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Optimization of location and rating of unified power flow controllers for congestion management

Vengadesan Alagapuri[1], Ashok Bakkiyaraj Radhakrishnan[1], Sakthivel Sithangkathan[2], Jayanthi Kalikrishnan[3]
[1]Department of Electrical Engineering, Annamalai University, Chidambaram, India
[2]Department of Electrical and Electronics Engineering, Nehru Institute of Engineering and Technology, Coimbatore, India
[3]Department of Computer Application, Government Arts and Science College, Chidambaram, India

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ABSTRACT

Large number of contracted power exchanges among sellers and purchasers, in a deregulated power market causes transmission line congestion. Congestion of lines undermines the security and economy of power networks. Flexible AC transmission system (FACTS) devices are introduced at appropriate spots to change the power flow in order to keep the flow of the lines within their capability. In this work, the most commonly used unified power flow controller (UPFC) is proposed for achievement of changing the line flow and for easing congestion from the over loaded lines. The size and site of UPFC controllers significantly impact their performance in congestion management task. The location and size of the UPFC devices are to be optimized by using an optimization algorithm. Whale optimization algorithm (WOA) is exploited in this effort for realizing the aim of determination of site and size of the FACTS converters. The present method has lesser quantity of variables which are tuned to get best outcomes. The suggested WOA based technique is executed on the IEEE 57 bus system. The outcomes comparison is made with particle swarm optimization algorithm (PSO) and firefly algorithm (FFA) and the better improved outcomes are found.

Corresponding Author:

Sakthivel Sithangkathan
Department of Electrical and Electronics Engineering, Nehru Institute of Engineering and Technology
Coimbatore, Tamil Nadu, India
Email: sithansakthi@gmail.com

1. INTRODUCTION

In a liberated power system, the role of generation, transmission and distribution are involved by three separate companies, generation by GENCOs, transmission by TRANSCOs and distribution by DISCOs [1]. Rivalry is created by having large number of GENCOs and DISCOs in power markets. Transmission framework is owned by an independent system operator (ISO) because of reasons of economy and precise control.

Load requirement is groining at a quicker amount in contrast to the extension in transmission structures. Huge amount of bilateral and multilateral agreements causes transmission line overloads [2]. In the event, if the agreed exchanges are not controlled, a few lines in specific regions might become over loaded, this is named as congestion [3]. The major challenge in expansion of new lines is acquiring of lands and requirement of large amount of investment [4].

Boosting the exploitation of offered transmission ability is easily accomplished by introducing flexible AC transmission system (FACTS) compensators [5]. The expanded utilization of these FACTS gadgets is as a result of two reasons. The advanced powers electronic technologies have made these gadgets are more efficient [6]. It is essential to distinguish the site and size of these gadgets for ideal execution and significant expenses. There is a little distinct technique accessible for deciding the best site and rating of FACTS gadgets in power networks [7], [8].

The unified power flow controller (UPFC) is added for voltage profile improvement and transmission congestion [9]. UPFC is utilized to lower the transmission line congestion by controlling the line flows by using it in suitable position [10]. The line voltage stability index is taken for the ideal location of UPFC for transmission network security extension [11]. To build the full utilization of UPFC and develop the monetary proficiency and fixed surveillance of a power framework, a prudent security-compelled power stream advancement strategy allowing for UPFC control modes is proposed [12].

Remarkable works where meta-heuristic techniques have been effectively applied for releasing the power flow overload by finest sitting of FACTS controllers. Genetic algorithm (GA) was the premier algorithm to be tried for the target of finest place of FACTS controllers to improve the exchange capacity of a line by Gerbex *et al.* [13]. UPFC has been utilized for the advancement in power surveillance of the transmission framework through appropriate position utilizing differential evolution (DE) [14]. The burden of a transmission framework has been enhanced with the base expense for the setting up of FACTS compensators through particle swarm optimization (PSO) strategy where a few kinds of gadgets like thyristor-controlled series capacitor (TCSC), static var compensator (SVC) and UPFC are picked [15]. The finest site and positioning for fitting place of FACTS gadgets has been looked for through different enhancement strategies like artificial bee colony (ABC) [16], bees' algorithm (BA) [17], cuckoo search (CS) [18] has additionally been tried for the finest place of FACTS. The current exchange capacity of a framework is further developed utilizing cat swarm optimization (CSO) [19].

Another strategy using whale optimization algorithm (WOA) algorithm is planned now to decide the finest site of UPFC gadgets. In part 2, static model of UPFC is given. In part 3 the aim capacity of limiting congestion, transmission loss and voltage difference is examined. In part 4, the WOA based procedure is demonstrated. In part 5, the result and thought are introduced lastly in part 6, the work is finished up. The arranged process has been shown on IEEE 57 bus system under three unique situations. The outcomes show that the new technique is proper for assuaging congestion.

2. MODELING OF UPFC DEVICE

2.1. Static model

The UPFC incorporates of two switching converters [20]. These series and shunt connected converters are sharing a common dc link provided by a capacitor as depicted in Figure 1. Converter 2 serves the major role of the UPFC by adding an ac voltage with convenient size and phase incline in sequence with the transmission line during the sequence transformer. The main purpose of converter 1 is to deliver or take up the actual power obligatory by the converter 2. Converter 1 can also produce or take up controllable reactive power and deliver autonomous shunt reactive reimbursement for the line. Converter 2 delivers or absorbs locally the necessary reactive power and exchange the active power as a effect of the sequence injection voltage.

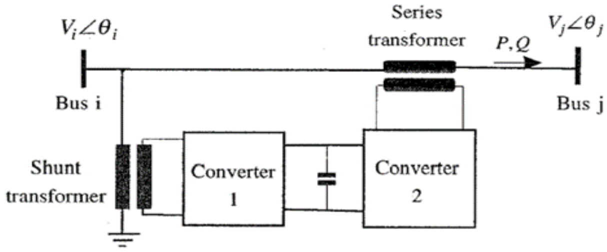

Figure 1. Circuit diagram of a UPFC

2.2. UPFC model

In UPFC, the shunt coupled voltage resource, the converter 1 is worn to supply the dynamic power demanded by converter 2 through injection. We have (1).

$$P_{CONV\,1} = P_{CONV\,2} \quad (1)$$

The above quality holds good for losses converters. The volt-ampere supplied by the sequence voltage source converter is written as (2).

$$S_{CONV\,2} = \overrightarrow{V_s}\overrightarrow{I_{ij}} = re^{j\gamma}V_i\left(\frac{\overrightarrow{V_i'}+\overrightarrow{V_j}}{jX_s}\right)^* \quad (2)$$

Actual and invented components of power supplied by converter 2 are illustrious as (3) and (4).

$$P_{CONV\,2} = rb_sV_iV_jsin(\theta_i - \theta_j + \gamma) - rb_sV_i^2 sin\gamma \quad (3)$$

$$Q_{CONV\,2} = -rb_sV_iV_jcos(\theta_i - \theta_j + \gamma) - rb_sV_i^2 cos\gamma + r^2b_sV_i^2 \quad (4)$$

The reactive power delivered or riveted by converter 1 is individually controllable by UPFC and can be modeled as a separate controllable shunt reactive source. The UPFC injection model is shown in Figure 2. The replica show that the net dynamic power exchange of UPFC with the power system is zero, as the UPFC is lossless.

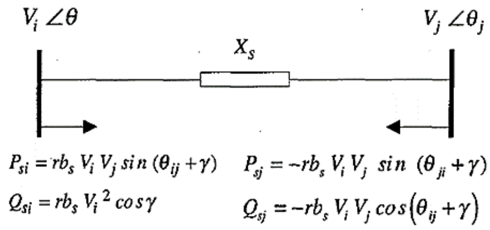

Figure 2. Power injection model of UPFC

3. MATHEMATICAL STATEMENT

3.1. Congestion management

In a liberated market, to maintain the synchronization between generation, transmission and distribution companies, there will be one frame administrator in a broad assortment of liberated power frame models, for the most part it is the ISO. In a restructured power market, enough instruction is given to the market members to cooperate among themselves. At this time, both the purchasers and dealers attempt to trade electric power in order to benefit as much as possible for their benefits. In liberated power markets, transmission congestion happens when there isn't sufficient bandwidth to simultaneously hold all contracts of the transmission line. Congestion must to be relieved as quick as possible since it may overload other lines of the system and lead to cascaded trappings.

3.2. Objectives

Three objectives considered are curtailing power flow violation, curtailing the power loss and suppress the voltage divergence. Congestion management (CM) alleviates the overload by curtailing the actual power destruction which is reserved as the primary objective [21].

$$f_1 = \sum_{k=1}^{N_l} |P_k - P_{k\,rat}| \quad (5)$$

Curtailing of transmission loss is the second objective [22].

$$f_2 = \sum_{k=1}^{N_l} G_k[V_i^2 + V_j^2 - 2|V_i||V_j|cos\delta_i - \delta_j] \quad (6)$$

Voltage variations at load buses harmfully affect the value of power. This can be eliminated by considering voltage divergence minimization as the third objective.

$$f_3 = \sum_{k=1}^{N_{pq}} |V_k - V_{k\,ref}| \quad (7)$$

The congestion removal problem is definite as an augmented multi-objective optimization problem of curtailing line power flow violations, transmission losses and voltage divergence.

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

Weighted sum approach is for converting the objective into a multi-objective model as [23].

$$F = w_1 f_1 + w_2 f_2 + w_3 f_3 \quad (8)$$

Determining the weightage factors of multi-objective optimization model, the weightage factor for the power flow violation and transmission loss is set as 0.2. The weightage factor for voltage divergence is set as 0.6. Hence, $w_1 = 0.2, w_2 = 0.2,$ and $w_3 = 0.6$.

3.3. Limitations

3.3.1. Equality limitations

The active and inactive power flow equilibrium limitations are specified by (9) and (10).

$$P_{Gi} - P_{Di} - \sum_{i=1}^{NB} V_i V_j Y_{ij} \cos(\delta_{ij} + \gamma_i - \gamma_j) = 0 \quad (9)$$

$$Q_{Gi} - Q_{Di} - \sum_{j=1}^{NB} V_i V_j Y_{ij} \sin(\delta_{ij} + \gamma_i - \gamma_j) = 0 \quad (10)$$

3.3.2. Inequality limitations

Generator limitations:

$$V_{Gi}^{min} \le V_{Gi} \le V_{Gi}^{max} i = 1,2, \ldots . N_G \quad (11)$$

$$Q_{Gi}^{min} \le Q_{Gi} \le Q_{Gi}^{max} i = 1,2, \ldots . N_G \quad (12)$$

Load bus voltage limitations:

$$V_i^{min} \le V_i \le V_i^{max} i = 1,2, \ldots . N_{PQ} \quad (13)$$

Transmission line limitations:

$$P_i \le P_i^{max} i = 1,2, \ldots, N_L \quad (14)$$

Transformer taps limitations:

$$T_i^{min} \le T_i \le T_i^{max} i = 1,2, \ldots, N_T \quad (15)$$

Shunt compensator limitations:

$$Q_{Ci}^{min} \le Q_{Ci} \le Q_{Ci}^{max}, \quad i = 1,2 \ldots, N_c \quad (16)$$

4. WHALE OPTIMIZATION ALGORITHM

4.1. General

Whales are attentive at every epoch to helps a whale that it can imagine, discover, critic, commune and turn into even exciting by its spindle cells [24]. Crooked back whales are one of the main creatures with exceptional hawking activities termed bubble lattice feeding. Bubble lattice feeding is an exclusive activities that can seen in crooked back scenery enthused theorems are mocked from the food incisive technique, and survival technique of the livelihood. WOA is refined situated on the survival technique of whale in deep oceanic.

4.1.1. Encompassing of the prey

WOA algorithm adopts the near finest contestant slam to the finest possible outcome. Formerly the finest outcome is recognized, the new contestant endeavor to fill in their point. This updating action is expressed by the following (17) and (18).

$$\vec{D} = \left| \vec{C} . \vec{X^*}(t) - \vec{X}(t) \right| \quad (17)$$

$$\vec{X}(t+1) = \vec{X^*}(t) - \vec{A} \cdot \vec{D} \quad (18)$$

Where t denotes the current iteration count, A and C are coefficients, X* is the position of the most excellent result obtained so far, X is the location vector, | | is the modulus value, and dot (·) is an element-by-element multiplication operator.

Vectors A and C are calculated using (19) and (20).

$$\vec{A} = 2\vec{a} \cdot \vec{r} - \vec{a} \tag{19}$$

$$\vec{C} = 2 \cdot \vec{r} \tag{20}$$

Where a is linearly decreased starting 2 to 0 more the iterations and r is a arbitrary vector in [0,1]. The point (X,Y) of a exploration mediator be able to restructured according to the place of the present finest account (X*,Y*). Dissimilar spaces about the finest mediator be able to be achieved through admiration to the present position by adjusting the rate of C and A vectors.

4.1.2. Bubble-net aggressive method

Two techniques can be succeeded for sketching the balloon-net manners of crooked back whales viz, declining bounding system and coiling amendment location. Declining bounding system is used here. This manner is fulfilled by decreasing the rate of a by changing the vacillation range of A. In further expressions, A is an arbitrary value in the period [−a, a] where a is decreased from 1 to 0 above the way of iterations. Setting random values for A as [1, 1], the new location of a search mediator can be defined anywhere in between the original place of the mediators and the place of the present finest mediator.

4.1.3. Exploration for prey

The similar technique situated on the discrepancy of the A track be able to be employed to discover for prey. In fact, crooked back whales explore arbitrarily according to the place of apiece other. Consequently, we utilize A among the arbitrary values larger than 1or fewer than −1 to strength exploration mediator to go extreme left from orientation whale. This system and |A|>1 accentuate investigation and permit the WOA algorithm to carry out a universal explore. The numerical replica is as pursues:

$$\vec{D} = \left|\vec{C}.\overrightarrow{X_{rand}} - \vec{X}\right| \tag{21}$$

$$\vec{X}(t+1) = \overrightarrow{X_{rand}} - \vec{A} \cdot \vec{D} \tag{22}$$

where $\overrightarrow{X_{rand}}$is a arbitrary location track (a arbitrary whale) preferred from the existing inhabitants.

The WOA method commence through a rest of arbitrary explications. At every iteration, exploration mediators fill in their location with respect to both a arbitrarily chosen search mediator or the finest answer obtained so far. The parameter is decreased from 2 to 0 in order to provide exploration and exploitation respectively. A random search mediator is chosen when |A|>1, while the finest solution is preferred when |A|<1 for updating the location of the search mediators.

4.1.4. WOA algorithm applied for congestion management problem

Stepwise procedure of WOA algorithm is explained:

Step 1: Interpret the network information referring to the trial arrangement and resolve for the line flow trouble from the arrangement by Newton Raphson load flow technique in the current arrangement conditions.

Step 2: Instantiate the whales, inhabitants dimension NP as 30 and iteration contradict as 300. Every whale is a deposit of control parameter values caught within the lesser and greater limits.

Step 3: Set as control variables such as generator bus voltage magnitude, transformer tap position, location and range of the UPFC gadgets.

Step 4: Erratically create whale inhabitants and instantiate the iteration counter.

Step 5: Scamper the NR power flow and determine the target value of every whale. Do this process for the entire the 30 whales to complete 1 iteration.

Step 6: Formerly the target rate based on the entire the whales are calculated, arrange the whales in the rising order of its target value. The first whale is the current finest that has the minimum target value.

Step 7: Updates the whales via the eqns. (17)–(22).

Step 8: Calculate the objective of the updated population of whales by running the NR load flow analysis.

Step 9: Discover the current most excellent whale. Contrast this finest whale by the finest whale so far. If this whale is improved, then replace the current most excellent solution with it or else go back to step 7

Step 10: If the stopping is met, end the program and return the outcomes.

5. COMPUTATIONAL RESULTS AND ANALYSIS

Redesigned IEEE 57-bus test structure incorporated of 7 generator buses, 50 load buses and 80 transmission lines and is taken for simulation [25]. The entire dynamic and reactive power loads are 1250.8 MW and 336 MVAR, discretely. The three distinct simulation illustration examined for this case are state1, state2 and 3, are displayed in Table 1.

Table 1. Different states of congestion in IEEE-57 bus system

State	Cause of congestion	
State 1	14.2% overload at all the load buses.	
State 2	5 MW of bilateral power transaction between GENCO 6 and DISCO 13.	
State 3	GENCOS	DISCOS
	Generator 2-5MW	Load bus 11-4 MW
	Generator 4-5 MW	Load bus 13-4 MW
		Load bus 15-2 MW
	Total 10 MW	Total 10 MW

State 1-114.2% load at all load buses

In this state, the total load of the system is increased to 114.2% to create overload in line 2 connected between buses 2 and 3. Competence of this line is 85 MW but it conveys 85.2506 MW of power causing transmission congestion. To relieve this congestion, the WOA based method is implemented and its performance is compared against PSO and firefly algorithm (FFA) algorithms in Table 2. It is clear that the flow through line 2 is reduced to below its capacity indicating congestion relief.

Table 2. Power flows in state1

Line no.	Power flow prior to CM	Power flow behind CM		
		PSO	FFA	WOA
2	85.2506	84.6766	84.8921	84.2068

Objectives of loss and voltage divergence curtailment are compared in Table 3. WOA curtail the loss to 35.2872 MW from 42.3775 MW while PSO and FFA algorithms have curtailed the loss level to 35.6321 MW and 35.4706 MW respectively. Voltage divergence at load buses from the reference voltage is curtailed as shown in the Table 3. From Table 3, it is obvious that the voltage profile achieved by WOA based method is really encouraging. 4.5555p.u. 3.739 p.u. and 2.8034 p.u. are the sum of voltage divergence from PSO, FFA and WOA algorithms. There is considerable reduction from 6.0185 p.u. to 2.8034 p.u. by WOA algorithm. The locations identified by the three algorithms for the FACTS gadgets for this state is as given in Table 4. It can be seen that locations for the three UPFCs are different by different algorithms.

Table 3. Objective values with UPFCs in state1

Parameter	In Congestion	Congestion is Alleviated		
		PSO	FFA	WOA
Total power loss (MW)	42.3775	35.6321	35.4706	35.2872
Voltage deviation (p.u.)	6.0185	4.5555	3.739	2.8034

Table. 4 Optimal site and dimension of UPFCs in state 1

Label of UPFC	Location of UPFC			Size of UPFC		
	PSO	FFA	WOA	PSO	FFA	WOA
UPFC1	78 (39,49)	65 (11,51)	51 (37,39)	0.0607, -0.0588	0.0540, 0.0034	0.0644, 0.0370
UPFC2	14 (13,15)	35 (24,25)	24 (12,13)	0.0608, -0.0558	0.0325,0.1000	0.0248, -0.0424
UPFC3	20 (8,18)	30 (19,20)	38 (26,27)	0.0249, -0.0226	0.0200, 0.0447	0.0350, -0.0342

Concurrence of WOA in this large scale power system is decorated in Figure 3. It is evident that in this state, WOA convene to the universal finest outcomes in a better way as compared to the other two algorithms. Outperformance the other two algorithms.

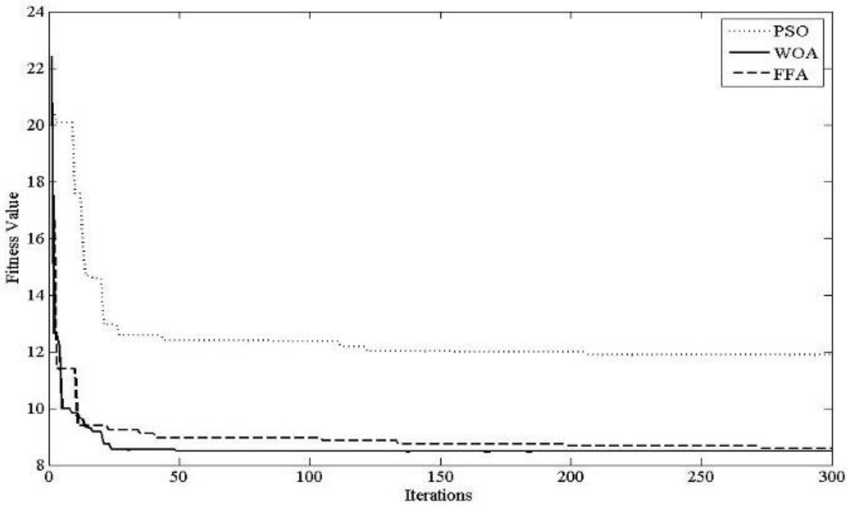

Figure 3. Quality of concurrence of the algorithms in state 1

State 2 - Bilateral transaction

The attainment of the suggested method is tested in a bilateral transaction under deregulated environment. The 5 MW of bilateral power agreement among GENCO 6 and DISCO 13, causes line 10 that links buses 6 and 12 gets overloaded. Capacity of the line is only 50 MW were as the power flow is 50.8971 MW forcing the line to be in congested condition. WOA based approach is utilized to place three UPFCs at suitable locations and tune the system control variables for removing the overload from the line. Table 5 compares the power flow yield by the three algorithms.

Table 5. Power flows in state2

Line no.	Power flow prior to CM	Power flow behind CM		
		PSO	FFA	WOA
10	50.8971	49.4003	49.4051	48.0355

Loss and voltage divergence curtailment by the WOA algorithm are afford in Table 6 for comparison. All the algorithms are succeeded in reducing loss from the loss level in congested condition. Again, WOA reports the lesser value for loss and voltage divergence among the algorithms. WOA reduces the loss from 30.5584 MW to 25.5578 MW leading to reduced operating cost of the power system. The line number and its starting bus and ending bus in which UPFCs are located are given in Table 7. Three UPFCs are used and the end buses of the line are given within the bracket. Concurrence characteristics of WOA show that it could produce lower value than the value reported by PSO and FFA algorithms. It is depicted in Figure 4.

Table 6. Objective values with UPFCs in state 2

Parameter	In congestion	Congestion is alleviated		
		PSO	FFA	WOA
Total power loss (MW)	30.5584	26.0843	25.9471	25.5578
Voltage deviation (p.u.)	4.9477	3.6141	3.524	3.4054

Table 7. Optimal site and dimension of UPFCs in state 2

Label of UPFC	Location of UPFC			Size of UPFC		
	PSO	FFA	WOA	PSO	FFA	WOA
UPFC1	4 (8,9)	36 (24,25)	36 (24,25)	0.0338, -0.0642	0.0449, -0.0099	0.0946, 0.0150
UPFC2	37 (24,26)	47 (34,35)	69 (53,54)	0.1000, -0.0765	0.0200, -0.0331	0.0539, 0.0011
UPFC3	55 (41,42)	54 (12,41)	64 (50,51)	0.0413. -0.0172	0.0311, 0.0356	0.0636, 0.1000

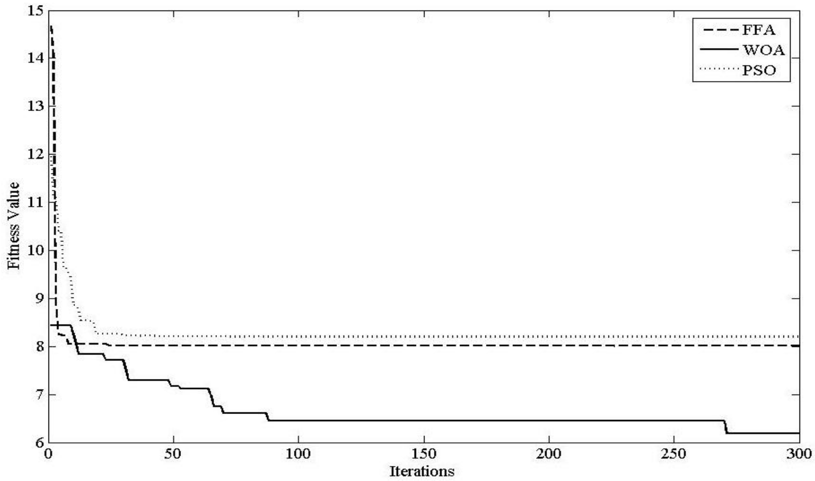

Figure 4. Quality of concurrence of the algorithms in state 2

State 3 - Multilateral transactions

10 MW of power is transacted with two GENCOs and three DISCOs as afford in Table 8. Line 8 that connects bus 5 and bus 6 is overloaded due to this transaction. After optimization, the line flow patterns are changed as shown in Table 8. This line carries 200.3235 MW of power which is above its capacity of 200 MW. It is ensured that entire the lines are conveying power under their limits.

Table 8. Power flows in state 3

Line no.	Power flow prior to CM	Power flow behind CM		
		PSO	FFA	WOA
8	200.3235	193.3848	198.9523	196.7710

Outcomes of the equally important loss and voltage divergence curtailment objectives are afford in Table 9. Total loss of the system is curtailed by WOA to 23.8681 MW from 30.8946 MW. This loss deduction is better than the loss reported by the other two algorithms. Voltage divergence reached by WOA is 2.4443 p.u. In Table 9, loss and voltage divergence curtailment values are compared to prove the attainment of the new optimization method. Three UPFCs are located at three different lines as given in Table 10. The UPFCs are located only at lines that do not have tap changer transformers.

Table 9. Objective values with UPFCs in state 3

Parameter	In congestion	Congestion is alleviated		
		PSO	FFA	WOA
Total power loss (MW)	30.8946	27.4263	24.6765	23.8681
Voltage deviation (p.u.)	4.9563	3.3235	2.679	2.4443

Table10. Optimal site and dimension of UPFCs in state 3

Label of UPFC	Location of UPFC			Size of UPFC		
	PSO	FFA	WOA	PSO	FFA	WOA
UPFC1	34 (23,24)	56 (41,43)	41 (10,29)	0.0338, -0.0642	0.0392, 0.0058	0.0257, 0.0075
UPFC2	37 (24,26)	19 (8,18)	67 (29,52)	0.1000, -0.0765	0.0200, -0.0207	0.0918, 0.0268
UPFC3	55 (41,42)	40 (28,29)	75 (56,42)	0.0413, -0.0172	0.0227, 0.0825	0.0673, 0.0112

Figure 5 expose the concurrence behaviour of WOA is a multilateral case in a large scale power system. It is clear that in this state, WOA takes considerable number of iterations but converges to global finest results. It is also found that the WOA gives better outcomes in IEEE 30 bus system.

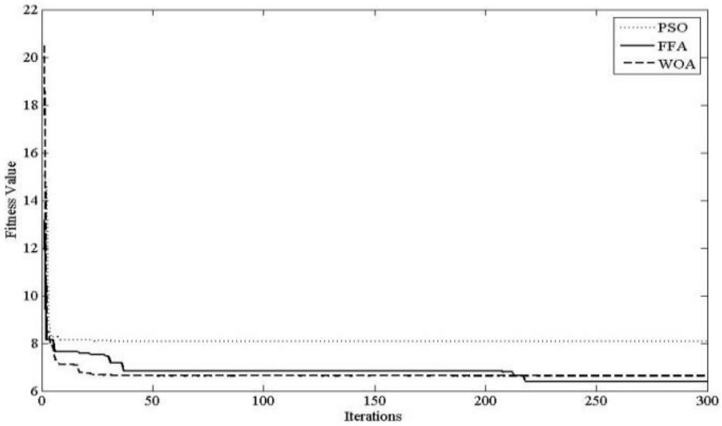

Figure 5. Quality of concurrence of the algorithms in state 3

6. CONCLUSIONS

A new bio motivated algorithm, specifically WOA, is engaged to observe the utmost reasonable site and ranking of UPFC regulators in power grids for congestion alleviation. The shunt-series UPFC regulators have been hired for congestion removal. Ideal place and intensity of FACTS regulators are chosen for reducing congestion, line losses and voltage divergence of load buses. The outcomes exhibit that for UPFC, WOA yield least values in the objectives. Consequently, WOA might be employed as a proficient calculation method for optimizing of FACTS regulators in congestion alleviation. From the correlation of outcomes gathered from dissimilar methods, WOA, PSO, and FFA calculations the suggested method outperforms in congestion removal.

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BIOGRAPHIES OF AUTHORS

Mr. Vengadesan Alagapuri he is as Research Scholar, Department of Electrical Engineering, FEAT, Annamalai University, Chidambaram, Tamilnadu, India. He has received his B.E Degree in Electrical and Electronics Engineering in 2003, Madras University, Chennai, India. M.E power systems in 2005, Annamalai University, Chidambaram, Tamil Nadu, India. His area of interest includes power system reliability, power systems operation & control, power system deregulation, FACTS devices and optimization techniques. He can be contacted at email: avmithrankavin@gmail.com.

Dr. Ashok Bakkiyaraj Radhakrishnan received his Bachelor, Master and Doctoral degrees in Electrical Engineering from Annamalai University. He is presently working as Associate Professor in the Department of Electrical Engineering, Annamalai University. He has published 15 papers in International Journal and presented papers in 10 international/national conferences. His research areas are power system reliability, power systems operation & control, high voltage engineering, nature inspired computing and image processing. He can be contacted at email: auashok@gmail.com.

Dr. Sakthivel Sithangkathan received the Degree in Electrical and Electronics Engineering and Master Degree in Power Systems Engineering in 1999 and 2002 respectively. He obtained the Ph.D. Degree in Electrical Engineering faculty from Anna University, Chennai, Tamil Nadu, India in 2014. Currently, He is a Professor of Electrical and Electronics Engineering at Nehru Institute of Engineering and Technology, Coimbatore, Tamil Nadu, India. His research areas of interest are power system control, optimization techniques, power system deregulation, facts and voltage stability improvement. He has published 48 papers in various internationally reputed journals. He can be contacted at email: sithansakthi@gmail.com.

Dr. Jayanthi Kalikrishnan working as Assistant Professor in the Department of Computer Application, Government Arts College, Chidambaram, India. She completed M.C.A from Bharathidhasan University and M.Phil [Computer science] in Annamalai University. She received Ph.D in Computer Science from Annamalai University. Her research of interest includes applications of soft computing algorithms for engineering problems, image processing applications and data processing. She has published 6 research articles in international journals and presented research papers in 8 international/national conferences. She can be contacted at email: jayanthirab@gmail.com.