OPTIMAL PLACEMENT OF STATCOM FOR POWER LOSS MINIMIZATION AND VOLTAGE PROFILE IMPROVEMENT USING JELLYFISH SEARCH OPTIMIZATION

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ABSTRACT

The rising global electricity demand forces power systems to operate near their stability limits, which leads to increased losses and reduced efficiency. Effective approaches, such as reactive power compensation using devices like flexible alternating current transmission system (FACTS), are needed to maintain system stability while satisfying growing demand. However, to maximize their benefits, it is essential to ensure a proper placement and sizing of these devices on the power system network. In this study, Jellyfish Search Optimization (JSO) algorithm was used to appropriately determine the size and location of Static Synchronous Compensator (STATCOM) – a member of FACTS devices in minimizing power losses. Power flow analysis was applied to the IEEE 14-bus and IEEE 30-bus standard test systems to determine the voltage magnitude, phase angle, and transmission line losses using the MATPOWER analysis tool package with a MATLAB program. After optimization, the optimal locations for the IEEE 14-bus and IEEE 30-bus networks were found to be bus 14 and bus 30, respectively. The results obtained indicate a 4.88% reduction in active power losses for the IEEE 14-bus system and a decrease of 8.03% for the IEEE 30-bus system. There is also a notable improvement in the voltage profile of the test systems after the optimization. The results from the JSO were compared with those obtained using Particle Swarm Optimization (PSO) algorithm. Using the PSO algorithm, the power losses were reduced by 4.44% and 6.66% for the IEEE 14-bus system and IEEE 30-bus system respectively. This shows that JSO algorithm achieved better performance in power loss reduction than PSO algorithm.

Keywords: Reactive power compensation, Power loss reduction, FACTS devices, JSO, STATCOM

1 INTRODUCTION

The need to operate power systems securely is essential as load demand rises globally. As demand increases, it is necessary to balance power demand with available generation while also developing new transmission infrastructure. The increase in load demand and certain economic and environmental constraints on electricity production stress power systems, pushing them to operate near critical limits, and also make the system more vulnerable to voltage instability [1, 2]. To address these problems, there is a continuous search for methods to improve power system performance in terms of efficiency, reliability, and stability. The two main strategies to address the power system overloading issues

are the construction of new transmission lines and the installation of compensators [3]. A common technique is the use of reactive compensating devices, which can be accomplished through flexible alternating current transmission system (FACTS) devices or capacitor banks when sized and installed at appropriate locations. While capacitor banks are conventional methods that can enhance voltage stability, they have performance limitations during sudden changes in reactive power. FACTS devices are considered a technically smart solution to solve the above challenges if they are appropriately installed in the power system with some effective controls. These devices can be connected in series with a line, shunt-connected, or as a series-shunt combination [4]. Common FACTS devices include the static VAR compensator (SVC), thyristor-controlled series capacitor (TCSC), static synchronous compensator (STATCOM), and unified power flow controller (UPFC), with STATCOM recognized as one of the most effective for voltage regulation due to its dynamic performance, fast response, and modular design [2, 5]. To find the optimal location of FACTS devices is a complex optimization challenge [6]. Early optimization methods use the sensitivity indices to assess how various parameters affect the power system's performance. These techniques can help to identify weak buses or lines where compensators could be effective, but they might not offer a complete solution, as these methods lack robustness in large and dynamically changing networks. Conventional optimization methods such as Linear Programming (LP), Nonlinear Programming (NLP), and Quadratic Programming (QP) are commonly employed to determine the optimal configuration of FACTS devices in electrical power systems to solve nonlinear optimization problems [7, 6]. Recently, metaheuristic optimization techniques have become increasingly popular due to their flexibility and ability to handle complex, multi-objective functions. Studies show that metaheuristic optimization techniques perform better in global optima search than the classical and index methods. For example in [3, 8], authors applied Particle Swarm Optimization to optimally place a STATCOM device on the IEEE 14-bus system, achieving reduced active power loss and improved voltage profile. [9, 10] applied a Genetic algorithm (GA) to determine the optimal locations for STATCOM devices sufficient to reduce power losses and voltage deviation. The Firefly algorithm was applied in [3] for optimal STATCOM control settings. The use of nature-inspired metaheuristic algorithms such as the Slime Mould Algorithm (SMA), Marine Predator Algorithm (MPA), and the Jellyfish Search Optimization has been proposed in [11, 12] for Optimal Power Flow (OPF), and all demonstrate improved performance. However, many of these algorithms have problems with premature convergence and an imbalance between exploration and exploitation. The Jellyfish Search Optimization, a novel metaheuristic algorithm inspired by the jellyfish movement patterns in ocean currents, has shown notable potential in OPF [12]. With fewer algorithm parameters than other classical optimization techniques, JSO offers advantages such as quick convergence and robust search capability. In addition to that, compared to other algorithms, JSO maintains a superior equilibrium between exploration and exploitation [13]. Despite its advantages, JSO has seen limited application in power system optimization problems, particularly in STATCOM allocation. This research proposes JSO for optimal STATCOM placement and sizing in the IEEE 14-bus and IEEE 30-bus systems to address these challenges.

2 METHODOLOGY

This section presents the methodological framework and simulation tools used to evaluate STATCOM placement using Jellyfish Search Optimization. It provides a clear path from problem identification to solution implementation. All simulations were carried out using MATPOWER analysis toolbox on a MATLAB software.

2.1 Test Systems and Data

The standard IEEE 14-bus system, with 5 generators and 20 branches, and the IEEE 30-bus system, with 6 generators and 41 branches, were used. Bus and line data are obtained from IEEE datasets [14, 15].

2.2 Problem Definition

The primary goal of the optimal power flow problem is to optimize a predefined objective function. This research aims to determine the optimal STATCOM location and size to minimize active and reactive

power losses, thereby enhancing the system voltage profile. The optimal placement of a FACTS device for loss minimization is mathematically expressed as follows [16].

Minimize $f(x,u)$ (1)

Subject to;

$$g(x,u) = 0 \quad (2)$$

$$h(x,u) \leq 0 \quad (3)$$

where f(x, u) is the objective function to be optimized, the set of equality and inequality constraints is given by g(x,u) and h(x, u), respectively.
The minimization of active power losses in the transmission network is used as an objective function, which can be given as;

$$f = \min(P_{loss}) \quad (4)$$

$$P_{loss} = \sum_{k=1}^{Nl} G_{ij}\left(V_I^2 + V_j^2 - 2V_iV_j\cos(\delta_i - \delta_j)\right) \quad (5)$$

where; P_{loss} is the total power loss, G_{ij} is the conductance of line *ij*, V_i and V_j are the magnitudes of the sending end and receiving end voltages of the line. δ_i and δ_j are the phase angles of the end voltages. *Nl* is the number of transmission lines. The problem is subject to the following constraints, which are categorized into equality and inequality constraints. The equality constraints are load flow equations expressed as;

$$P_{Gi} - P_{Di} - V_i\sum_{k=1}^{Nb} V_j\left(G_{ij}\cos(\delta_i - \delta_j) + B_{ij}\sin(\delta_i - \delta_j)\right) = 0 \quad (6)$$

$$Q_{Gi} - Q_{Di} - V_i\sum_{k=1}^{Nb} V_j\left(G_{ij}\sin(\delta_i - \delta_j) + B_{ij}\cos(\delta_i - \delta_j)\right) = 0 \quad (7)$$

where P_{Gi} and Q_{Gi} refer to the active and reactive generating power at bus i and j, respectively. P_{Di} and Q_{Di} refer to the active and reactive power demands at bus i and j, respectively. N_b refers to the total number of buses. The inequality constraints include control and state variables, such as generator voltages, active power, and line flow limits, and reactive power injection.

Real power generation limits:

$$P_{Gi}^{min} \leq P_{Gi} \leq P_{Gi}^{max} \quad (8)$$

where P_{Gi}^{min} is the minimum real power at the generator bus, P_{Gi} is the actual real power at the generator bus, and P_{Gi}^{max} is the maximum real power at the generator bus.

Reactive power generation limit:

$$Q_{Gi}^{min} \leq Q_{Gi} \leq Q_{Gi}^{max}; \quad i = 1, \ldots\ldots N_C \quad (9)$$

where Q_{Gi}^{min} is the minimum reactive power at the generator bus, Q_{Gi} is the actual reactive power at the generator bus, and Q_{Gi}^{max} is the maximum reactive power at the generator bus. N_c is the total number of compensators.

Voltage limits for generator buses:

$$V_{Gi}^{min} \leq V_{Gi} \leq V_{Gi}^{max}; \quad i = 1, \ldots\ldots, N_G \quad (10)$$

where V_{Gi}^{min} is the minimum voltage at the generator bus, V_{Gi} is the actual voltage at the generator bus, and V_{Gi}^{max} is the maximum voltage at the generator bus. N_G is the total number of generators.

Power flow limit:

$$S_i \leq S_i^{max}; \quad i = 1, \ldots\ldots N_i \quad (11)$$

Where S_i is the sending end of apparent power.

2.3 Load Flow Analysis

The load flow analysis is performed using the Newton-Raphson method due to its accurate and fast convergence [17]. The bus voltages and line flows obtained from the baseline for evaluating the effect of STATCOM deployment. The Newton-Raphson method solves power balance equations, implemented via MATPOWER as shown in equations (12) and (13).

$$P_i = \sum_{j=1}^{n} |V_i| \left|V_j\right| \left|Y_{ij}\right| \cos(\theta_{ij} - \delta_i + \delta_j) \tag{12}$$

$$Q_i = -\sum_{j=1}^{n} |V_i| \left|V_j\right| \left|Y_{ij}\right| \sin(\theta_{ij} - \delta_i + \delta_j) \tag{13}$$

where, P_i = active power at bus i. Q_i = reactive power at bus i. Y_{ij} = mutual admittance between buses i and j. V_i and V_j = calculated voltage of bus i and j. θ_{ij} = phase angle at bus i and bus j. δ_i and δ_j = Voltage angles at buses i and j. n = number of buses in the system.

2.4 Jellyfish Search Optimization

Jellyfish Search Optimization (JSO) is a recently developed metaheuristic optimization algorithm inspired by the way Jellyfish navigate the water in search of food. This approach draws inspiration from the moving patterns and exploring actions of Jellyfish in the ocean [18]. Since the amount of food at different locations in the ocean varies, jellyfish identify the best locations by comparing the quality of food in different areas. This process enables the algorithm to achieve a better balance between exploration and exploitation strategies, which leads to the fast detection of optimal solutions [13]. A flowchart of the JSO is shown in Figure 1. This optimization is centered on three rules [18, 19]. Jellyfish either follow the ocean current or move within the swarm. A time control mechanism controls the switch between these two types of motion [19]. Jellyfish are more likely to move to areas with higher food quantity as they move in search of food. The amount of food found depends on the location and the corresponding objective function. The time control mechanism consists of a time control function C(t) and a constant Co that regulates the Jellyfish's movement between entering the Jellyfish swarm and following the ocean current. Over time, the value of the time control function varies randomly from 0 to 1. The Jellyfish follow the ocean current when the C(t) value is greater than Co, and travel within the swarm when the value is smaller than Co [19]. There is no known precise value for Co, thus, the time control fluctuates randomly between zero and one. As a result, Co is set to 0.5, the average of 1 and 0 [13]. The time control function can be given as;

$$C(t) = \left|\left(1 - \frac{t}{\mathrm{Max}_{\mathrm{iter}}}\right) \times (2 \times rand(0,1) - 1)\right| \tag{14}$$

where t = the time specified as the iteration number. Max_{iter} = the maximum number of iterations. Jellyfish have two types of movement: Passive motion (exploitation) and active motion (exploration). *Passive motion* is the motion of Jellyfish in their respective locations to explore their immediate surroundings. It represents a local search strategy, focusing on exploitation to refine solutions. Each Jellyfish's updated location is provided by;

$$X_i(t+1) = X_i(t) + Y \times rand(0,1) \times (\mathrm{Ub} - \mathrm{Lb}) \tag{15}$$

where Y stands for the motion coefficient, Lb and Ub represent the lower and upper bounds in the search zone, respectively. *Active motion* is the motion of a Jellyfish (j) opposite to the passive motion. It is a global search strategy where jellyfish move toward or away from other Jellyfish in the swarm based on the food quality at those locations [18]. The direction of motion and the updated location of a Jellyfish are given in equations (17) and (18), respectively.

$$\overrightarrow{Step} = rand(0,1) \times \overrightarrow{Direction} \tag{16}$$

$$\overrightarrow{Direction} = \begin{cases} X_j(t) - X_i(t); \ if \ f(X_i) \geq f(X_j) \\ X_i(t) - X_j(t); \ if(X_i) < f(X_j) \end{cases} \tag{17}$$

where f is an objective function of location X.

$$X_i(t+1) = X_i(t) + \overrightarrow{Step} \quad (18)$$

The Jellyfish are drawn to an ocean current because of the abundance of nutrients it contains [19]. The following formula can be used to determine ocean current.

$$X_i(t+1) = X_i(t) + rand(0,1) \times X^* - \beta \times rand(0,1) \times \mu \quad (19)$$

where $X_i(t + 1)$ determines the relevant updated position; $X_i(t)$ is the Jellyfish's current location; X^* is the Jellyfish that is currently in the best location within the swarm; and β is a distribution coefficient that is related to the length of the ocean current.

2.5 Parameter Settings for the Jellyfish Search Optimization

The parameter settings for the Jellyfish Search Optimization and other input data used in this research are given in Table 1. A population of 30 Jellyfish was employed, and the maximum number of iterations was set to 100. The two decision variables are bus number (nbus) and the reactive power injection (Q). The upper bound (Ub) and lower bound (Lb) of the variables are given in Table 1.

Table 1. Input Parameters and Jellyfish Optimization Settings

S/N	Parameters	Quantity
1	Population size	30
2	Number of iterations	100
3	Number of decision variables	2
4	Bus index Lb - Ub	2 - nbus
5	Reactive power injection Lb-Ub	0 – 100
6	Time control function C_o	0.5
7	Distribution Coefficient β [18]	3
8	Motion Coefficient γ [18]	0.1

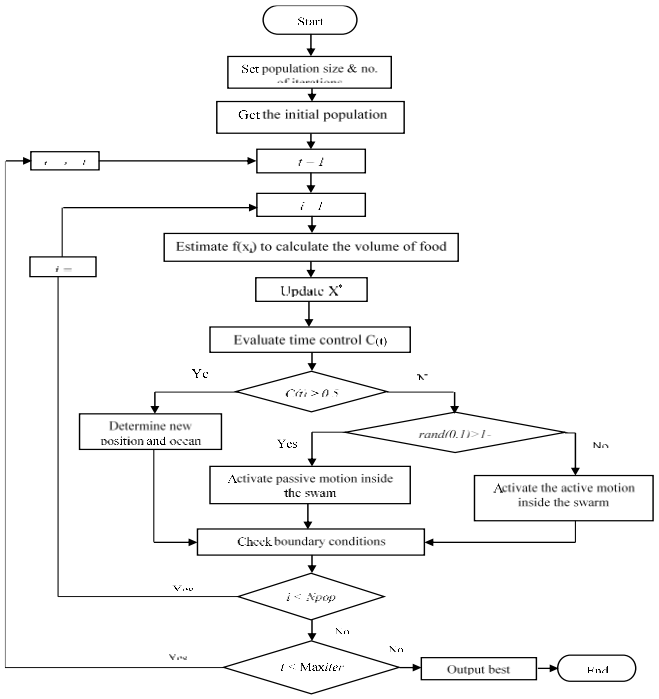

Figure 1. Flowchart of JSO [18]

3 RESULTS AND DISCUSSION

The load flow solution results and the effectiveness of JSO for optimal STATCOM placement for reducing active power loss and improving voltage profile on the IEEE 14-bus and IEEE 30-bus networks are discussed in this section. All simulations were carried out using MATLAB 2023b with MATPOWER 8.0 toolbox. Power flow calculations were performed using the Newton-Raphson method.

3.1 Optimal STATCOM size and location

After applying Jellyfish Search Optimization, the optimal STATCOM size for the IEEE 14-bus system is 7.51 MVar, located at bus 14. For the IEEE 30-bus system, the STATCOM size is 9.82MVar, and bus 30 is the optimal location.

3.2 IEEE 14-bus Test System

Table 2 details the active power loss for the base case and after STATCOM was optimally allocated using JSO and PSO. The total active power loss without any device is 13.52 MW, which is reduced to 12.86 MW and 12.92 MW after optimal placement using JSO and PSO, respectively.

Table 2. Active Power Loss of IEEE 14-bus System

	Without STATCOM	STATCOM with JSO	STATCOM with PSO
1	4.258	4.056	4.075
2	2.804	2.658	2.672
3	2.290	2.244	2.248
4	1.667	1.581	1.590
5	0.912	0.858	0.863
6	0.371	0.392	0.389
7	0.473	0.460	0.461
8	0.000	0.000	0.000
9	0.000	0.000	0.000
10	0.000	0.000	0.000
11	0.131	0.127	0.127
12	0.081	0.074	0.075
13	0.254	0.218	0.221
14	0.000	0.000	0.000
15	0.000	0.000	0.000
16	0.008	0.008	0.008
17	0.094	0.040	0.044
18	0.058	0.056	0.056
19	0.012	0.009	0.009
20	0.111	0.076	0.078
Total	13.52	12.86	12.92

The plot of active power loss reduction for the case without STATCOM, STATCOM with PSO, and STATCOM with JSO is shown in Figure 2.

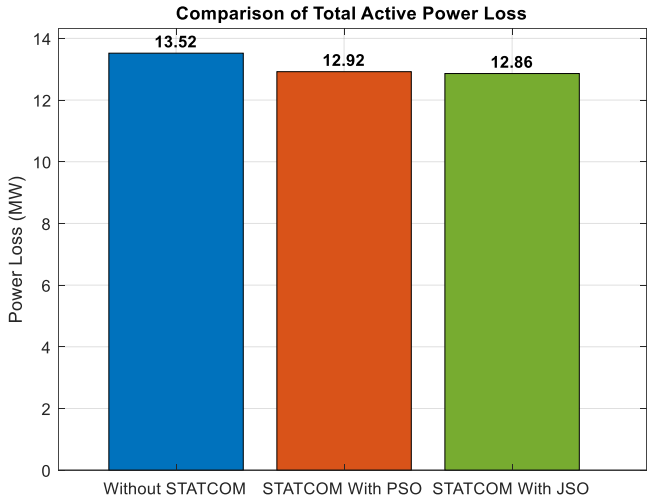

Figure 2. Comparison of Active Power Loss for IEEE 14-bus System

Similarly, the voltage magnitude of the IEEE 14-bus system is compared before and after placement of the STATCOM, as shown in Table 3 and in Figure 3. When the optimal size of STATCOM (7.51MVar) was placed at the optimal location (bus 14), the voltage magnitudes showed a noticeable improvement, particularly at buses 13 and 14 for both JSO and PSO.

Table 3. Voltage Profile of IEEE 14-bus System

Bus No.	V(pu) Before STATCOM	V (pu) STATCOM with JSO	V (pu) STATCOM with PSO
1	1.060	1.060	1.060
2	1.045	1.045	1.045
3	1.011	1.012	1.012
4	1.025	1.026	1.027
5	1.032	1.033	1.034
6	1.070	1.070	1.070
7	1.044	1.045	1.046
8	1.090	1.090	1.090
9	1.027	1.028	1.029
10	1.027	1.028	1.029
11	1.045	1.045	1.046
12	1.053	1.053	1.054
13	1.046	1.047	1.049
14	1.017	1.022	1.027

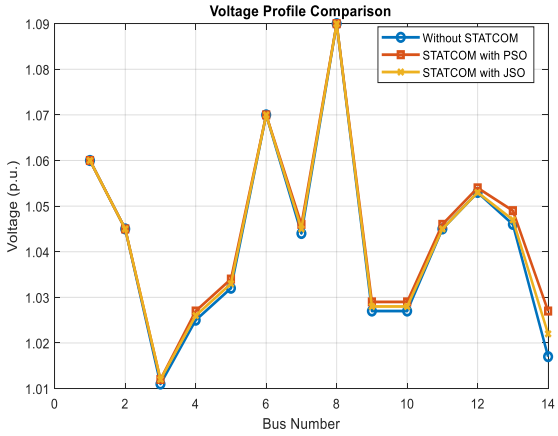

Figure 3. Voltage profile of IEEE 14-bus System

A comparison between the convergence curve of JSO and PSO for the IEEE 14-bus after running 100 iterations is provided in Figure 4.

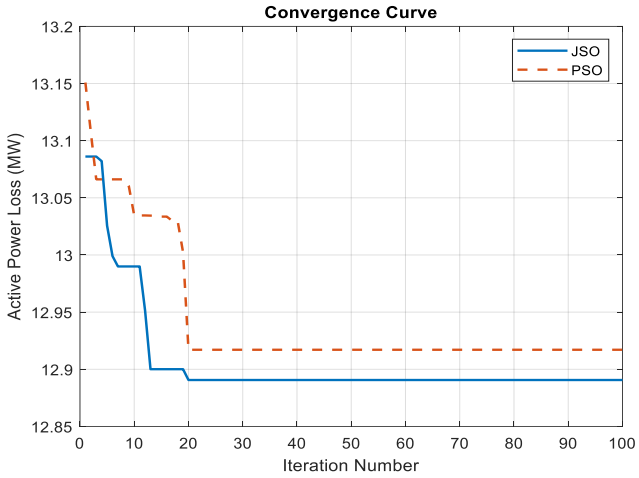

Figure 4. Convergence Plot of PSO and Jellyfish Optimization for IEEE 14-bus System

3.3 IEEE 30-bus Test System

The voltage magnitude of the IEEE 30-bus system is compared before and after placement of the STATCOM, shown in Table 4. The active power loss before and after the sizing and placement of the STATCOM using the JSO and PSO is given in Table 5.

Table 4. Voltage Profile of IEEE 30-bus System

Bus No.	Voltage(pu) Before STATCOM	Voltage(pu) STATCOM with JSO	Voltage(pu) STATCOM with PSO
1	1.060	1.060	1.060
2	1.045	1.045	1.045
3	1.021	1.022	1.022
4	1.012	1.013	1.013
5	1.010	1.010	1.010
6	1.011	1.012	1.012
7	1.003	1.003	1.003
8	1.010	1.010	1.010
9	1.051	1.052	1.052
10	1.045	1.046	1.046
11	1.082	1.082	1.082
12	1.057	1.058	1.058
13	1.071	1.071	1.071
14	1.043	1.043	1.043
15	1.038	1.039	1.039
16	1.045	1.045	1.045
17	1.040	1.041	1.041
18	1.028	1.029	1.029
19	1.026	1.026	1.027
20	1.030	1.031	1.031
21	1.033	1.034	1.034
22	1.034	1.034	1.035
23	1.027	1.029	1.030
24	1.022	1.024	1.026
25	1.018	1.023	1.028
26	1.000	1.006	1.034
27	1.024	1.031	1.028
28	1.007	1.009	1.009
29	1.004	1.021	1.009
30	0.992	1.018	0.997

Table 5. Active Power Loss of IEEE 30-bus System

S/N	Without STATCOM	STATCOM with JSO	STATCOM with PSO
1	5.213	4.809	4.810
2	3.108	2.854	2.850
3	1.018	0.927	0.925
4	0.856	0.784	0.783
5	2.943	2.847	2.849
6	1.946	1.761	1.764
7	0.632	0.565	0.572
8	0.169	0.187	0.187
9	0.381	0.407	0.406
10	0.108	0.096	0.098
11	0.000	0.000	0.000
12	0.000	0.000	0.000
13	0.000	0.000	0.000
14	0.000	0.000	0.000
15	0.000	0.000	0.000
16	0.000	0.000	0.000
17	0.074	0.071	0.069
18	0.217	0.199	0.190
19	0.054	0.050	0.049
20	0.006	0.005	0.004
21	0.008	0.007	0.006
22	0.039	0.038	0.039
23	0.005	0.005	0.005
24	0.017	0.017	0.017
25	0.082	0.082	0.081
26	0.014	0.015	0.015
27	0.111	0.101	0.095
28	0.053	0.046	0.042
29	0.001	0.001	0.002
30	0.031	0.023	0.019
31	0.046	0.028	0.020
32	0.006	0.003	0.003
33	0.010	0.046	0.074
34	0.045	0.044	0.093
35	0.024	0.065	0.000
36	0.000	0.000	0.000
37	0.086	0.016	0.085
38	0.162	0.014	0.161
39	0.034	0.001	0.033
40	0.002	0.002	0.002
41	0.058	0.031	0.037
Total	17.56	16.15	16.39

The total loss without any device is 17.56MW, which is reduced to 16.15MW and 16.39MW after optimal placement using JSO and PSO, respectively. The voltage magnitude also shows significant improvement at the selected buses. The plot for voltage magnitude and the plot of active power loss reduction for the case without STATCOM, STATCOM with PSO, and STATCOM with JSO are depicted in Figures 5 and 6, respectively.

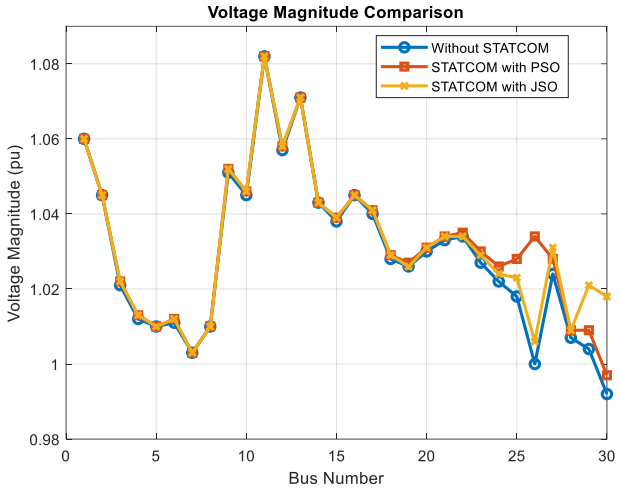

Figure 5: Voltage profile of the IEEE 30-bus System

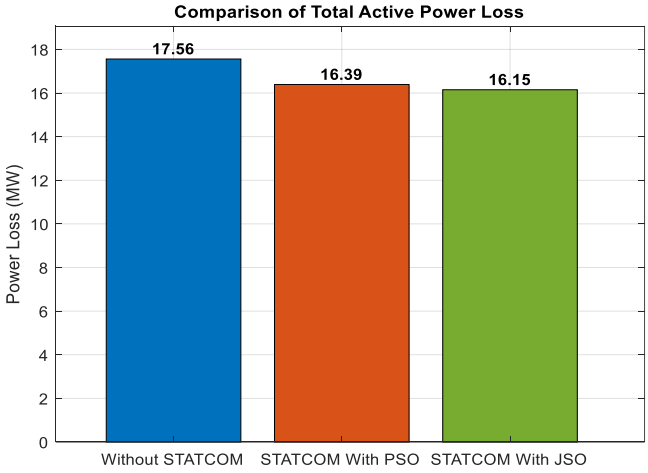

Figure 6. Comparison of Active Power Loss for IEEE 30-bus System

The performance of the algorithms in minimizing active power loss is shown in Figure 7 for the IEEE 30-bus system.

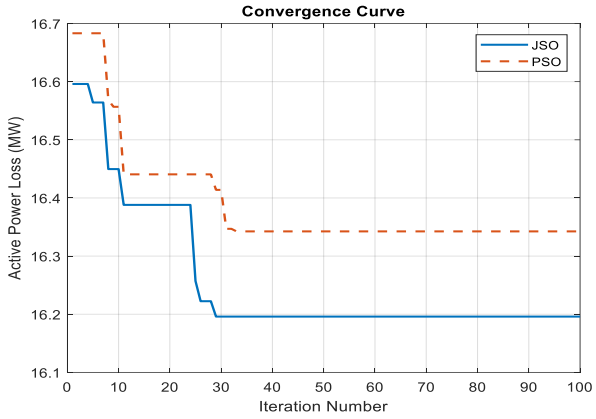

Figure 7. Convergence Plot of PSO and Jellyfish Optimization for IEEE 30-bus System

4 CONCLUSIONS

This study presented the use of Jellyfish Search Optimization for optimal placement and sizing of the STATCOM device in electrical power transmission networks. The effectiveness of the proposed optimization technique is demonstrated through simulations carried out on IEEE 14-bus and IEEE 30-bus test systems. The results show a reduction in active power loss of 4.88% for the IEEE 14-bus system and 8.03% for the IEEE 30-bus system. There is also a notable improvement in the voltage profile of the test systems after the optimization. This study confirms that Jellyfish Search Optimization is a reliable solution for the optimal location and sizing of STATCOM devices, effectively enhancing power system performance. Compared with Particle Swarm Optimization, JSO achieved a greater reduction in total active power loss. Active power loss is reduced by 4.44% for the IEEE 14-bus system and 6.66% for the IEEE 30-bus system using PSO. Additionally, the iteration convergence plots indicate that JSO outperforms PSO, converging faster and achieving a better result for both the IEEE 14-bus and IEEE 30-bus systems.

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