Research Article

Transmission Congestion Management through Optimal Placement and Sizing of TCSC Devices in a Deregulated Power Network

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Abstract: Transmission congestion is mainly caused by agreed transactions between generating companies and distributing companies in deregulated power system networks across the world. Secured and economic operation of power system networks in the deregulated scenario can be ensured by managing the congestion in the transmission lines. FACTS devices are used for changing the power flow through the lines so that all the lines are carrying power flow below their respective limit. In this work, series connected Thyristor Controlled Switched Capacitor(TCSC) devices are installed in suitable lines for relieving congestion in the over loaded lines of the system. The size and location of TCSC devices greatly affect their efficiency in congestion management problem. To maximize the benefits of TCSC in congestion management problem, the site and size of the TCSC devices are optimized by using an optimization technique. The recent bio inspired Whale Optimization Algorithm (WOA) is employed in this proposed work for the optimization of the objective value through identifying the position and size of FACTS devices. This algorithm involves low number of parameters to be tuned for attaining global best results and can be easily coded in Matlab platform. The proposed WOA based method for optimal position and sizing of TCSC is implemented on the IEEE 30 bus test system. The results obtained are compared against the results reported by Particle Swarm Optimization algorithm (PSO), Firefly algorithm(FFA)and are found to be outperforming.

Keywords: Deregulation, Congestion management, Whale optimization algorithm, FACTS, TCSC, FFA, PSO

1. Introduction

Competitive markets are introduced for all commodities including electricity for economic benefits. Monopolistic electricity market has been restructured into three separate entities, viz, generation companies (GENCOS), transmission companies (TRANSCOS) and distribution companies (DISCOS) [1]-[2]. Competition is being introduced to GENCOS and DISCOS to achieve higher efficiency in electricity generation and utilization. Transmission network is operated by a system operator (SO) which may be a private or government entity.

Transmission infrastructure is generally owned by one entity for benefits of economy and of proper control of power flow. Power demand is increasing at a faster rate as compared to the expansion in transmission networks. In addition, the large numbers of bilateral and multilateral contracts cause intense transmission line utilization [3]. When all the contracted transactions are not accommodated in a controlled manner, some lines in certain areas may get overloaded; this is referred to as congestion [4]. It forces for the enhancement of transmission capability or expansion of transmission networks. Congestion management may be defined as actions taken to remove overloading of lines. Acquiring of right-of-way and cost of installations are the key limitations in transmission network expansion. Moreover, depending on the transactions, higher capacity of lines may be temporary only during the transaction period which justifies the capacity enhancement as best alternative to expansion.

Transaction contracts leading to heavy flows results in increased line losses, threaten stability, security and reliability of the system. Therefore, maximizing the utilization of already installed transmission capability is required. This can be easily achieved by installing flexible AC transmission systems (FACTS) devices [5]-[7].

The increased use of these FACTS devices is because of two reasons. Firstly, the recent advancements in high power electronic switches made these devices cost less and involve low loss [8] and secondly, their use in power flow control for dispatching specified power transactions. It is crucial to identify the location and size of these devices for optimal performance and considerable costs. There are many different ways available for determining the optimal location and sizing of FACTS devices in power systems [9]-[11].

In [12] sensitivity-based approaches are used for finding the best location of TCSC to relieve congestion from overloaded lines. TCSC parameters are optimized to reduce the line overloading under contingency conditions in [13]. Reference [14] discusses congestion relief and voltage stability enhancement in deregulated electricity market using multiple FACTS devices. Total congestion cost minimization by placing FACTS devices at suitable locations has been discussed in [15]. Differential Evolution algorithm is applied for improving power system security under single line outage condition for reducing congestion [16]. Management of congestion and cost minimization is done through Bee Colony Optimization in [17]. TCSC is placed at best locations for optimizing social benefit and congestion [18]. Genetic algorithm is used for finding optimal location of TCSC to solve transmission line congestion problem [19].

A new method based on WOA is proposed here to find the optimal location of TCSC devices. In Section 2, static power injection modeling of TCSC is presented. In Section 3, the objective function of minimizing congestion, loss and voltage deviation is discussed. InSection 4, the whale algorithm technique is explained.In section 5 the results and discussions are presented and finally in section 6, the work is concluded. The proposed method is tested on IEEE 30 bus system under three different scenarios.

2. Modelling Of Tcsc Device

The series connected TCSC is capable of operating both in lagging and leading power factor modes. It is connected in series with a line to adjust its effective reactance [20].Its simplicity in implementation and low cost when compared to other types of FACTS devices is the principal reason for its widespread use. Figure 1 shows the π-equivalent model of the line connected between buses 'i' and 'j'.

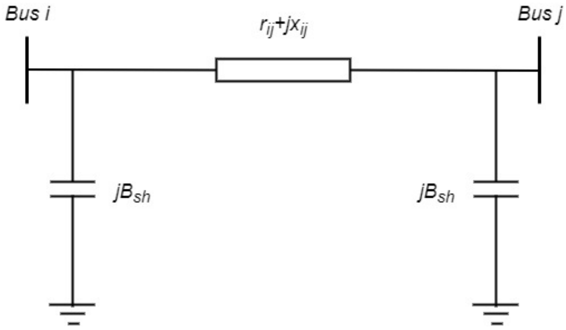

Figure 1. π-model of a line

If $V_i\angle\delta_i$ and $V_j\angle\delta_j$ are the voltages at bus-i and bus-j respectively, the equations representing active and reactive power flow through the line connected between buses 'i' and 'j'can be given by equations (1) and (2) respectively.

$$P_{ij} = V_i^2 G_{ij} - V_i V_j \left(G_{ij} cos\delta_{ij} + B_{ij} sin\delta_{ij}\right) \qquad (1)$$

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

The equations for real and reactive power flow from bus-j to bus-i are represented by equations (3) and (4) respectively.

$$P_{ji} = V_j^2 G_{ij} - V_i V_j \left(G_{ij} cos\delta_{ij} + B_{ij} sin\delta_{ij}\right) \qquad (3)$$

$$Q_{ji} = -V_j^2 \left(B_{ij} + B_{sh}\right) - V_i V_j \left(G_{ij} sin\delta_{ij} + B_{ij} cos\delta_{ij}\right) \qquad (4)$$

Insertion of TCSC can be thought of as a variable reactance connected in series with the transmission line. Transmission line model incorporating TCSCis depicted in fiure 2. Under steady-state conditions, the TCSC can be modelled as a static capacitor (leading power factor) or inductor (lagging power factor).

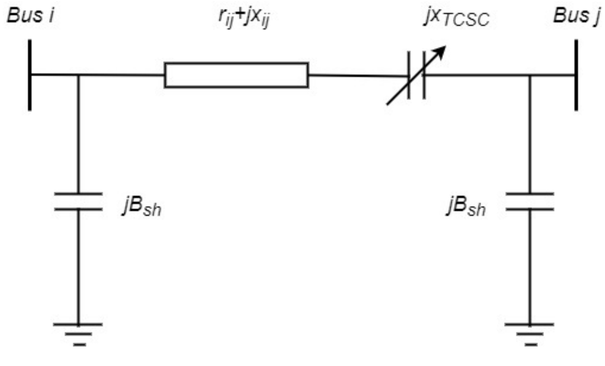

Figure 2. π-model representation of a branch with TCSC

After the incorporation of the TCSC, the power flow between bus-i to bus-j gets modified as shown in equations (5) and (6).

$$P'_{ij} = V_i^2 G'_{ij} - V_i V_j \left(G'_{ij} cos\delta_{ij} + B'_{ij} sin\delta_{ij} \right) \qquad (5)$$

$$Q'_{ij} = -V_i^2 \left(B'_{ij} + B'_{sh} \right) - V_i V_j \left(G'_{ij} sin\delta_{ij} + B'_{ij} cos\delta_{ij} \right) \qquad (6)$$

Where,

$$G'_{ij} = \frac{r_{ij}}{r_{ij}^2 + \left(x_{ij} - x_{TCSC} \right)^2}$$

$$B'_{ij} = \frac{-\left(x_{ij} - x_{TCSC} \right)}{r_{ij}^2 + \left(x_{ij} - x_{TCSC} \right)^2}$$

Congestion management problem is considered under static conditions and employs static model of TCSC device as power injections at the endbuses of the line. According to this model TCSC device can be modelled as real and reactive power injections to the end nodes. The power injection model of TCSC device is given in figure 3.

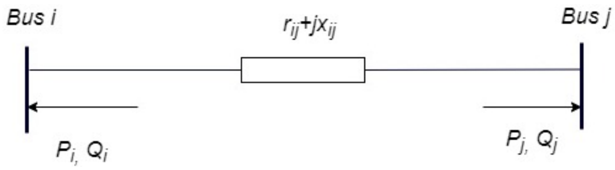

Figure 3. Power injection model of TCSC

The real and reactive power injections at sending end bus-i and receiving end bus-j after inclusion of TCSC is given by equations (7) to (10).

$$P'_i = V_i^2 \Delta G_{ij} - V_i V_j \left(\Delta G_{ij} cos\delta_{ij} + \Delta B_{ij} sin\delta_{ij} \right) \qquad (7)$$

$$P'_j = V_j^2 \Delta G_{ij} - V_i V_j \left(\Delta G_{ij} cos\delta_{ij} + \Delta B_{ij} sin\delta_{ij} \right) \qquad (8)$$

$$Q'_i = -V_i^2 \Delta B_{ij} - V_i V_j \left(\Delta G_{ij} sin\delta_{ij} + \Delta B_{ij} cos\delta_{ij} \right) \qquad (9)$$

$$Q'_j = -V_j^2 \Delta B_{ij} - V_i V_j \left(\Delta G_{ij} sin\delta_{ij} + \Delta B_{ij} cos\delta_{ij} \right) \qquad (10)$$

Where,

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

$$\Delta B_{ij} = \frac{-x_{TCSC} \left(r_{ij}^2 - x_{ij}^2 + x_{TCSC} x_{ij} \right)}{\left(r_{ij}^2 + x_{ij}^2 \right) \left[r_{ij}^2 + \left(x_{ij} - x_{TCSC} \right)^2 \right]}$$

3. Congestion Management Problem

3.1Congestion management

In a deregulated environment, the three major stake holders of TRANSCOs, GENCOs and DISCOs are owned by different organizations. For maintaining the coordination among them there should be one system operator in all types of deregulated power system models, generally it is called the independent System Operator (ISO). In a competitive electricity market, high level of freedom is provided to all the market participants for interactions. Here, both the DISCOs and GENCOs try to buy and sell electric power in a way so as to maximize their profit. In deregulated electricity markets, transmission congestion occurs when there is insufficient transmission capacity to simultaneously accommodate all transactions. Congestion ought to be mitigated as quick as attainable to avoid cascaded tripping of overloaded lines. FACTS devices can be better utilized to reduce the power flows in the loaded branches, which results in an increased loadability (ATC enhancement).

3.2Objectives

The main objective is to remove overload from the congested lines by adjusting the generator bus voltages, transformer tap settings and reactance of TCSC devices. The other two objectives are line loss and voltage deviation at load buses.

The transmission lines are designed to carry power within their thermal limits. Congestion management removes these violations by minimizing the real power violation which is taken as first objective here.

$$f_1 = \sum_{k=1}^{N_l} |P_k - P_{k\,rat}| \quad (11)$$

Where P_k is the power flow at k^{th} line and $P_{k\,rat}$ is the maximum power flow limit of the line.

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

$$f_2 = \sum_{k=1}^{N_l} G_k[V_i^2 + V_j^2 - 2|V_i||V_j|\cos\delta_i - \delta_j] \quad (12)$$

Where G_k is the conductance of k^{th} line. V_i and V_j are the sending end and receiving end voltage magnitudes of the k^{th} line. δ_i and δ_j are the sending end and receiving end voltage angles of the k^{th} line.

The objective of ensuring quality power at consumer end by eliminating voltage variations at load buses is done by minimizing voltage deviation and that is the third objective.

$$f_3 = \sum_{k=1}^{N_{pq}} |(V_k - V_{k\,ref})| \quad (13)$$

Where V_k is the voltage of k^{th} bus. $V_{k\,ref}$ is the reference voltage at bus k. it is taken as 1.0 p.u. in this work.

The congestion management problem has been formulated as anaugmented multi-objective optimization problem of minimizing the overloads, reducing the transmission losses and minimizing the voltage deviation at load buses.

$$F = \min(f_1, f_2, f_3)$$

Weighted aggregated method is employed to convert the multi-objective model in to single objective model as [21].

$$F = w_1 f_1 + w_2 f_2 + w_3 f_3 \quad (14)$$

For determining the weight factors for the augmentation of the objectives, weight factor for voltage deviation is set as the highest value (0.6). The other two objectives are given equal weights of 0.2.

since,$w_1 = 0.2, w_2 = 0.2, w_3 = 0.6$ for the optimization work.

3.3 Constraints

3.3.1 Equality constraints

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

$$P_{Gi} - P_{Di} - \sum_{j=1}^{NB} V_i V_j Y_{ij} \cos(\delta_{ij} + \gamma_j - \gamma_i) = 0 \quad (15)$$

$$Q_{Gi} - Q_{Di} - \sum_{j=1}^{NB} V_i V_j Y_{ij} \sin(\delta_{ij} + \gamma_i - \gamma_j) = 0 \quad (16)$$

Where, P_{Gi}, Q_{Gi} are the active and reactive power of i^{th} generator, P_{Di}, $Q_{Di}$the active and reactive power of i^{th}load bus.

3.3.2 Inequality constraints

Generator constraints:

Generator voltage and reactive power of i^{th} bus lies between their upper and lower limits as given below:

$$V_{Gi}^{min} \le V_{Gi} \le V_{Gi}^{max} i = 1,2,\ldots.N_G \quad (17)$$

$$Q_{Gi}^{min} \leq Q_{Gi} \leq Q_{Gi}^{max} i = 1,2,\ldots.N_G \quad (18)$$

Where, V_{Gi}^{min}, V_{Gi}^{max} are the minimum and maximum voltage of i[th] generating unit and Q_{Gi}^{min}, Q_{Gi}^{max} are the minimum and maximum reactive power of i[th] generating unit.

Load bus voltage constraints:

The upper and lower bound of load bus voltages are given by

$$V_i^{min} \leq V_i \leq V_i^{max} i = 1,2,\ldots.N_{PQ} (19)$$

Where, V_i^{min}, V_i^{max} are the minimum and maximum value voltage of load bus ‘i’.

Transmission line constraints:

$$P_i \leq P_i^{max} i = 1,2,\ldots,N_L \quad (20)$$

Where, P_i is the apparent power flow of i[th] branch and P_i^{max} is the maximum apparent power flow limit of i[th] branch.

Transformer taps constraints:

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

$$T_i^{min} \leq T_i \leq T_i^{max} i = 1,2,\ldots,N_T (21)$$

Where, T_i^{min}, T_i^{max} are the minimum and maximum tap setting limits of i[th] transformer.

4. Whale Optimization Algorithm

4.1 Overview

Whales do not sleep as they need to come to the surface of water for breathing. Whales are alert of all the times that helps a whale to think, learn, judge and communicate emotional by its spindle cells [22]. Most of the whale species are living in a family during their life time. Humpback whale is one of the biggest spices that has a special prey hunting behavior called bubble net feeding. Bubble-net feeding is a unique behavior that can only be seen in humpback whale is mathematically modeled for searching optimal solution in the search space. Nature inspired algorithms are mimicked from the food searching mechanism, survival mechanism etc. of the living beings. WOA is developed based on the survival mechanism of whale in deep ocean.

4.1.1Encircling of the Prey

WOA algorithm takes the current best candidate close to the optimum solution. Once the best solution is identified, the other candidates try to update their positions.

This updating action is expressed by the following equations:

$$\vec{D} = \left|\vec{C}.\vec{X^*}(t) - \vec{X}(t)\right| \quad (22)$$

$$\vec{X}(t+1) = \vec{X^*}(t) - \vec{A} \cdot \vec{D} \quad (23)$$

Where‘t’ refers the current iteration number, A and C are coefficient vectors, X*is the best solution obtained so far, X is the current solution. | | is for absolute value, and dot (·) is for element level multiplication operator.

Equation (24) is used for calculating coefficients A and C.

$$\vec{A} = 2\vec{a} \cdot \vec{r} - \vec{a} \quad (24)$$

$$\vec{C} = 2 \cdot \vec{r} \quad (25)$$

‘a’is linearly decreased from 2 to 0 over the course of iterations,‘r’is a random number in the range[0,1].

The position (X,Y) of a search agent can be updated according to the position of the current best history(X*,Y*).New solutions around the current best one can be generated with respect to the current position through changing the value of A and C vectors.

4.1.2Bubble-net attacking (exploitation phase)

Two approaches can be followed for modeling the bubble-net behavior of humpback whales viz, shrinking encircling mechanism and spiral updating position. Shrinking encircling mechanism is used here.

This behaviour is satisfied by decreasing the value of ‘a’, it may be noted that the fluctuation range of A is also decreased by ‘a’ in other words A is a random value in the interval [−a , a] where a is decreased from 1 to 0over the course of iterations.

4.1.3 Search for Prey (exploration phase)

The same approach based on the variation of the A vector can be utilized to search for prey (exploration).Infact, humpback whales search randomly according to the position of each other. Therefore, we use A with the random values greater than1or less than −1 to force search agent to move far away from a reference whale.

This mechanism and |A|>1emphasize exploration and allow the WOA algorithm to perform a global search. The mathematical model is as follows:

$$\vec{D} = \left|\vec{C}.\overrightarrow{X_{rand}} - \vec{X}\right| \qquad (26)$$

$$\vec{X}(t+1) = \overrightarrow{X_{rand}} - \vec{A} \cdot \vec{D} \qquad (27)$$

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

The WOA algorithm begins with a set of random initial solutions. At each iteration, search agents update their positions with a randomly generated search agent or search agent generated around the best solution. Random search process is chosen when |A|>1, while the current best solution is selected for updating the agent when |A|<1.

Implementation of WOA for congestion management

The steps followed in the implementation of the algorithm are as given below:

Step 1: Read line data and bus data of the test system and solve for line flow problem of the

system using NR load flow method for the present system state.

Step 2: Initialize the whales, population size NP as 30 and iteration counter as 300. Each whale is a set of control variable values taken within their limits.

Step3: Set the control variables with randomly selected values.

Step4: Randomly generate whale population and initialize the iteration counter.

Step5: Run the load flow and for each whale (different value for control variables) calculate the objective function value. Repeat this procedure for all the 30 whales and this completes one iteration.

Step 6: Once the objective function value of all the search agent are found, sort the whales in the ascending or their objective function. The current best solution is the whale with minimum objective value (first whale).

Step 7: Based on Eqns. (23) – (28) update the position of search agents.

Step 8: For the new updated population of whales, determine objective function values by performing Newton-Rapson load flow.

Step 9: Identify the best whale in this iteration. Compare this best whale with the best whale obtained so far. If this current best is better than the best so far replaces the best solution with current best or else go back to step 7.

Step 10: If the stopping is met, then print the results.

5. Simulation Resuls And Analysis

The proposed WOA based method for congestion management approach by placing suitable sized TCSC devices is tested on IEEE 30 bus test system. This system is with 6 generator nodes24 load nodes and 41 lines[23].Three different reasons of transmission congestion are taken for this study viz, Increased load, bilateral transactions and multilateral transactions. The three cases of congestion are given along with amount of transactions in table 1. The decision variables of this optimization work are generator node voltages, transformer tap changer settings and reactance of TCSC devices. The lower and upper bounds for generator node voltages and transformers tap setter positions are within 0.9 p.u. and 1.1 p.u. TCSC reactance is allowed between 20 % inductance to 70 % capacitance.

Table 1. Different operating conditions

Case	Operating condition
Case 1	35 % overload at all the load buses.

Case 2	11.5 MW of bilateral power transaction between GENCO 13 and DISCO 26	
Case 3	GENCOS Generator 8-11MW Generator 11-10 MW Total 21 MW	DISCOS Load bus 21-8 MW Load bus 29-13 MW Total 21 MW

Case 1- 1.35p.u.load

System load is increased by 35 percent causing overload in line 1 which is carrying a load of131.267 MW. The capacity of this line is 130 MW only while it carries an excess power of 1.267 MW. This line connects the reference bus to the rest of the network and crucial for security of the system. Congestion is to be relieved otherwise severe security problems will takes place in the system.

To remove the line flow violation, line flow patterns of the other lines are adjusted by inserting TCSC devices at suitable lines connecting load buses. The TCSC devices change the reactance of the line in which they are located and thereby the line flows are changed. Power flow through all the lines of the system during and after congestion management are presented in table 2 for comparison. It is clear from the power flows that the congested line is relieved and the flows of all the lines are so adjusted that they carrying power below their capacity.

Table 2. Power flow comparison in case 1

Line number	**MW flow before CM**	**MW flow after CM**		
		PSO	**FFA**	**WOA**
1	**131.267**	**128.839**	**128.725**	**128.670**
2	77.7204	78.3058	77.2428	77.1170
3	45.1248	46.2526	44.4892	44.8157
4	72.8314	72.3697	71.4094	70.9269
5	74.1643	77.4879	74.4018	74.8208
6	59.3274	54.5948	58.6516	59.1426
7	63.3811	67.5346	62.9974	64.6010
8	7.93120	4.36360	11.3948	13.3623
9	37.5064	36.5524	36.4299	35.9749
10	22.1891	31.1238	22.7541	22.8529
11	25.4170	22.8614	25.4740	22.9542
12	18.3791	16.9454	13.4256	18.2134
13	47.4478	22.2079	37.3714	38.6959
14	46.4785	44.2980	53.4742	43.6413
15	42.8541	40.0214	42.4660	40.2370
16	53.8331	46.5975	28.5627	22.0865
17	12.0257	11.0097	11.0211	10.7795
18	29.0165	25.4560	25.8492	24.8155
19	13.6922	11.1082	11.3856	10.5187
20	3.2679	2.1607	2.2005	1.9462
21	8.1316	5.6265	6.1768	5.2901
22	9.8363	8.8524	8.9907	8.5715
23	5.2405	4.2391	4.4335	4.0150
24	8.5512	9.4177	9.4490	9.8111
25	11.9157	12.8395	12.8647	13.2507
26	6.6694	9.1849	9.8320	10.3443
27	28.9593	28.9398	29.3731	30.3810
28	10.8002	8.1141	8.4442	8.3159
29	1.7056	1.2725	0.7449	1.7154
30	10.5278	6.6038	6.9033	6.0511
31	10.6332	8.0416	8.3692	8.2246
32	5.6166	2.5022	3.2057	2.9218
33	4.2880	3.1879	3.6502	2.0369
34	5.8192	5.7934	5.7922	5.7441
35	3.5019	8.8219	8.7931	7.7395

36	30.9965	24.6938	23.7233	25.0278
37	8.8276	8.7463	8.7427	8.7514
38	10.0438	9.9450	9.9406	9.9512
39	5.1140	5.0916	5.0906	5.0930
40	1.7674	4.9394	2.5793	1.9606
41	20.3357	22.5722	22.1440	22.6412

Optimization of power flow pattern by locating TCSC devices relieved the congestion and also achieves minimization of line loss and total voltage deviation of load nodes. These benefits are given in table 3. During congestion, line loss was 15.2375 MW, in post congestion management loss is reduced to 13.3062 MW. There is a reduction of 1.9313 MW of loss reduction is achieved. For proving the strength of the proposed WOA based method, the loss and voltage deviation reported by FFA and PSO are also given in table 3.

Table 3. Power loss and voltage deviation with TCSC in case 1

Parameter	During congestion	After congestion is relieved		
		PSO	FFA	WOA
Total power loss (MW)	15.2375	13.5592	13.4278	13.3062
Voltage deviation (p.u.)	0.9000	0.4526	0.4456	0.4150

The design variables are adjusted during the optimization process for reaching the best results. The best set of control variables corresponding to global best results are shown in table 4. These values are ensured to be lying within their maximum and minimum limits.

Table 4. Optimal control variables in case 1

Parameter	Best value PSO	Best value FFA	Best value WOA
V1 (p.u.)	1.0913	1.0890	1.1000
V2(p.u.)	1.0694	1.0642	1.0785
V5(p.u.)	1.0172	1.0384	1.0456
V8(p.u.)	1.0398	1.0401	1.0397
V11(p.u.)	1.0105	1.1000	1.1000
V13(p.u.)	1.0932	1.0615	1.0456
T11(p.u.)	0.9629	1.0099	1.0551
T12(p.u.)	1.0010	1.0834	0.9765
T15(p.u.)	1.0419	1.0043	0.9782
T36(p.u.)	0.9594	0.9578	0.9782
TCSC1(p.u.)	0.2000	-0.2924	0.2000
TCSC2 (p.u.)	0.2000	-0.4998	-0.7000

Two TCSCs are suggested at different line locations by the three algorithms as shown in the table5.The locations are the most suitable ones for congestion management in case 1.

Table.5 Optimal locations ofTCSCs in case 1

Label of TCSC	Location of TCSC		
	PSO	FFA	WOA
TCSC1	6	15	28
TCSC2	7	14	34

The convergence speed of the proposed WOA algorithm is depicted in figure4.It is clear from the figure4that the algorithm is quick in convergence and it is reliable.

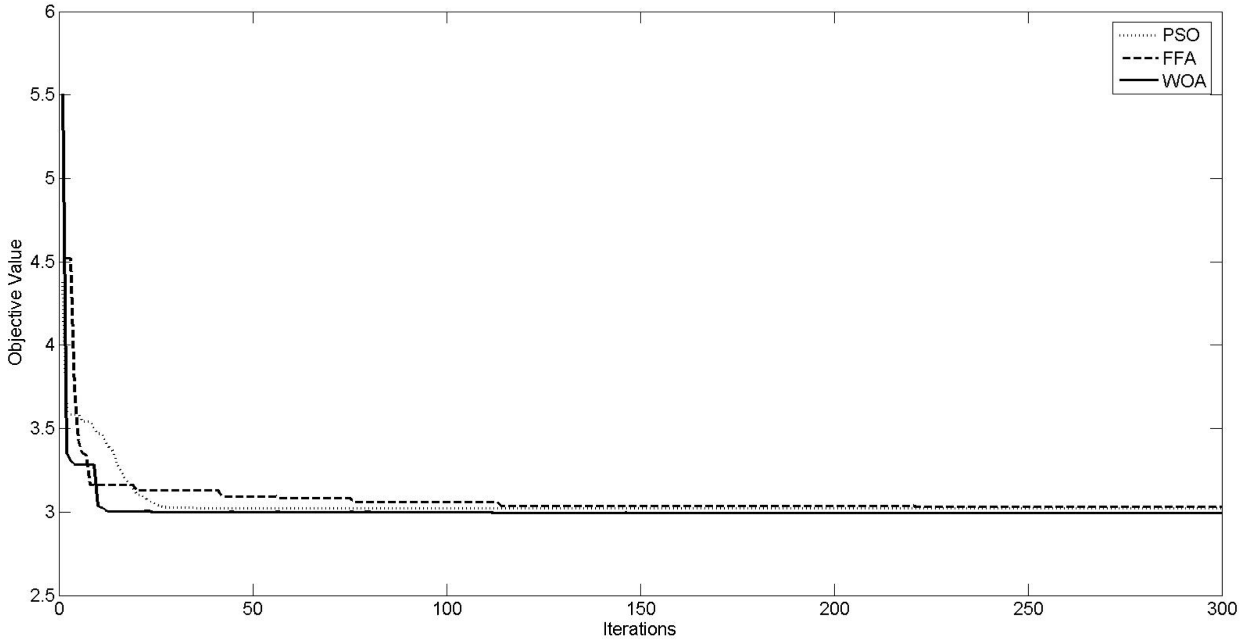

Figure 4. Convergence of PSO, FFA and WOA in case 1

Case2- Bilateral transaction

In this case, a bilateral transaction between buses 13 and 26 is taken. This transaction is with bus 13 as the Genco and bus 26 as the Disco bus for power transaction. The agreement is for a power transaction of 11.5 MW and this result in congestion in line number 34 whose capacity is 16 MW. Power flow during this transaction period is 16.1233 MW. The proposed WOA based method is exploited for removing congestion caused in line 34. Overload of the line is relieved and the post line flows obtained by the PSO, FFA and WOA algorithms are shown in table 6.

Table 6. Power flow comparison in case 2

Line number	**MW flow before CM**	**MW flow after CM**		
		PSO	**FFA**	**WOA**
1	57.0233	58.4314	57.3960	52.6136
2	43.6815	43.4656	42.7549	48.5362
3	31.0181	29.9513	29.6274	27.3848
4	40.6146	39.9488	39.5946	45.0083
5	45.4808	46.9800	46.1995	45.3741
6	39.6320	39.4394	39.1706	37.5486
7	39.8581	47.4073	42.5602	46.1712
8	2.3672	4.3525	8.9289	9.7721
9	25.7829	22.1727	21.9447	22.7289
10	24.7471	15.6223	14.3421	15.7805
11	15.7261	25.2807	17.2836	16.5637
12	12.4440	13.8421	11.4780	10.4672
13	43.3236	40.5165	26.4023	20.8236
14	34.9827	34.9306	36.2057	35.1271
15	22.6015	18.9676	18.3901	17.7028
16	51.3706	39.9473	34.2877	32.0608
17	9.7744	7.9772	8.2759	8.2357
18	25.0675	20.0735	20.4327	20.2776
19	12.4633	9.7548	10.1261	9.5679
20	3.2225	2.3522	2.1288	2.0930

21	8.2686	7.6230	7.1481	6.5617
22	8.3147	6.8927	6.9395	7.0524
23	4.8852	4.2027	3.8600	3.9848
24	5.2431	8.2852	7.3984	7.3568
25	7.6561	10.6815	9.8130	9.7613
26	2.6326	11.6590	9.3616	9.2550
27	21.9695	25.1072	23.9413	23.1646
28	11.3091	8.6022	8.9394	7.4266
29	1.5164	4.5179	2.9527	2.9400
30	10.8513	8.2901	7.3584	7.0640
31	11.1538	8.5404	8.8692	7.3691
32	8.0211	5.7142	5.6746	3.9511
33	9.8490	6.6007	6.3325	2.9282
34	**16.1233**	**15.2770**	**15.1496**	**15.0929**
35	7.0327	13.7128	12.2870	14.5605
36	29.2238	28.8556	24.2614	29.0848
37	6.4457	6.4066	6.4111	6.4108
38	7.3265	7.2791	7.2845	7.2841
39	3.7625	3.7518	3.7530	3.7529
40	5.0213	4.4228	3.3212	4.3069
41	17.9584	21.4768	21.0286	23.1701

In table7 the additional benefits of loss level and voltage deviation minimization reported by the algorithms are given. The real power loss achieved by WOA algorithm in this bilateral transaction period is 6.5223MW which is less than the loss levels shown by the other two algorithms. It is clear that the proposed algorithm relieves the congestion and also minimizes the line loss is considerable. Total voltage deviation during congestion was 0.7370 that is reduced to 0.2154 by WOA algorithm. 0.2392 and 0.2227 are the voltage deviation achieved by PSO and FFA algorithms.

Table 7. Power loss and voltage deviation with TCSC in case 2

Parameter	**During congestion**	**After congestion is relieved**		
		PSO	**FFA**	**WOA**
Total power loss (MW)	7.1254	6.8444	6.5810	6.5223
Voltage deviation (p.u.)	0.7370	0.2392	0.2227	0.2154

Magnitudes of generator bus voltages, transformer tap changer positions and TCSC parameters are all optimized by PSO, FFA and WOA algorithms. The control variables are adjusted respecting the upper and lower limits during optimization process. The well tunes control variables corresponding to best results are presented in table 8.

Table 8. Optimal control variables in case 2

Parameter	**Best value PSO**	**Best value FFA**	**Best value WOA**
V_1(p.u.)	1.0185	1.0354	1.0442
V_2(p.u.)	1.0039	1.0275	1.0305
V_5(p.u.)	0.9763	1.0126	1.0117
V_8(p.u.)	0.9836	1.0044	1.0075
V_{11}(p.u.)	1.1000	1.0663	1.0420
V_{13}(p.u.)	0.9710	1.0346	1.0052

T_{11}(p.u.)	1.0042	0.9839	0.9598
T_7(p.u.)	0.9211	0.9901	0.9908
T_{21}(p.u.)	0.9000	1.0099	0.9598
T_{36}(p.u.)	0.9000	0.9395	0.9602
TCSC1(p.u.)	0.1878	-0.1916	-0.4873
TCSC2(p.u.)	0.2000	-0.1991	-0.2494

Table 9 shows the best locations(lines) identified for TCSCs in relieving congestion in this case that are different for different algorithms.

Table. 9 Optimal locations of TCSCs in case 2

Label of TCSC	**Location of TCSC**		
	PSO	**FFA**	**WOA**
TCSC1	15	19	36
TCSC2	9	34	2

The behaviour of the algorithm in converging to the global best objective value of the problem is shown in figure 5. The proposed method achieves the minimumvalue of the objective function less number of iterations.

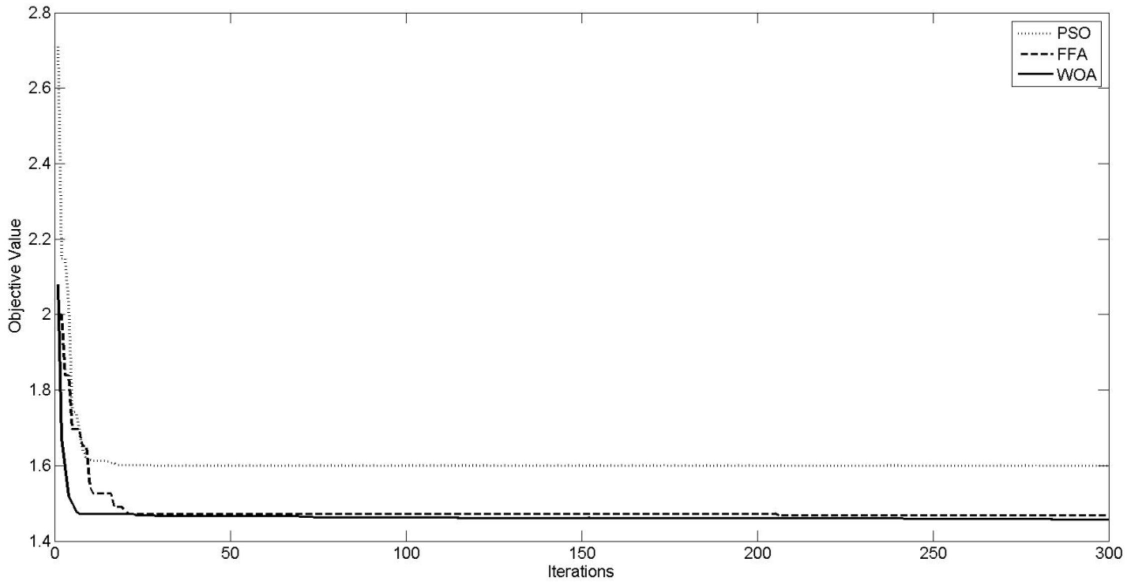

Figure 5. Convergence of PSO, FFA and WOA in case 2

Case 3- Multilateral transactions

The multilateral transaction considered in this case uses GENCOs at buses 8 and 11 to sell a power of 11MW and 10 MW respectively. DISCOs are located at buses 21 and 29 and the power distributed are of 8MW and 13MW respectively. This multilateral transaction creates congestion in line37 which is with a capacity of 16 MW but overloaded due to the power flow of 16.2977 MW. The line flows under and after congestion management are compared in table 10.

Table 10. Power flow comparison in case 3

Line number	**10MW flow before CM**	**MW flow after CM**		
		PSO	**FFA**	**WOA**
1	56.5202	56.4743	56.7669	56.6482
2	43.9787	43.3788	43.0665	43.1822
3	31.4777	30.6121	30.1077	30.2788
4	40.8836	40.2752	39.8549	39.9667

5	45.1716	45.7809	46.0863	45.5694
6	38.7853	38.6383	38.3788	38.6127
7	34.0998	44.8264	37.3898	37.6653
8	1.9086	3.0802	5.2124	5.1066
9	25.8442	23.7029	22.4531	22.9466
10	22.4069	5.1680	8.5747	8.5181
11	14.6906	11.9075	13.0179	12.9590
12	13.5454	12.7228	12.1663	12.1279
13	48.4644	35.3254	44.5386	44.5492
14	43.4359	41.5148	43.4333	43.3733
15	29.2591	24.6584	24.9520	24.9595
16	46.5368	59.9930	21.2579	21.2617
17	9.3830	8.1738	7.8773	7.8817
18	23.4450	19.4377	18.6234	18.6432
19	10.7910	7.9691	7.3910	7.3736
20	2.9020	1.6528	1.6218	1.6273
21	6.7331	3.9317	4.2374	4.2150
22	7.2961	6.2035	5.8816	5.8658
23	3.9619	2.8221	2.7007	2.6816
24	6.3395	7.2789	7.9589	7.9663
25	8.7636	9.7640	10.4583	10.4667
26	4.3122	6.9103	9.2921	9.2887
27	28.1567	27.1291	28.3994	28.5217
28	10.8685	7.6385	7.6684	7.3192
29	1.4134	2.9810	0.2454	0.1759
30	10.1178	5.9379	6.0292	6.0763
31	10.7265	7.6123	7.6340	7.2860
32	5.9264	3.8309	4.1200	4.3916
33	7.4464	6.9832	6.6871	6.6513
34	4.2746	4.2618	4.2621	4.2621
35	2.9917	9.7618	9.3894	9.3940
36	33.0062	31.1674	30.7529	30.8615
37	**16.2977**	**15.4582**	**15.3689**	**15.2735**
38	11.2768	11.8489	11.8450	11.6249
39	0.5275	1.0344	1.0279	0.8388
40	6.4117	6.4680	6.0354	6.0526
41	19.7638	24.8623	25.1007	25.1459

The other objectives of loss and voltage deviation minimization are given in table 11. Total loss of the system is minimized by WOA to 6.1261MW from 6.9355 MW. This loss reduction is an indication of the effective congestion management achieved by the proposed WOA approach. Deviation of load bus voltages from the nominal voltage are minimized as shown in the table11 validate the suitability the proposed approach for relieving congestion in transmission line.

Table 11. Power loss and voltage deviation with TCSC in case 3

Parameter	**During congestion**	**After congestion is relieved**		
		PSO	**FFA**	**WOA**
Total power loss (MW)	6.9355	6.1666	6.1343	6.1261

Voltage deviation (p.u.)	0.7313	0.2275	0.2138	0.2059

Best control variable values corresponding to congestion management in this case is shown in table 12. It is maintained that all the variables are taking values within the respective limits.

Table 12. Optimal control variables in case 3

Parameter	**Best value PSO**	**Best value FFA**	**Best value WOA**
V_1 (p.u.)	1.0412	1.0349	1.0349
V_2 (p.u.)	1.0316	1.0249	1.0249
V_5 (p.u.)	1.0013	1.0060	1.0060
V_8 (p.u.)	1.0087	1.0059	1.0059
V_{11} (p.u.)	0.9627	1.0916	1.0916
V_{13} (p.u.)	1.1000	1.0188	1.0188
T_{11}(p.u.)	0.9852	1.0269	1.0269
T_7(p.u.)	0.9621	1.0197	1.0197
T_{21}(p.u.)	1.0984	0.9914	0.9914
T_{36}(p.u.)	0.9081	0.9115	0.9115
TCSC1(p.u.)	0.2000	0.1342	0.1342
TCSC2(p.u.)	0.2000	0.1979	0.1979

From the locations identified by the three algorithms, it can be seen that line number 36 is found to be one of the best locations by two of the algorithms for this case as given table 13.

Table. 13 Optimal locations of TCSCs in case 3

Label of TCSC	**Location of TCSC**		
	PSO	**FFA**	**WOA**
TCSC1	20	9	37
TCSC2	37	37	31

Convergence characteristics of WOA is depicted in figure6. It is clear that in this multilateral transaction case, WOA outperformance the other two algorithms. The proposed algorithm keeps on optimizing the objective value beyond the 110thiteration. This ensures that the algorithm can not easily trapped in to local minimum.

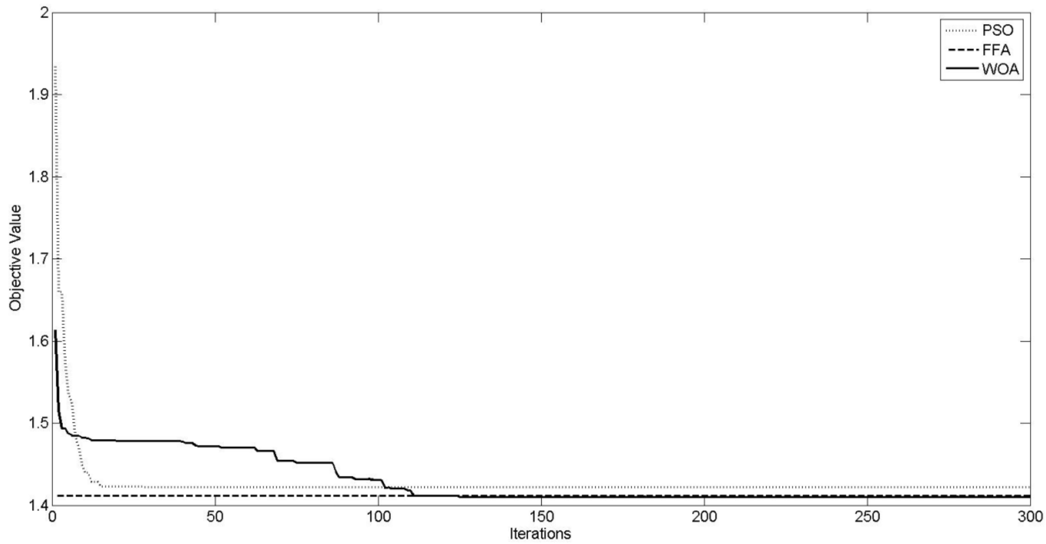

Figure 6. Convergence of PSO, FFA and WOA in case 3

6. Conclusions

A new bio inspired optimization algorithm, namely WOA, is employed to find the most suitable location and size of TCSC controllers in electric power system networks for congestion relief. Series connected TCSC compensator has been used for congestion management. In the case of TCSC allocation, optimal location and reactance of TCSC units are selected for relieving congestion with minimum line losses and voltage deviation at load buses. The results show that for TCSC position and sizing, WOA produces minimum values for the objectives. Therefore, WOA can be used as an efficient algorithm for solving optimal allocation of TCSC devices in congestion management problem. From the comparison of results obtained from the other algorithms, PSO and FFA algorithms, and their convergence characteristics it is clear that WOA performs better in relieving congestion...

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