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Research article

Optimization of position and rating of shunt and series connected FACTS devices for transmission congestion management in deregulated power networks

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Abstract: Transmission congestions are caused by electricity trading between generators and distribution companies in a deregulated environment.   Power system operation and security in liberalized scenarios are maintained by removing branch overloads. A flexible alternating current transmission system (FACTS) controller is installed in a suitable location to redistribute the power flow among the transmission lines so that the power flows are brought within the capacity of the lines. In this work, series-connected thyristor-controlled switched compensators (TCSCs) and shunt-connected Volt-Ampere reactive (VAR) static compensators (SVCs) are installed in appropriate locations to alter the power flow patterns and to remove overloads. It is proposed to reduce the overload of transmission lines by locating series and shunt connected FACTS devices at proper locations. The size and location of TCSC and SVC devices greatly affect their ability to meet a congestion management goal. An optimization process optimizes the location and size of these devices to maximize the congestion mitigation benefits of the TCSC and SVC controllers. In this work, the whale optimization algorithm (WOA) is used to optimize the value of the objective function by appropriately choosing the location and size of the FACTS controllers. This algorithm has a few parameters that are tuned to give the best overall results. A WOA-based method is proposed to optimize the size and location of the FACTS devices and is implemented on the IEEE-30 bus test case. The results were compared and found to be improved with those of other algorithms such as the particle swarm optimization algorithm (PSO) and the firefly algorithm (FFA).

Keywords: congestion management; whale optimization algorithm; FACTS; TCSC; SVC

1. Introduction

A competitive market will be introduced for all commodities, including electricity in the future. The monopoly electricity market has now been reorganized into three distinct entities: generation companies (GENCOs), transmission companies (TRANSCOs), and distribution companies (DISCOs) [1, 2]. Competition will be introduced between GENCOs and DISCOs to increase the efficiency of generation and consumption. The grid is operated by a separate entity, the system operator.

A power grid is generally managed by one entity for economic reasons and for better control of the flow of power. Electricity demand is growing faster than the expansion of the grid. In addition, a large number of bilaterally or multilaterally agreed power contracts are increasing congestion on transmission lines [3]. Line congestion [4], can occur if all transactions are not properly controlled. It forces transmission capacity improvement or transmission network expansion. Congestion management is defined as the recommended measures to reduce line congestion. Land acquisition and installation costs are the most important limitations in the development of transmission networks. Additionally, depending on the deal, the increase in bandwidth may only be temporary during the duration of the deal, justifying capacity expansion as the best alternative to expansion.

Trade agreements that lead to increased currents lead to increased line losses, jeopardizing system stability and security. Therefore, it is required to make the best use of the transmission capacity already installed. This can be easily done by just installing the FACTS device [5–7]. There are two reasons for the increased use of these FACTS devices. First, recent advances in power electronic switching devices have made them cheaper and more efficient [8]. Identifying the location and size of these devices is critical for optimal performance and minimal cost. Various methods are available to select the optimal location and size of FACTS devices in the energy system [9–11]. Reference [12] recommends a sensitivity-based method for choosing the best location for TCSC and also examines the impact of line impedance on congestion mitigation. The TCSC location is optimized to reduce line congestion in the event of contingencies in [13]. Reference [14] deals with congestion mitigation and improved voltage stability in liberalized electricity markets using several FACTS devices. Minimizing the total congestion cost using FACTS devices is described in [15]. Differential evolution algorithms are applied to improve safety and reduce overload in power systems under conditions of single-line faults in [16]. Management of congestion using Bee colony optimization and cost minimization is also done in [17]. TCSC is placed at best locations for maximizing social benefit and reducing congestion in transmission lines in [18]. A genetic algorithm is used for finding the optimal location of TCSC to solve a transmission line congestion problem in [19].

In most of the studies on congestion management, the cause of congestion considered is the outage of transmission lines. The other equally important causes of line congestion like bilateral and multilateral transactions in deregulated power markets are not sufficiently addressed in the literature. The research gap of transmission congestion caused by increased load, bilateral transaction, and multilateral transaction in deregulated power networks is addressed in this work.

A new method based on whale optimization algorithm is proposed here to determine the optimal location and rating of TCSC and SVC devices.

The main contributions of this work are as follows: 1. The WOA, which is a recent optimization algorithm, is proposed. The algorithm exhibits better searching ability and convergence speed. 2. A comparison of the proposed WOA with some state-of the-art algorithms demonstrates the superior

performance of the algorithm. The WOA tops the rank on the performance comparison with these algorithms. 3.Three different causes of congestion are taken in this study, viz, increase in load, bilateral transaction and multilateral transaction. 4. Experimental results of the CM task reveal that series and shunt connected combination of FACTS devices perform better than when they are used individually.

In Section 2 static power injection modeling of TCSC and SVC are presented. In Section 3 the objective function of minimizing congestion, loss, and voltage deviation is discussed. Searching behaviur and modelling of WOA algorithm are described in section 4. In section 5, the results and discussion are presented. Finally, in section 6, the work is concluded, and future scope is proposed.

2. Modelling of FACTS devices

2.1. Static modeling of SVC device

SVC devices can be operated as reactive power sources and sinks. This can be modeled as an ideal reactive power source/sink on bus i (2.1).

$$\Delta Q_{is} = \Delta Q_{SVC} \tag{2.1}$$

The main purpose of the SVC is usually to keep the weak bus voltage near its nominal value. It can be installed in the middle of the transmission line. The reactive power associated with SVC can be mathematically expressed as Equation (2.2) [20].

$$Q_{SVC} = V_i(V_i - V_r)/X_{sl} \tag{2.2}$$

where, X_{sl} is the equivalent slope reactance denoted by p.u. V_r is the magnitude of the reference voltage. The SVC is modelled as a variable susceptance connected to bus i as shown in Figure 1.
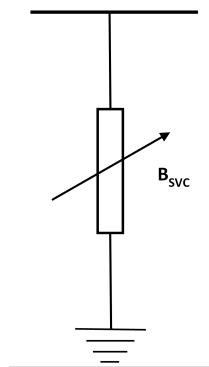

Figure 1. Static modelling of SVC.

2.2. Static modeling of TCSC device

A TCSC device is connected in series with a line and changes its reactance to change the power flow level [21]. It can act like a capacitor to generate reactive power, or it can act like an inductor to absorb reactive power. Its low cost compared to the cost of other FACTS devices makes it suitable for congestion management problems. Figure 2 shows the π model of a line between bus i and bus j.
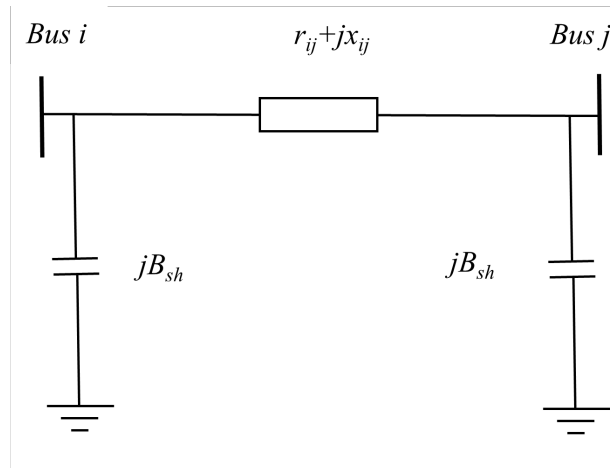
Figure 2. Static modelling of TCSC.

If $V_i \angle \delta_i$ and $V_j \angle \delta_j$ are the polar forms of voltages at buses i and j. Active and reactive power flow from bus-i to bus-j can be given by Equations (2.3) and (2.4), respectively.

$$P_{ij} = V_i^2 G_{ij} - V_i V_j (G_{ij} \cos \delta_{ij} + B_{ij} \sin \delta_{ij}) \tag{2.3}$$

$$Q_{ij} = -V_i^2 (B_{ij} + B_{sh}) - V_i V_j (G_{ij} \sin \delta_{ij} + B_{ij} \cos \delta_{ij}) \tag{2.4}$$

Power flows in the reverse direction, i.e, from bus j to bus i are given by Equations (2.5) and (2.6).

$$P_{ji} = V_j^2 G_{ij} - V_i V_j (G_{ij} \, co\delta_{ij} + B_{ij} \sin \delta_{ij}) \tag{2.5}$$

$$Q_{ji} = -V_j^2 (B_{ij} + B_{sh}) - V_i V_j (G_{ij} \sin \delta_{ij} + B_{ij} \cos \delta_{ij}) \tag{2.6}$$

The TCSC insertion can be viewed as a variable reactance in series with the transmission line. Figure 3 shows a transmission line model with a TCSC. In steady state, TCSC can be modelled as a static capacitor/inductor with impedance jx_{TCSC}.
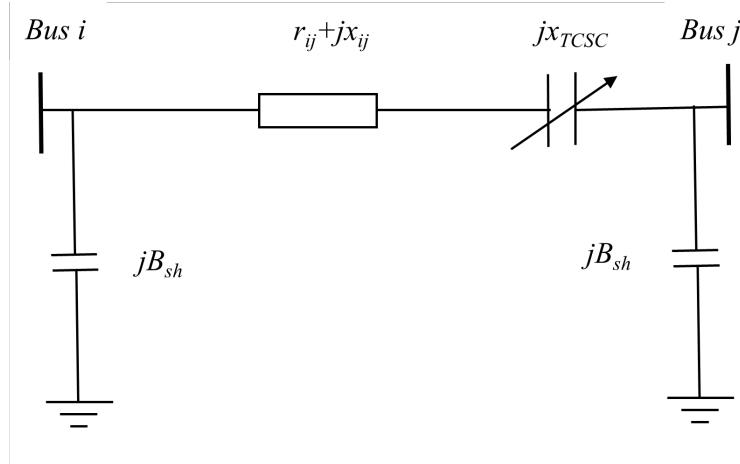
Figure 3. π-model of a line.

The TCSC implementation modifies the power flow from bus i to bus j as given by Equations (2.7) and (2.8).

$$P'_{ij} = V_i^2 G'_{ij} - V_i V_j (G'_{ij} \cos \delta_{ij} + B'_{ij} \sin \delta_{ij}) \tag{2.7}$$

$$Q'_{ij} = -V_i^2 (B'_{ij} + B'_{sh}) - V_i V_j (G'_{ij} \sin \delta_{ij} + B'_{ij} \cos \delta_{ij}) \tag{2.8}$$

where, $G'_{ij} = \frac{r_{ij}}{r_{ij}^2 + (x_{ij} - x_{TCSC})^2}$ $B'_{ij} = \frac{-(x_{ij} - x_{TCSC})}{(r_{ij}^2 + (x_{ij} - x_{TCSC})^2)}$

The congestion management problem is considered a static problem and uses the static model of FACTS devices that injects current at the ends of the line. According to this model, a TCSC device can be modelled as a PQ injection into a specific node. Figure 4 is the power injection model for the TCSC device.
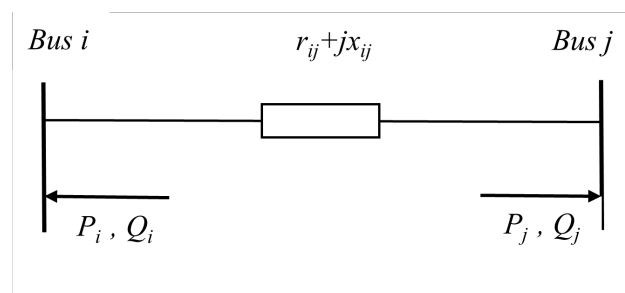

Figure 4. Power injection model of a line with a TCSC.

The active and reactive power injections of bus i and bus j after inserting TCSC are given by Equations (2.9) to (2.12).

$$P'_i = V_i^2 \Delta G_{ij} - V_i V_j (\Delta G_{ij} \cos \delta_{ij} + \Delta B_{ij} \sin \delta_{ij}) \tag{2.9}$$

$$P'_j = V_j^2 \Delta G_{ij} - V_i V_j (\Delta G_{ij} \cos \delta_{ij} + \Delta B_{ij} \sin \delta_{ij}) \tag{2.10}$$

$$Q'_i = -V_i^2 \Delta B_i j - V_i V_j (\Delta G_{ij} \sin \delta_{ij} + \Delta B_{ij} \cos \delta_{ij}) \tag{2.11}$$

$$Q'_j = -V_j^2 \Delta B_i j - V_i V_j (\Delta G_{ij} \sin \delta_{ij} + \Delta B_{ij} \cos \delta_{ij}) \tag{2.12}$$

where, $\Delta G_{ij} = \frac{(x_{TCSC} r_{ij}(x_{TCSC} - 2x_{ij}))}{r_{ij}^2 + x_{ij}^2 [r_{ij}^2 + (x_{ij} - x_{TCSC})^2]}$ $\Delta G_{ij} = \frac{-x_{TCSC}(r_{ij}^2 - x_{ij}^2 + x_{TCSC} x_{ij})}{r_{ij}^2 + x_{ij}^2 [r_{ij}^2 + (x_{ij} - x_{TCSC})^2]}$

3. Formulation of congestion management problem

3.1. Congestion management

In a deregulated environment, TRANSCO, GENCO, and DISCO are different organizations. In all kinds of deregulated power system models there are grid operators to maintain coordination between them. This is usually an independent system operator (ISO). In a competitive electricity market, market participants are given sufficient freedom to interact with each other. Here, both buyers (DISCO) and sellers (GENCO) try to buy and sell power to maximize their profits. Transmission bottlenecks occur in deregulated electricity markets when transmission capacity is not sufficient to allow all transmissions simultaneously. Overloads should be mitigated as soon as possible because they cause tripping of the overloaded line and the possible cascaded trips of other lines, and possibly voltage stability problems. Therefore, removing bottlenecks quickly, systematically, and efficiently is critical in maintaining market efficiency. FACTS devices may be an alternative solution for reducing flow in heavily loaded lines.

3.2. Objectives

The main purpose of this work is to eliminate overloading of the lines by adjusting the design variables of generator bus voltage, transformer tap changes, and reactive power outputs of installed SVC and TCSC devices. Changes in the values of design variables affect the level of power system losses and voltage excursions. To explain these effects, three objectives are considered. i.e, minimize power flow violations, reduce power loss, and control voltage deviations.

Transmission lines are designed to transmit power within their thermal limits. Congestion management eliminates these overruns by minimizing active power over flows. This is our first objective here.

$$f_1 = \sum_{k=1}^{N_L} |P_k - P_{krat})| \tag{3.1}$$

where P_k is the power flow at the kth line, and P_{krat} is the maximum power flow limit of the line.

For economical and efficient operations, the ISO should ensure minimum transmission loss, which is considered as the second objective.

$$f_2 = \sum_{k=1}^{N_L} G_k(V_i^2 + V_j^2 - 2|V_i||V_j|\cos\delta_i - \delta_j) \tag{3.2}$$

where G_k is the conductance of the kth line. V_i and V_j are the sending end and receiving end voltage magnitudes of the kth line. δ_i and δ_j are the sending end and receiving end voltage angles of the kth line.

The objective of power engineers is to ensure quality power at consumer end the voltage variations at load buses adversely affect the quality of power. This can be eliminated by considering voltage deviation as the third objective.

$$f_3 = \sum_{k=1}^{N_{PQ}} |(V_k - V_{kref})| \tag{3.3}$$

where V_k is the voltage of the kth bus. V_{kref} is the reference voltage at bus k. It is taken as 1.0 p.u. in this work.

The congestion management problem is formulated as an optimization problem with multiple goals: minimizing power flow violation in transmission lines, reducing transmission losses, and minimizing voltage drift on load buses.

The weighted aggregated method is employed to convert the multi-objective modeling to single objective model as [22].

$$F = w_1 f_1 + w_2 f_2 + w_3 f_3 \tag{3.4}$$

For determining the weight factors of multi-objective optimisation, since the power flow violation is the main concern, its corresponding weight factor is set as the highest value (0.6). The weights of other two objectives, i.e, loss and voltage deviation are set as 0.2.

i.e, C1 = 0.6, C2 = 0.2, C3 = 0.2.

3.3. Constraints

3.3.1. Equality constraints

The system must satisfy the real and reactive power flow constraints which are given by power flow equations as equality constraints.

$$P_{Gi} - P_{Di} - \sum_{j=1}^{NB} V_i V_j Y_{ij} \cos\delta_{ij} + \gamma_j - \gamma_i) = 0 \tag{3.5}$$

$$Q_{Gi} - Q_{Di} - \sum_{j=1}^{NB} V_i V_j Y_{ij} \sin\delta_{ij} + \gamma_j - \gamma_i) = 0 \tag{3.6}$$

where, P_{Gi}, Q_{Gi} are the active and reactive power of ith generator, and P_{Di}, Q_{Di} are the active and reactive power of the ith load bus.

3.3.2. Inequality constraints

Generator constraints:
Generator voltage and reactive power of ith bus lies between their upper and lower limits as given below:

$$V_i^{min} \leq V_i \leq V_i^{max} \qquad i = 1, 2, ...N_G \tag{3.7}$$

$$Q_{Gi}^{min} \leq Q_{Gi} \leq Q_{Gi}^{max} \qquad i = 1, 2, ...N_G \tag{3.8}$$

where, V_i^{min}, V_i^{max} are the minimum and maximum voltages of the ith generating unit, and Q_{Gi}^{min}, Q_{Gi}^{max} are the minimum and maximum reactive power of the ith generating unit.

Transmission line constraints:
Real power flow limit of a line is given as:

$$P_i \leq P_i^{max} \qquad i = 1, 2, ..., N_L \tag{3.9}$$

where, P_i is the apparent power flow of the ith branch, and P_i^{max} is the maximum apparent power flow limit of the ith branch.

Transformer taps constraints:
Transformer tap settings are bounded between upper and lower limit as given below:

$$T_i^{min} \leq T_i \leq T_i^{max} \qquad i = 1, 2, ...N_T \tag{3.10}$$

where, T_i^{min}, T_i^{max} are the minimum and maximum tap setting limits of the ith transformer.

Shunt compensator constraints:
Shunt compensation is restricted by their limits as follows:

$$SVC_i^{min} \leq SVC_i \leq SVC_i^{max} \qquad i = 1, 2, ...N_{SVC} \tag{3.11}$$

where, SVC_i^{min}, SVC_i^{max} are the minimum and maximum VAR injection limits of the ith shunt capacitor.

Series compensator constraints:
Series compensation is restricted by their limits as follows:

$$TCSC_i^{min} \leq TCSC_i \leq TCSC_i^{max} \qquad i = 1, 2, ...N_{TCSC} \tag{3.12}$$

where, $TCSC_i^{min}$, $TCSC_i^{max}$ are the minimum and maximum reactance limits of the ith series compensator of TCSC.

4. Whale optimization algorithm

4.1. Overview

Whales rarely sleep because they need to breathe on the surface. Whales are always on alert to help them think, learn, judge, communicate, and even become emotional through their spindle cells [23]. Most whale species are able to live in families throughout their lives. Humpback whales are one of the largest animals with a specialized hunting behavior called bubble net feeding. Bubble net feeding is a specialized activity found only in humpback whales and is mathematically modelled in the next section to find the optimal solution in the search space. Algorithms inspired by nature are mimicked by organisms, such as foraging and survival mechanisms. The whale optimization algorithm was developed based on whale survival mechanisms in the deep sea.

4.2. Modelling of whale optimization algorithm

4.2.1. Encircling of prey

The WOA brings the current best candidate closer to the best solution. Once the best solution is found, other candidates will try to update their positions. This update action is represented by Equations (4.1) and (4.2).

$$\vec{D} = |\vec{C} \cdot \vec{X^*}(t) - \vec{X}(t)| \tag{4.1}$$

$$\vec{X}(t + 1) = \vec{X^*}(t) - \vec{A} \cdot \vec{D} \tag{4.2}$$

where t is the current iteration number, A and C are the coefficients, X^* is the best solution so far, and X is the position vector. $\|$ stands for size only, and the period ($\cdot$) is the element-wise multiplication operator.

The A and C vectors are computed as follows:

$$\vec{A} = 2\vec{a}.\vec{r} - \vec{a} \tag{4.3}$$

$$\vec{C} = 2.\vec{r} \tag{4.4}$$

The value of a is decreased linearly starting from 2 to 0 through the iterations and r is a random vector in (0,1). The position (X, Y) of a whale is updated based on the position of the best history so far (X*, Y*). Positions around the current best position are obtained by adjusting the values of A and C vectors.

4.2.2. Bubble-net attacking (Exploitation phase)

There are two ways to model the behavior of a humpback's bubble web: the retracting enveloping mechanism and the spiral update position. We will use the former method here. This behavior is achieved by reducing the value of a. Note that the range of variation of A is also reduced by a. That is, A is a random value in the interval (–a, a), and a decreases from 1 to 0 with iteration. If the random values for A are set to (1, 1), the whale's new position can be defined between its original position and the current optimal agent's position.

4.2.3. Search for prey (Exploration phase)

Approaches using variations of the *A* vector are also used here to hunt for prey (reconnaissance). In fact, whales randomly seek each other's positions. Therefore, the value of *A* is chosen among values greater than 1 and less than -1 to prevent the search agent from straying too far from the reference whale. This notion and the |*A*| > 1 condition indicate search and allow the algorithm to perform a global search. The mathematical model is given by Equation (4.5).

$$\vec{D} = |\vec{C}.\overrightarrow{X_{rand}} - \vec{X}| \tag{4.5}$$

$$\overrightarrow{X_{t+1}} = \overrightarrow{X_{rand}} - \vec{A}.\vec{D} \tag{4.6}$$

where $\overrightarrow{X_{rand}}$ is a random whale chosen from the current population.

The WOA algorithm begins with a set of randomly selected solutions. Each search agent is updated for its their position with respect to either a random search agent or the current best solution. A random search agent is chosen when |*A*| > 1, while the best solution is selected when |*A*| < 1 for updating the position of the search agents. The WOA algorithm starts with a set of randomly chosen solutions. Each search agent is updated with respect to its position relative to either the random search agent or the current best solution. If |*A*| > 1, a random search agent is chosen. The optimal solution is chosen for |*A*| < 1 . Update the search agent location.

4.2.4. Application of WOA in congestion management problem

The implementation procedure for the WOA is explained below.

Step 1: Read the test system line and bus data and solve the system line flow problem using the NR load flow method for the current system state.

Step 2: Initialize the whales, and set the population size NP to 30 and the number of iterations to 300. Each whale is a set of control-variable values taken within the lower and upper bounds.

Step 3: Set as control variables such as generator bus voltage, transformer tap position, SVC, and TCSC device position and size.

Step 4: Randomly generate a population of whales and initialize an iteration counter.

Step 5: Run NR Power Flow to calculate objective values for each whale. Perform this procedure for all 30 whales to complete the iterations.

Step 6: Once the objective values for all whales have been computed, sort the whales in ascending order of objective function value. The first whale is the current best with the smallest objective function value.

Step 7: Update whales using Equations. (4.2)-(4.6).

Step 8: Run the NR tide analysis to calculate the updated whale population target.

Step 9: Identify the best current whales. Compare this best whale to the best whale ever saved. If this whale is better, keep this as the best solution or go back to step 7.

Step 10: When the stop is achieved, exit the program and return the result.

5. Computational results and analysis

The proposed WOA-based congestion handling method is implemented in an IEEE 30 bus test system case. The system has 6 generators at nodes 1, 2, 5, 8, 11, and 13, 24 load nodes, and 41 branches [24]. Bus 1 is the reference bus, and the data is 100 MVA based. Three different transmission congestion cases are used in the simulation study: 35 % increased load, two-way transactions, and multilateral transactions. Table 1 shows the three congestion cases and the power trading volume for each case. The minimum and maximum values of the control variables of generator voltage magnitude and transformer tap change position are within 0.9 p.u. and 1.0 p.u. The SVC VAR output can be in the (0-10) MVAR range. TCSC reactance is measured between 20 % capacitive and 70 % inductance of the line. The proposed algorithm is run 50 times in the three different cases, and the best and worst results are compared with other algorithms. The time of execution in each case is also compared.

Table 1. Different cases of congestion.

Case	Cause of congestion	
Case 1	35 % overload at all the load buses.	
Case 2	11.5 MW of bilateral power transaction between GENCO 13 and DISCO 26	
	GENCOS	DISCOS
Case 3	Generator 8-11MW	Load bus 21-8 MW
	Generator 11-10 MW	Load bus 29-13 MW
	Total 21 MW	Total 21 MW

5.1. Case 1. 135 % load at all load buses

The total active power load of the system increases to 135%, resulting in increased MW flow through all lines. The most affected power flow is that of line 1, which carries a load of 131.2674 MW. The nominal power of this transmission line is 130 MW, but there is 1.2674 MW of surplus power. To ensure the security of a system that wires the Slack bus to the rest of the network, congestion must be mitigated. System control variables and TCSC and SVC parameters are controlled using the proposed congestion management algorithm. TCSC and SVC devices are optimally placed to provide maximum congestion relief. For comparison, Table 2 shows the power flow through various lines in the system during and after congestion handling. From the power flow, we can see that the overloaded lines are released, and the flow of all lines is adjusted so that the power is below capacity.

Table 2. Power flow comparison in case 1.

Line no.	MW flow before CM	MW flow after CM			Line no.	MW flow before CM	MW flow after CM		
		PSO	FFA	WOA			PSO	FFA	WOA
1	**131.2674**	**127.1166**	**128.2412**	**125.1989**	22	9.8363	8.1865	8.7090	8.6592
2	77.7204	75.0097	75.8193	74.2556	23	5.2405	3.6808	4.2064	5.1400
3	45.1248	43.2307	43.2015	42.7181	24	8.5512	10.2505	9.7927	8.8475
4	72.8314	69.4883	69.6251	68.8218	25	11.9157	13.7223	13.2309	11.8875
5	74.1643	74.1887	74.4739	73.6354	26	6.6694	11.5236	11.4966	11.2112
6	59.3274	57.8368	58.0393	56.8173	27	28.9593	29.1638	27.9801	22.4926
7	63.3811	64.4707	65.7898	64.8420	28	10.8002	9.1367	8.4401	7.3881
8	7.93120	12.8620	15.2268	12.2036	29	1.7056	3.8475	2.9429	4.1995
9	37.5064	36.5992	36.3548	37.1752	30	10.5278	4.4165	3.6045	3.3333
10	22.1891	22.9065	23.4902	27.6507	31	10.6332	9.0324	8.3738	7.3340
11	25.4170	23.1346	21.7937	21.5930	32	5.6166	3.3569	2.2172	2.8031
12	18.3791	17.6891	17.2740	15.4786	33	4.2880	0.8294	3.9745	3.7617
13	47.4478	27.0789	20.3210	27.9462	34	5.8192	5.7996	5.7937	5.7936
14	46.4785	46.9837	42.1148	43.9273	35	3.5019	6.4873	9.4731	9.3541
15	42.8541	38.7400	37.0566	36.9979	36	30.9965	25.3566	24.6979	24.8266
16	53.8331	37.2635	38.4911	48.4069	37	8.8276	8.9778	8.7456	8.7457
17	12.0257	10.3300	10.2700	10.7133	38	10.0438	9.8753	9.9441	9.9443
18	29.0165	23.1251	22.8826	21.3487	39	5.1140	6.0776	5.0914	5.0914
19	13.6922	9.3345	9.2472	9.2246	40	1.7674	2.9780	2.8456	2.4313
20	3.2679	1.5180	1.4580	2.2925	41	20.3357	2.0586	2.7997	23.9190
21	8.1316	4.2744	4.1385	3.9422	-	-	-	-	-

SVC and TCSC devices are deployed to optimize power flow patterns to alleviate congestion and minimize load node power loss and total voltage deviation. These benefits are shown in Table 3. The line loss during congestion was 15.2375 MW, but after congestion management the loss is reduced to 13.162 MW. A loss reduction of 2.0755 MW is achieved. To prove the strength of the proposed WOA-based method, the losses and voltage deviations reported by FFA and PSO are also presented in Table 3.

Table 3. Active power loss and voltage deviation with SVCs and TCSCs in case 1.

Parameter	During	After congestion is relieved		
		PSO	FFA	WOA
Total power loss (MW)	15.2375	13.3491	13.3481	13.162
Voltage deviation (p.u.)	0.9000	0.4368	0.3423	0.3327

The best and worst values of objectives yielded by PSO, FFA, and WOA algorithms are given in Table 4. The values of reported by WOA are better than those of the other algorithms. The less

execution time taken by WOA proves its speed of calculations. This indicates that the proposed method is less time expensive.

Table 4. Statistical analysis of results in case 1.

Parameter	Statistical data	PSO	FFA	WOA
Total power loss (MW)	Best	13.3491	13.3481	13.162
	Worst	13.8762	13.6539	13.4356
Voltage deviation (p.u.)	Best	0.4368	0.3423	0.3327
	Worst	0.5789	0.4735	0.3465
Execution time (Sec)		124.68	122.53	120.34

Design variables are adjusted during the optimization process to get the best values for line overload, loss and voltage difference objectives. The best set of control variables corresponding to the best global results is shown in Table 5. These values are recommended for operating the power system under healthy conditions.

Table 5. Optimal control variables in case 1.

Parameter	Best value PSO	Best value FFA	Best value WOA
V1(p.u.)	1.0866	1.0901	1.0822
V2(p.u.)	1.0688	1.0611	1.0565
V5(p.u.)	1.0380	1.0292	1.0301
V8(p.u.)	1.0333	1.0243	1.0234
V11(p.u.)	1.0690	1.0124	1.0664
V13(p.u.)	1.0612	1.0644	1.0806
T11(p.u.)	1.0033	0.9839	1.0144
T12(p.u.)	1.0081	0.9489	1.0876
T15(p.u.)	1.0513	1.0433	1.0876
T36(p.u.)	1.0302	0.9454	0.9519
SVC1(p.u.)	1.0074	3.2545	8.8528
SVC2(p.u.)	8.8143	1.5495	8.9837
TCSC1(p.u.)	0.2000	-0.2768	-0.2483
TCSC2 (p.u.)	0.1627	-0.3371	0.1804

As shown in Table 6, two SVCs and two TCSCs are proposed for different bus and line locations by the three algorithms. The location is ideal for case 1 congestion management.

Table 6. Optimal locations of SVCs and TCSCs in case 1.

Label of SVC, TCSC	Location of SVC and TCSC		
	PSO	FFA	WOA
SVC1	4	13	21
SVC2	29	28	19
TCSC1	37	22	17
TCSC2	21	28	25

The convergence quality of the proposed WOA algorithm is depicted in Figure 5 and it is clear from the Figure that the WOA algorithm is faster than the remaining two algorithms. Comparing the change in objective values over iterations, reported by the three algorithms, it is obvious that WOA better maintains the objective value.
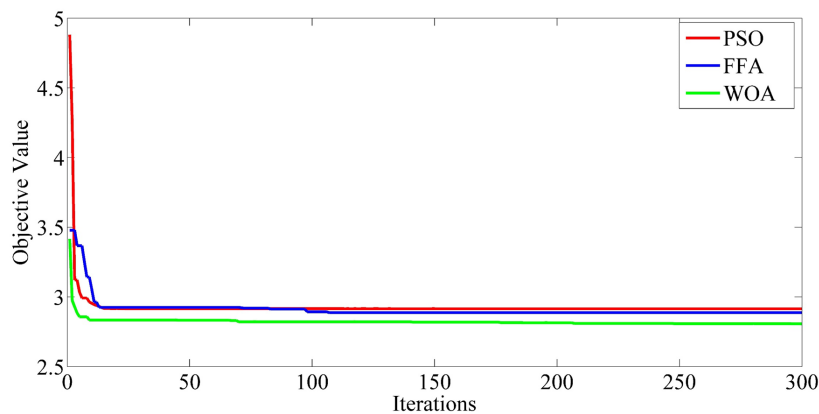
Figure 5. Convergence of PSO, FFA, and WOA in case 1

5.2. Case 2- Bilateral transaction

In this case, bi-directional transactions are performed between buses 13 and 26. This transaction is done using bus 13 as the GENCO and bus 26 as his DISCO bus for power transactions. The contract provides for a power deal of 11.5 MW, resulting in 16 MW capacity line no. 34 getting overloaded. The power flow during this transaction is 16.1233 MW. The proposed WOA-based method is utilized to remove the congestion caused by line no. 34. The post-line flows obtained by the PSO, FFA, and WOA algorithms after line congestion are shown in Table 7.

Table 7. Active power flow comparison in case 2.

Line no.	MW flow before CM	MW flow after CM			Line no.	MW flow before CM	MW flow after CM		
		PSO	FFA	WOA			PSO	FFA	WOA
1	57.0233	58.8873	56.6586	57.8673	22	8.3147	7.0358	7.1936	6.7068
2	43.6815	43.6303	44.0706	42.7216	23	4.8852	3.6846	3.8941	3.6183
3	31.0181	29.9268	29.4216	29.8110	24	5.2431	6.6591	6.6733	6.3522
4	40.6146	40.1990	40.7333	39.5424	25	7.6561	9.1047	9.1003	8.8002
5	45.4808	46.1908	46.0554	46.7183	26	2.6326	7.1752	8.4684	7.4627
6	39.6320	39.5434	38.9485	38.5417	27	21.9695	19.7922	22.3958	21.5405
7	39.8581	42.4776	42.9750	42.1190	28	11.3091	8.5998	8.9210	7.8082
8	2.3672	9.1103	8.6955	8.9257	29	1.5164	2.6761	1.4691	2.0758
9	25.7829	22.0543	22.0906	21.5574	30	10.8513	7.0932	7.4625	6.1584
10	24.7471	13.9963	14.2904	18.7578	31	11.1538	8.5580	8.8641	7.7619
11	15.7261	13.2819	14.2110	13.0692	32	8.0211	5.5036	6.0923	4.5671
12	12.4440	12.0949	11.8807	11.1906	33	9.8490	7.0819	7.5262	5.1054
13	43.3236	23.4617	25.2978	22.4414	**34**	**16.1233**	**14.8868**	**16.0375**	**12.8579**
14	34.9827	34.0180	32.9252	33.0242	35	7.0327	9.6894	10.2188	11.6211
15	22.6015	18.8723	19.8619	19.8234	36	29.2238	23.4491	23.8081	23.5225
16	51.3706	31.2894	31.1382	41.8936	37	6.4457	6.4123	6.4136	6.4103
17	9.7744	8.3627	8.2823	8.1735	38	7.3265	7.2860	7.2875	7.2836
18	25.0675	20.4409	21.1225	19.6811	39	3.7625	3.7533	3.7537	3.7528
19	12.4633	9.3543	9.8376	9.8049	40	5.0213	3.4364	3.9863	3.2971
20	3.2225	2.0372	2.5218	1.8469	41	17.9584	20.0304	19.8285	20.5734
21	8.2686	5.6617	6.5755	6.2436	-	-	-	-	-

Table 8 shows additional benefits of minimizing the loss levels and voltage deviations reported by the algorithm. The actual power loss achieved by the WOA during this bilateral transaction period was 6.193 MW, which is lower than the loss levels indicated by the two other algorithms. It is clear that the proposed method alleviates congestion and greatly minimizes line loss. The total voltage deviation under overload was 0.7370 and was reduced to 0.1678 by the WOA algorithm. Meanwhile, 0.2172 and 0.1747 are the voltage deviations obtained by the PSO and FFA algorithms.

Table 8. Power loss and voltage deviation with SVCs and TCSCs in case 2.

Parameter	During	After congestion is relieved		
		PSO	FFA	WOA
Total power loss (MW)	7.1254	6.6698	6.5439	6.1930
Voltage deviation (p.u.)	0.7370	0.2172	0.1747	0.1678

The statistical analysis of objective values obtained by the different algorithms are shown in Table 9

for comparison. The best and worst values of WOA are better than those of PSO and FFA algorithms. The execution time taken by WOA is less than the time taken by PSO and FFA algorithms. This proves the fast convergence quality of WOA.

Table 9. Statistical analysis of results in case 2.

Parameter	Statistical data	PSO	FFA	WOA
Total power loss (MW)	Best	6.6698	6.5439	6.1930
	Worst	6.9875	6.8976	6.5432
Voltage deviation (p.u.)	Best	0.217	0.1747	0.1678
	Worst	0.245	0.1954	0.1726
Execution time (Sec)		203.68	200.83	117.34

Generator voltage magnitude, transformer tap-changer settings, SVC and TCSC parameters are all optimized by the PSO, FFA, and WOA algorithms. Control variables are adjusted during the optimization process, taking into account upper and lower bounds. The well-matched control variables corresponding to the best results are shown in Table 10.

Table 10. Optimal control variables in case 2.

Parameter	Best value PSO	Best value FFA	Best value WOA
V1(p.u.)	1.0491	1.0323	1.0381
V2(p.u.)	1.0314	1.0215	1.0219
V5(p.u.)	1.0075	1.0053	1.0107
V8(p.u.)	0.9992	0.9982	0.9990
V11(p.u.)	0.9761	1.0472	1.0347
V13(p.u.)	1.0330	1.0117	1.0582
T11(p.u.)	0.9869	1.0130	1.0043
T12(p.u.)	0.9591	0.9572	0.9983
T15(p.u.)	0.9681	0.9651	1.0452
T36(p.u.)	0.9625	0.9587	0.9345
SVC1(p.u.)	9.3156	6.7702	2.3240
SVC2(p.u.)	7.9593	6.0915	2.5471
TCSC1(p.u.)	0.2000	-0.2537	-0.2810
TCSC2 (p.u.)	0.2000	-0.2276	0.1533

Table 11 shows the best bus and line locations identified for SVC and TCSCs in relieving congestion in this case that are different for different algorithms. when SVC and TCSC devices are located at the positions (bus and line numbers), the line overload, line loss and load bus voltages are optimized, and this helps the power system to be free from stressed conditions.

Table 11. Optimal locations of SVCs and TCSCs in case 2.

Label of SVC, TCSC	Location of SVC and TCSC		
	PSO	FFA	WOA
SVC1	21	26	23
SVC2	25	15	19
TCSC1	13	40	19
TCSC2	15	4	9

Figure 6 shows how the algorithm behaves in converging to the optimal goal value of the problem in this congestion managing problem caused by bilateral transaction. The proposed WOA method achieves the best results in fewer iterations and retains them throughout the optimization process.
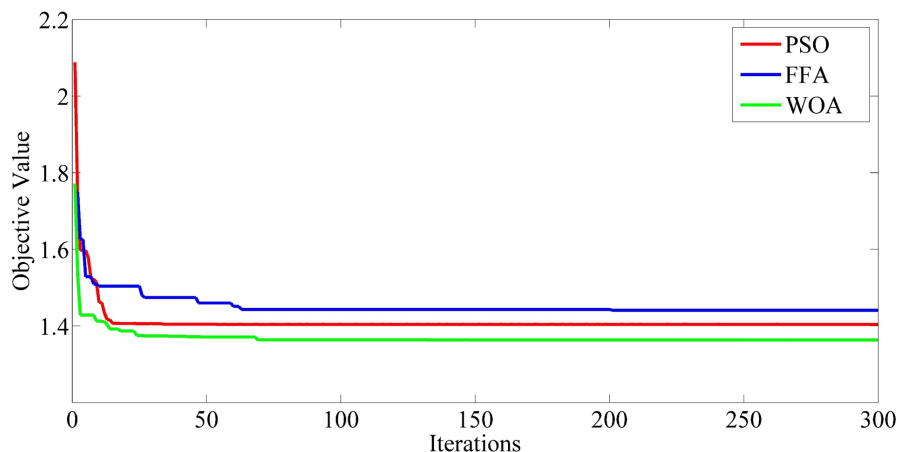
Figure 6. Convergence of PSO, FFA, and WOA in case 2.

5.3. Case 3- Multilateral transactions

In the multilateral transaction considered in this case, buses 8 and 11 use GENCO to sell 11 MW and 10 MW of electricity, respectively. DISCO is located on buses 21 and 29 with distributed power of 8 MW and 13 MW, respectively. This multilateral transaction causes congestion on branch 37, which has a capacity of 16 MW, but it is overloaded due to a power flow of 16.2977 MW. Table 12 compares line flows during and after congestion management.

Table 12. Active power flow comparison in case 3.

Line no.	MW flow before CM	MW flow after CM			Line no.	MW flow before CM	MW flow after CM		
		PSO	FFA	WOA			PSO	FFA	WOA
1	56.5202	57.8191	58.0784	57.6420	22	7.2961	6.1769	5.9659	6.2039
2	43.9787	43.7776	44.6104	43.3757	23	3.9619	3.4775	3.7910	2.8469
3	31.4777	30.6419	31.3852	30.5404	24	6.3395	6.9598	7.1139	7.3705
4	40.8836	40.6835	41.2298	40.2889	25	8.7636	9.3934	9.4446	9.8572
5	45.1716	46.0254	45.7397	45.6811	26	4.3122	8.1862	9.3348	7.5598
6	38.7853	38.8103	38.4267	38.6532	27	28.1567	26.5213	26.9289	27.1962
7	34.0998	40.3718	38.9514	36.5221	28	10.8685	7.1685	8.1045	8.8196
8	1.9086	9.2172	3.1440	0.2566	29	1.4134	1.9080	2.7821	0.8442
9	25.8442	22.0831	23.7882	25.0715	30	10.1178	5.4462	5.4113	6.1364
10	22.4069	13.9856	6.1048	7.2179	31	10.7265	7.1441	8.0559	8.7329
11	14.6906	13.3366	13.3710	11.9650	32	5.9264	3.8187	3.2626	3.9279
12	13.5454	10.3683	13.2505	13.0898	33	7.4464	6.9079	4.3595	3.8564
13	48.4644	28.8257	29.2884	31.0595	34	4.2746	4.2621	4.2644	4.2649
14	43.4359	43.8016	41.2053	40.2306	35	2.9917	9.9742	6.2947	4.7208
15	29.2591	25.9076	26.0431	26.3193	36	33.0062	30.3584	27.8713	25.9812
16	46.5368	39.8101	20.2248	31.1723	**37**	**16.2977**	**15.4280**	**15.8463**	**14.5274**
17	9.3830	7.8217	7.6213	8.2148	38	11.2768	10.8759	11.0532	11.0848
18	23.4450	18.3971	17.8870	19.4660	39	0.5275	0.5958	0.5447	2.9151
19	10.7910	7.4358	6.9576	7.9322	40	6.4117	5.7153	5.5762	5.2771
20	2.9020	1.5656	1.7314	1.7333	41	19.7638	25.5606	22.9897	21.0860
21	6.7331	3.7340	3.7371	4.1038	-	-	-	-	-

Other goals for minimizing losses and voltage deviation are shown in Table 13. The total system loss is minimized by WOA from 6.9355 MW to 6.1216 MW. This loss reduction is an indicator of the effective congestion management achieved by the proposed WOA approach. As shown in Table 13, the deviation of the load bus voltage from the nominal value is minimal, confirming the suitability of the proposed approach for alleviating congestion on transmission lines.

Table 13. Active power flow comparison in case 3.

Parameter	During	After congestion is relieved		
		PSO	FFA	WOA
Total power loss (MW)	6.9355	6.1561	6.1261	6.1216
Voltage deviation (p.u.)	0.7313	0.2249	0.2036	0.1999

Objective values of voltage deviation and loss produced by the algorithms used are given in Table 14 for comparison. The best and worst values of loss and voltage deviation reported by WOA are

encouraging when compared to that of the values by PSO and FFA algorithms. The time taken by WOA for achieving the best results is less than the time required by PSO and FFA algorithms. This shows the speed of convergence of WOA.

Table 14. Statistical analysis of results in case 3.

Parameter	Statistical data	PSO	FFA	WOA
Total power loss (MW)	Best	6.1561	6.1261	6.1216
	Worst	7.0456	6.5683	6.1593
Voltage deviation (p.u.)	Best	0.2249	0.2036	0.1999
	Worst	0.3657	0.3197	0.2034
Execution time (Sec)		156.63	153.68	150.23

Best control variable values, corresponding to congestion management in this case, are shown in Table 15. It is maintained that all the variables are taking values within the respective limits. It is recommended that these values are the highly suitable for relieving congestion and minimizing loss and voltage deviation.

**Table 15.** Optimal control variables in case 3.

Parameter	Best value PSO	Best value FFA	Best value WOA
V1(p.u.)	1.0436	1.0582	1.0236
V2(p.u.)	1.0363	1.0425	1.0200
V5(p.u.)	1.0210	1.0113	0.9881
V8(p.u.)	1.0102	1.0169	0.9999
V11(p.u.)	1.0283	1.0177	1.0364
V13(p.u.)	1.0639	1.0205	1.0554
T11(p.u.)	0.9808	1.0222	1.0263
T12(p.u.)	1.0864	0.9858	0.9508
T15(p.u.)	1.0814	1.0113	1.0021
T36(p.u.)	0.9156	0.9508	0.9762
SVC1(p.u.)	2.4780	6.4882	6.9114
SVC2(p.u.)	5.1137	4.5855	4.5718
TCSC1(p.u.)	0.1826	-0.1952	0.1972
TCSC2 (p.u.)	0.1114	-0.2854	-0.0458

From the information about the locations, identified by the three algorithms, for the FACTS devices for this case is as given in Table 16.

Table 16. Optimal locations of SVCs and TCSCs in case 3.

Label of SVC, TCSC	Location of SVC and TCSC		
	PSO	FFA	WOA
SVC1	12	19	29
SVC2	18	23	22
TCSC1	12	7	37
TCSC2	16	20	33

Figure 7 shows the convergence characteristics of WOA. It is clear that WOA outperforms the two other algorithms in this multilateral transaction case. The proposed algorithm further optimizes the desired value and prevents the algorithm from easily being trapped in local minima.
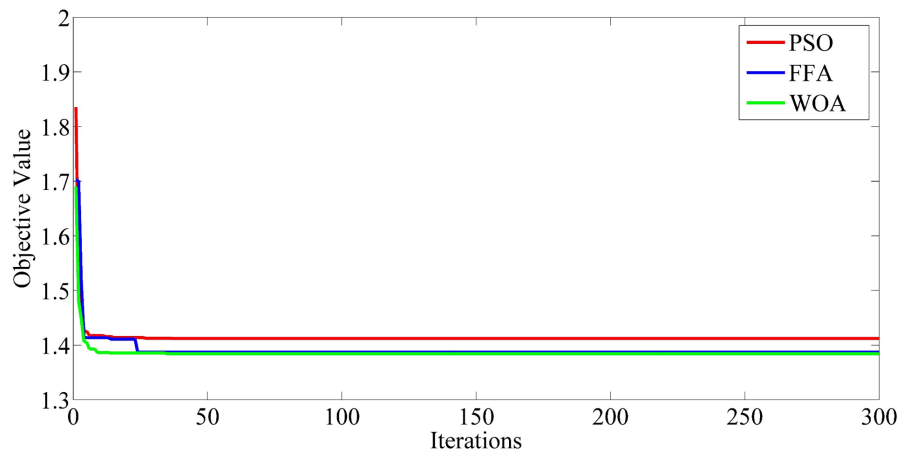
Figure 7. Convergence of PSO, FFA, and WOA in case 3.

6. Conclusions and future work

This work employs a novel biologically-inspired WOA to find the optimal location and size of SVC and TCSC controllers in the grid to alleviate congestion. Parallel-connected SVCs and series-connected TCSC compensators were used for congestion management. For SVC and TCSC allocation issues, appropriate location and size of the FACTS controllers that remove line flow violation, minimize loss, and minimize voltage excursions in the load bus are considered. The results show that WOA produces low ratings for SVC and TCSC controllers, ensuring low capital cost of the devices. Therefore, the WOA method can be used as an efficient technique to solve the optimal allocation of FACTS compensators in congestion management problems. Comparing the results obtained from other algorithms, the PSO and FFA algorithms, and their convergence properties, it is clear that the WOA-based method outperforms the others.

The work can be enhanced in the future by considering other FACTS devices like SSSC, STATCOM, UPFC or by using the multi objective optimization approaches.

Use of AI tools declaration

The authors declare they have not used artificial intelligence (AI) tools in the creation of this article.

Conflict of interest

The authors have no conflict of interest

References

1. Fang RS, David AK (1999) Optimal Dispatch under transmission contracts. *IEEE T Power Syst* 14: 732–737. https://doi.org/10.1109/59.761905

2. Choudekar P, Asija D (2021) Transmission congestion management using multi objective hybrid flower pollination and particle swarm optimization algorithm by optimal placement of TCSC. *Metaheuristic and Evolutionary Computation: Algorithms and Applications*, 569–583. https://doi.org/10.1007/978-981-15-7571-6_26

3. Patel NK, Suthar BN, Thakkar J (2021) Transmission congestion management considering voltage stability margin. *SN Applied Sciences* 3: 261. https://doi.org/10.1007/s42452-020-04132-9

4. Gad M, Shinde P, Kulkarni SU (2012) Optimal location of TCSC by sensitivity methods. *Int J Comput Eng Res* 2: 162–168.

5. Leung HC, Chung TS (2000) Optimal power flow with a versatile FACTS controller by genetic algorithm approach. *Proc. Power engineering society winter meeting* 4: 2806–2811. https://doi.org/10.1049/cp:20000387

6. Hingorani NG, Gyugyi L (1998) *Understanding FACTS*. The Institution of Electrical and Electronics Engineers, 1998.

7. Gyugyi L, Schauder CD, Williams SL, Rietman TR, Torgerson DR, Edris A (1995) The unified power flow controller: a new approach to power transmission control. *IEEE T Power Deliver* 10: 1085–1097. https://doi.org/10.1109/61.400878

8. Larsen E, Millers N, Nilsson S, Lindgren S (1992) Benefits of GTO-based compensation systems for electric utility applications. *IEEE T Power Deliver* 7: 2056–2064. https://doi.org/10.1109/61.157009

9. Preedavinchit P, Srivastava SC (1998) Optimal reactive power dispatch considering FACTS devices. *Electric Power Syst Res* 46: 251–257. https://doi.org/10.1016/S0378-7796(98)00075-3

10. Momoh JA, Zhu JZ (1998) A new approach to optimal power flow with phase shifter. *SMC'98 Conference Proceedings. 1998 IEEE International Conference on Systems, Man, and Cybernetics (Cat. No. 98CH36218)* 5: 4794–4799.

11. Liu JY, Song YH (1999) Comparison studies of unified power flow controller with static var compensators and phase shifters. *Electric Machines & Power Systems* 27: 237–251. https://doi.org/10.1080/073135699269271

12. Besharat H, Taher SA (2008) Congestion management by determining optimal location of TCSC in deregulated power systems. *Int J Elec Power* 30: 563–568. http://dx.doi.org/10.1016/j.ijepes.2008.08.007

13. Singh SN, David AK (2001) Optimal location of FACTS devices for congestion management. *Electr Power Syst Res* 58: 71–79. https://doi.org/10.1016/S0378-7796(01)00087-6

14. Amjady N, Hakimi M (2012) Dynamic voltage stability constrained congestion management framework for deregulated electricity markets. *Energy Convers Manag* 58: 66–75. https://doi.org/10.1016/j.enconman.2012.01.006

15. Gerbex S, Cherkaoui R, Germond AJ (2003) Optimal location of FACTS devices to enhance power system security. *2003 IEEE Bologna Power Tech Conference Proceedings* 3: 7-pp. IEEE.

16. Rashed GI, Sun Y (2011) Optimal placement of Thyristor controlled series compensation for enhancing power system security based on computational intelligence techniques. *Procedia Engineering* 15: 908–914. https://doi.org/10.1016/j.proeng.2011.08.168

17. Rahim MA, Musirin I, Abidin IZ, Othman MM (2010) Contingency based congestion management and cost minimization using bee colony optimization technique. *PECon2010 - 2010 IEEE International Conference on Power and Energy* 891–896. https://doi.org/10.1109/PECON.2010.5697705

18. Shrestha GB, Feng W (2005) Effects of series compensation on spot price power markets. *Int J Elec Power* 27: 428–436. https://doi.org/10.1016/j.ijepes.2005.03.001

19. Hosseinipoor N, Nabavi SMH (2010) Optimal locating and sizing of TCSC using genetic Algorithm for congestion management in deregualted power markets. *2010 9th International Conference on Environment and Electrical Engineering* 136–139. https://doi.org/10.1109/EEEIC.2010.5489968

20. Biswas PP, Arora P, Mallipeddi R, Suganthan PN, Panigrahi BK (2021) Optimal placement and sizing of FACTS devices for optimal power flow in a wind power integrated electrical network. *Neural Comput Appl* 33: 6753–6774. https://doi.org/10.1007/s00521-020-05453-x

21. Verma KS, Singh SN, Gupta HO (2001) FACTS devices location for enhancement of total transfer capability. *2001 IEEE Power Engineering Society Winter Meeting. Conference Proceedings (Cat. No. 01CH37194)* 2: 522–527.

22. Jordehi AR (2015) Brainstorm optimisation algorithm (BSOA): An efficient algorithm for finding optimal location and setting of FACTS devices in electric power systems. *Int J Elec Power* 69: 48–57. https://doi.org/10.1016/j.ijepes.2014.12.083

23. Mirjalili S, Lewis A (2016) The whale optimization algorithm. *Adv Eng Softw* 95: 51-67. https://doi.org/10.1016/j.advengsoft.2016.01.008

24. The IEEE 30-Bus Test System. Available from: `http://www.ee.washington.edu/research/pstca/pf30/pg$_$tca30bus.htm`.