000	0.000	−220.000	−154.800
14	1.047	15.870	114.000	90.000	0.000	0.000	−114.000	−90.000
15	1.007	7.915	110.000	80.000	0.000	0.000	−110.000	−80.000
16	1.026	9.820	104.000	70.000	0.000	0.000	−104.000	−70.000
17	1.061	12.207	36.000	25.000	0.000	0.000	−36.000	−25.000
18	1.075	11.395	72.000	45.000	0.000	0.000	−72.000	−45.000
19	0.973	5.694	136.000	84.000	0.000	0.000	−136.000	−84.000
20	0.977	6.142	72.000	45.000	0.000	0.000	−72.000	−45.000
21	0.999	24.720	39.000	27.400	0.000	0.000	−39.000	−27.400
22	1.008	30.120	84.000	50.000	0.000	0.000	−84.000	−50.000

Table 13. *Cont.*

Bus Data								
Bus No.	Voltage Mag.	Angle Degree	Load		Generation		Power	
			MW	Mvar	MW	Mvar	MW	Mvar
23	1.011	27.9991	146.0000	84.5000	0.000	0.000	−146.0000	−84.5000
24	1.026	15.948	32.0000	17.8000	0.000	0.000	−32.0000	−17.8000
25	0.995	−0.3332	110.0000	80.0000	0.000	0.000	−110.0000	−80.0000
26	1.089	12.607	100.0000	58.4000	0.000	0.000	−100.0000	−58.4000
27	1.122	14.731	80.000	49.600	0.000	0.000	−80.000	−49.600
28	1.147	14.324	26.000	15.500	0.000	0.000	−26.000	−15.300
	Total		1961.000	1462.000	2566.012	−2862.145	755.012	−4218.945

In **Table 14**, the total line loss recorded is 732.052 MW. Reactive power values (Mvar) vary widely, indicating diverse operational conditions. Many lines exhibit notable differences in power flow from "From" to "To" and vice versa. Line 17–30 shows a massive power flow of 3559.512 MW.

Table 14. Line Data Analysis for Optimal Sizing using HOA for 28 Bus System.

Line Data							
Line from to		From»To		To»From		Power	
		MW	Mvar	MW	Mvar	MW	Mvar
1	8	−301.903	75.682	302.000	−75.294	0.097	0.387
1	20	−3395.807	1487.329	3450.782	−1088.763	54.975	398.566
1	25	110.123	73.364	−110.000	−72.366	0.123	0.998
3	17	659.865	−259.139	−656.218	287.857	3.647	28.719
2	24	682.000	−477.280	−676.457	520.934	5.543	43.654
3	26	101.195	−147.986	−100.000	156.848	1.195	8.862
3	12	−94.134	504.732	96.525	−485.125	2.391	19.607
4	27	339.947	−810.086	−332.247	877.991	7.701	67.905
4	12	144.053	160.809	−143.123	−150.916	0.930	9.893
4	14	115.999	−105.053	−114.000	106.542	1.999	1.488
5	17	1659.666	−993.124	−1652.880	1044.019	6.786	50.895
5	24	−639.666	501.030	644.457	−463.305	4.791	37.726
6	12	578.000	−535.495	−577.391	537.929	0.609	2.434
7	23	931.600	−353.495	−917.566	364.353	14.034	11.227
9	21	480.000	−172.142	−477.877	188.857	2.123	16.715
10	23	600.000	−403.496	−522.705	469.884	77.295	66.388
11	13	−0.000	217.031	1.052	−216.143	1.052	0.888
12	16	589.454	−125.129	−582.712	181.553	6.742	56.424
13	27	−221.052	448.734	225.807	−413.161	4.755	35.573
15	16	−360.273	−135.343	362.176	149.982	1.903	14.639
15	20	250.273	197.562	−248.666	−184.098	1.608	13.465
16	17	−192.713	−121.851	194.199	134.430	1.486	12.579
16	20	309.249	183.068	−305.189	−155.140	4.060	27.928
17	18	72.242	−81.404	−72.000	83.486	0.242	2.082
17	20	3559.512	−1544.445	−3105.082	1758.294	454.430	213.850
17	21	−1552.854	846.414	1597.281	−460.452	44.427	385.962
19	20	−136.000	−47.559	136.154	48.811	0.154	1.252
21	22	−906.776	349.984	917.219	−257.901	10.442	92.083
21	23	−251.627	140.318	265.223	−128.641	13.595	11.677
22	23	−181.194	−264.972	−178.716	283.398	2.478	18.426
27	28	26.440	−140.703	−26.000	143.992	0.440	3.289
			Total			732.052	1655.580

3.5. Simulation Results Summary of the 28 Bus System

Additionally, the measurement of real power loss for the base case was 802.372 MW, with the reactive power loss amounting to 1674.9194 Mvar, with a system cost attributed to losses of $401,185.9824. However, for manual sizing, the real power loss measured was 769.1636 MW with an increase of 1701.8139 Mvar of reactive power loss, with a reduced system cost of $390,005.9549. Optimal sizing using the Hippopotamus Optimization Algorithm (HOA) resulted in minimizing losses to 732.052 MW with a real power loss of 1655.5801 Mvar, accompanied by a significantly low system cost of $372,541.2951. Finally, the best solution for the objective function F1, using the HOA, consisted of the values −0.780028, −0.412723, 0.0217067, 6.68636, 7.01023, and 30.3071 with an optimum value of 733.3514 for the objective function. Finally, the bar graph given in **Figure 6** below plots real power loss in megawatts (MW) using three approaches: Base Case, Manual Sizing, and HOA Sizing. These three approaches utilized considerable quantities of power loss, amounting to approximately 800 MW for each. These approaches utilized almost equal quantities of reactive power loss. This signifies that power loss is unaffected by the approach selected, as shown in **Figure 7**. All approaches utilized costs approximately below $450,000. This graph explains that even with a closer look, there were no significant differences in costs among the approaches, as shown in **Figure 8**. As shown in **Figure 9**, this graph plots the voltage magnitude with respect to bus number for the three approaches. This graph explains that there were a considerable number of peaks for HOA Sizing with respect to other approaches that signify higher voltage for such bus numbers. This graph plots the best solution for 100 iterations of the HOA graphically. Convergence of objective function was shown in **Figure 10**.

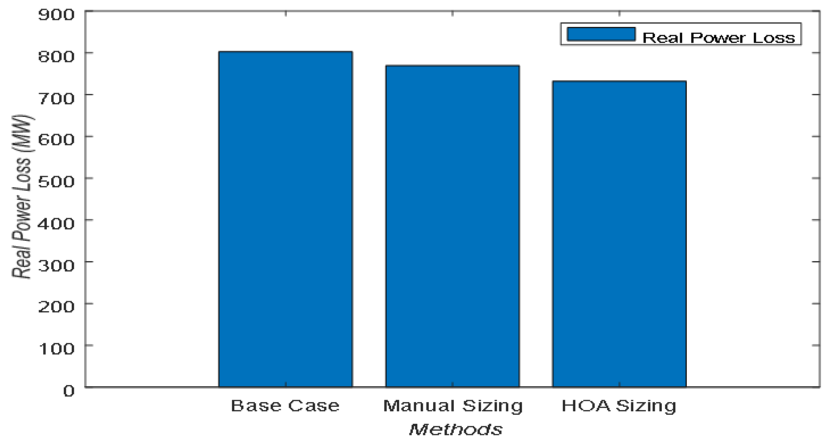

Figure 6. 28-Bus System Real Power Loss.

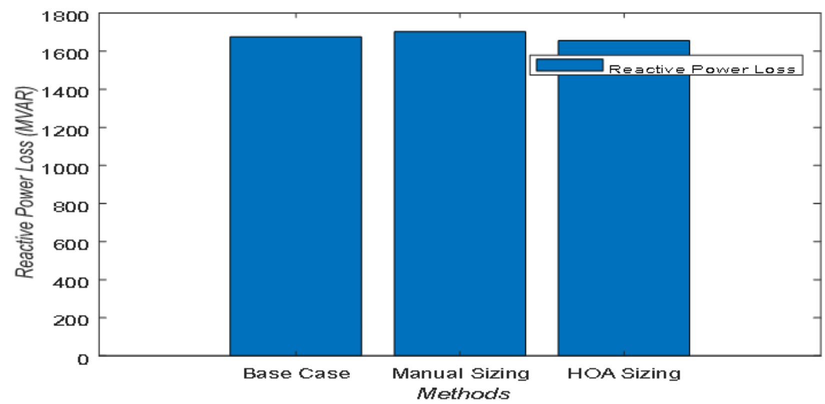

Figure 7. 28-Bus System Reactive Power Loss.

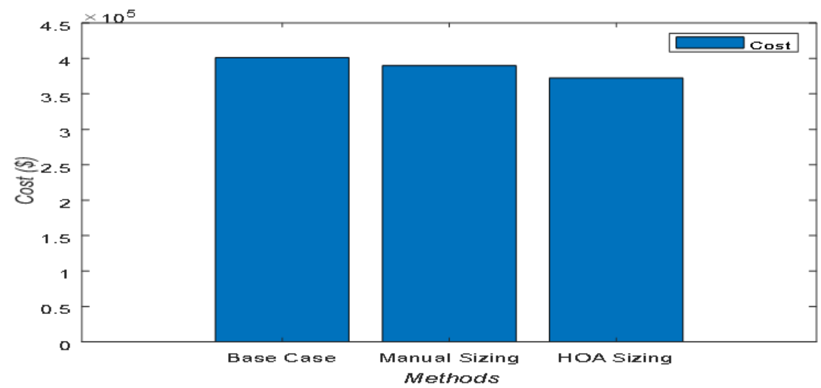

Figure 8. 28-Bus System Cost Accounted for Losses.

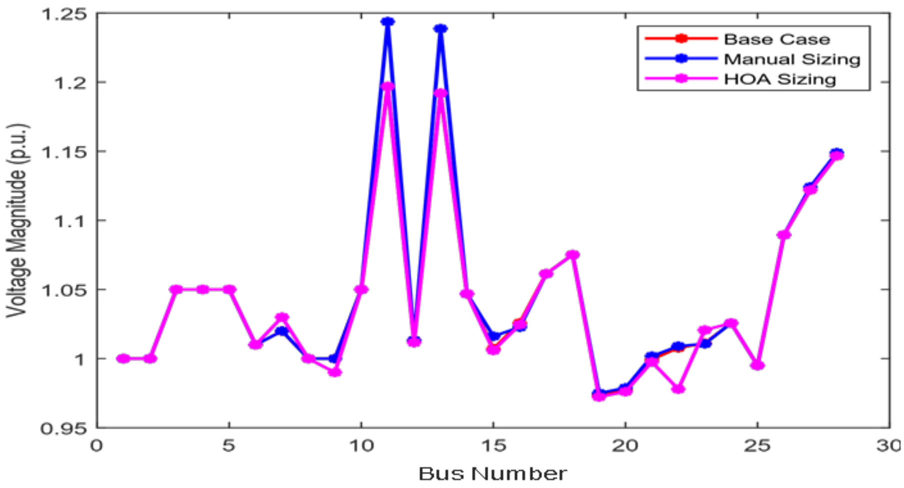

Figure 9. 28-Bus System Voltage Profile.

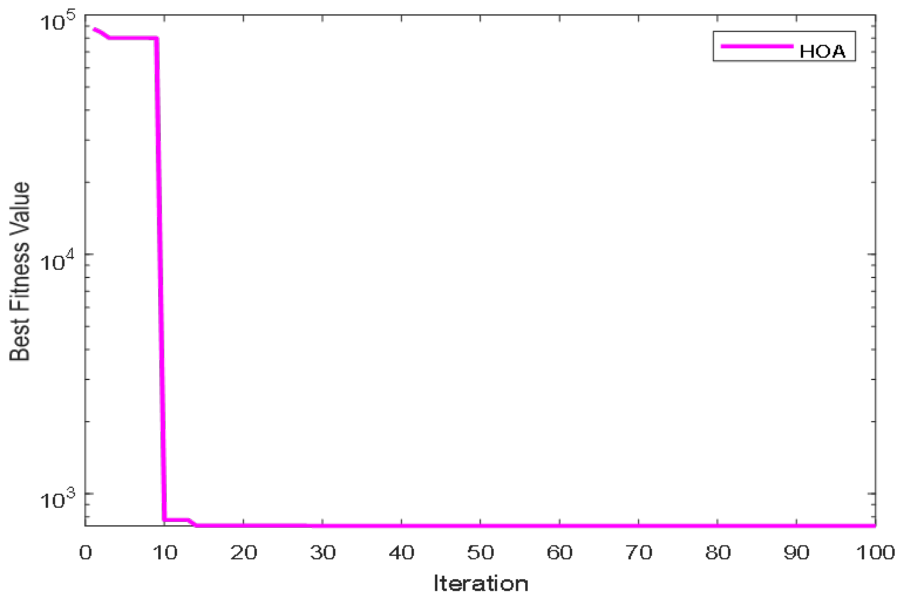

Figure 10. 28-Bus System Convergence of the Objective Function.

Table 15 shows that HOA selects different and more significant reactance values at alternative locations compared to the Manual Method, indicating improved optimization capability for enhanced power flow control and loss minimization.

Table 15. TCSC Sizes and Locations for Nigerian 28-Bus System.

TCSC Specification	Manual Method	HOA
Location	19, 20, 28	7, 7 30
Reactance Size	−0.01, 0.01, 0.006	−0.7800, −0.4127, 0.02171

4. Conclusions

The study presents an advanced optimization strategy using the Hippopotamus Optimization Algorithm to determine the optimal placement of a Thyristor Controlled Series Compensator within the Nigerian 28-bus power system for minimal power losses. Power flow analysis was carried out in the presence and absence of the TCSC device, using the Newton-Raphson method and implemented in MATLAB (R2021). For accuracy, the methodology was validated first on the IEEE 14-bus benchmark system before being extended to the Nigerian 28-bus network. The system performance assessment focuses on some key indicators: active power loss reduction, annual generation cost, and voltage profile improvements. In the Nigerian 28-bus system, the total load accounted for 1961 MW and a reactive power demand of 1462 Mvar, indicating excess reactive power consumption. Application of HOA for optimal TCSC placement resulted in a reduction of 36.25% on active power losses, which is considerably higher than the 24.83% reported earlier using a Genetic Algorithm-based approach. These results reflect the ability of HOA to enhance the deployment of TCSC and its potential for improving the efficiency and stability of the power system without the need for expensive infrastructure expansion.

Recommendation

Future work should investigate the dynamic performance analysis of the Thyristor Controlled Series Compensator (TCSC) for various loading conditions in power systems. This would enable a better understanding of the performance of TCSC devices for various loading levels. Additionally, it is necessary to investigate the application of more advanced metaheuristics for TCSC devices. Some of these algorithms include the Political Optimizer, Equilibrium Optimizer, and Dragonfly Algorithm. It is important to make a comparison of the performance of such algorithms with the Hippopotamus Optimization Algorithm (HOA) used in the present work. This would enable the selection of the best optimization solution for minimizing active power loss. It would also enable a better understanding of the improvement of voltage profiles by employing effective TCSC devices. Future work should explore research on the dynamic performance analysis of TCSC devices for various loading levels in power systems. In addition, research should be directed to investigate the application of more advanced techniques for improving power systems. This would enable the development of more optimized power systems that would improve the efficiency of power systems with minimal losses. This work would contribute significantly to improving the efficiency of power systems by selecting the best TCSC devices that could improve power systems by ensuring better operational stability without any expansion of the power systems. Some of the objectives of this work include finding the best TCSC devices that could improve power systems with better stability without any expansion of power systems.

Author Contributions

A.O.O.: writing experimental procedure; O.J.A.: modify the experimental procedure; M.O.O.: supervise the experiment; J.A.O.: prepare the manuscript first draft; J.O.A. and J.A.O.: compile and editing the manuscript. All authors have read and agreed to the published version of the manuscript.

Funding

This work received no external funding.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

Data are available from the corresponding author upon reasonable request.

Acknowledgments

The authors acknowledge the lecturers, researchers and staff from the Department of Electronic and Electrical Engineering, Faculty of Engineering and Technology, LAUTECH, Department of Engineering and Scientific Services, NCAM, Department of Soil and Water Engineering, NCAM and Mechatronics Department, BELLS University for their support and contribution towards the success of this research.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. Okelola, M.O.; Akinsanya, O.A.; Oyedokun, J.A.; et al. Optimization-Based Adaptive Coordination of Directional Overcurrent Relays in Multi-DG Radial Distribution Systems. *J. Eng. Res. Rep.* **2025**, *27*, 410–417.
2. Njukang, S.C. Electrical Power System with Environmental Sustainability Electricity Generation, Transmission, Distribution and Utilization with Environmental Sustainability and Affordability. *Int. J. Sci. Eng. Res.* **2020**, *11*. Available online: https://www.researchgate.net/publication/339251937
3. Nadeem, M.; Imran, K.; Khattak, A.; et al. Optimal Placement, Sizing and Coordination of FACTS Devices in Transmission Network Using Whale Optimization Algorithm. *Energies* **2020**, *13*, 753. [CrossRef].
4. Altaee, A.H.; Altahir, A.A.R.; Hassan, Y.F. Integration of High Voltage DC Link for Minimizing Short Circuit Level and Improving Voltage Profile for Iraqi Network. In Proceedings of the International Research Conference on Engineering and Applied Sciences 2023, Baghdad, Iraq, 16–17 October 2023. Available online: https://www.researchgate.net/publication/386019372
5. Chethan, M.; Kuppan, R. A Review of FACTS Device Implementation in Power Systems Using Optimization Techniques. *J. Eng. Appl. Sci.* **2024**, *71*, 18. [CrossRef].
6. Malla, N.B.; Parajuli, V.; Kalwar, D.K.; et al. Enhancement of Power Transfer Capability of Transmission Line Using Thyristor Controlled Series Capacitor (TCSC). *J. Electron. Comput. Netw. Appl. Math.* **2024**, *4*, 26–37. [CrossRef].
7. Shinde, S.; Gandhi, R.; Margarat, G.S.; et al. Enhancing Power System Stability and Efficiency Using Flexible AC Transmission Systems (FACTS): A Comprehensive Analysis of Control Strategies and Applications. *E3S Web Conf.* **2024**, *591*, 01014. [CrossRef].
8. Amiri, M.H.; Hashjin, N.M.; Montazeri, M.; et al. Hippopotamus Optimization Algorithm: A Novel Nature-Inspired Optimization Algorithm. *Sci. Rep.* **2024**, *14*, 5032. [CrossRef].
9. Luo, X.; Wang, J.; Dooner, M.; et al. Overview of Current Development in Electrical Energy Storage Technologies and the Application Potential in Power System Operation. *Appl. Energy* **2015**, *137*, 511–536. [CrossRef].
10. Adebisi, O.I.; Adejumobi, I.A.; Ogunbowale, P.E.; et al. Performance Improvement of Power System Networks Using Flexible Alternating Current Transmission Systems Devices: The Nigerian 330 kV Electricity Grid as a Case Study. *LAUTECH J. Eng. Technol.* **2018**, *12*, 46–55.
11. Hazeltine, B. Chapter 10—Other Technologies. In *Field Guide to Appropriate Technology*; Hazeltine, B., Bull, C., Eds.; Academic Press: Burlington, MA, USA, 2003; pp. 847–862.
12. Fasina, E.T.; Adebanji, B.; Oyedokun, J.A. Power Flow Analysis of the Nigerian Power Grid with FACTS Devices. *Int. J. Eng. Res. Dev.* **2024**, *20*, 131–136.
13. Fasina, E.T.; Adebanji, B.; Abe, A.; et al. Impact of Distributed Generation on the Nigeria Power Network. *Indones. J. Electr. Eng. Comput. Sci.* **2020**, *3*, 1263–1270.
14. Adepoju, G.A.; Komolafe, O.A. Power Injection Model of High Voltage Direct Current–Voltage Source Converter for Power Flow Analysis. In Proceedings of the International Conference on Power System Analysis, Control, and Optimization (PASCO), Vishakhapatnam, India, 13–15 March 2008; pp. 67–72.
15. Adebayo, I.G.; Adejumobi, I.A.; Olajire, O.S. Power Flow Analysis and Voltage Stability Enhancement Using Thyristor Controlled Series Capacitor (TCSC) FACTS Controller. *Int. J. Eng. Adv. Technol.* **2013**, *2*, 100–104.
16. Nguyen, T.T.; Mohammadi, F. Optimal Placement of TCSC for Congestion Management and Power Loss Reduction Using Multi-Objective Genetic Algorithm. *Sustainability* **2020**, *12*, 2813.
17. Khan, A.N.; Imran, K.; Nadeem, M.; et al. Ensuring Reliable Operation of Electricity Grid by Placement of FACTS Devices for Developing Countries. *Energies* **2021**, *14*, 2283.
18. Okelola, M.O.; Olabode, E.O. Application of Genetic Algorithm Solution Approach to Voltage Drop Issues on 33 kV/11 kV Injection Feeders: A Case Study of Ogbomoso, South West, Nigeria. *Curr. J. Appl. Sci. Technol.* **2018**, *27*, 1–10.
19. Gerbex, S.; Cherkaoui, R.; Germond, A.J. Optimal Location of Multi-Type FACTS Devices in a Power System by Means of Genetic Algorithms. *IEEE Trans. Power Syst.* **2001**, *16*, 537–544.
20. Johansson, N.; Angquist, L.; Nee, H.P. An Adaptive Controller for Power System Stability Improvement and Power Flow Control by Means of a Thyristor Switched Series Capacitor (TSSC). *IEEE Trans. Power Syst.* **2010**, *25*, 381–391.
21. Malachi, Y.; Singer, S. A Genetic Algorithm for the Corrective Control of Voltage and Reactive Power. *IEEE*

Trans. Power Syst. **2006**, *21*, 295–300.
22. Kar, M.K.; Kanungo, S.; Alsaif, F.; et al. Optimal Placement of FACTS Devices Using Modified Whale Optimization Algorithm for Minimization of Transmission Losses. *IEEE Access* **2024**, *12*, 130816–130831. [CrossRef].
23. Kar, M.K.; Parida, R.N.R.; Dash, S. Series and Shunt FACTS Controllers Based Optimal Reactive Power Dispatch. *Int. J. Appl. Power Eng.* **2023**, *13*, 247–254. [CrossRef].
24. Okelola, M.O.; Akinrinade, S.A.; Onatoyinbo, O.O.; et al. Enhancing ICMT OCR Performance and Relay Coordination in Nigeria Distribution Network using a Cascade Algorithm. *Int. J. Adv. Res. Electr. Electron. Instrum. Eng.* **2025**, *14*, 2150–2160. [CrossRef].
25. Fasina, E.T.; Adebanji, B.; Oyedokun, J.A. Frequency Regulation in Power Grid Solar PV and Energy Storage. *Int. J. Eng. Res. Dev.* **2024**, *9*, 67–71.