Optimal Utilization of IPFC for Congestion Management Using Disparity Line Utilization Factor and Cuckoo Search Algorithm

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Abstract: Recently, due to adoption of power reforms there is a marked increase of contracted power that flows in the transmission line and the spontaneous power exchanges leading to complex power transmission congestion problems. Appearance of FACTS devices specifically IPFC has opened up new opportunities to overcome the congestion problem by increasing the system loadability. Proper placement and tuning of IPFC in this respect is very important for maximum utilization of its benefits. This paper proposes a Disparity Line Utilization Factor (DLUF) for the optimal placement of IPFC to control the congestion in transmission lines. DLUF determines the difference between the percentage MVA utilization of each line connected to the same bus. The IPFC is placed in the lines with maximum DLUF. The multi objective function consisting of the reduction of active power loss, minimization of total voltage deviations, and minimization of security margin with the usage of minimum value of installed IPFC is considered for the optimal tuning of IPFC using Cuckoo Search. The proposed method is implemented for IEEE-30 bus test system under different loading conditions and the results are presented and analyzed to ascertain the effectiveness for the reduction of congestion.

Key words: Congestion, cuckoo search algorithm, interline power flow controller, line utilization factor, optimal placement, optimal tuning.

1. Introduction

Lately, deregulated electric power industries have changed the way of operation, structure, ownership and management of the utilities. The issue of transmission congestion is more prominent in deregulated and competitive markets, and it needs an appropriate management strategy [1]. In the new competitive electric market, it is now mandatory for the electric utilities to operate such that it makes better utilization of the existing transmission facilities in conjunction with maintaining the security, stability and reliability of the supplied power [2]. Therefore the use of FACTS devices has become inevitable. Economic constraints put a limitation on the number of FACTS devices that can be used. Hence, optimal placement and tuning of FACTS devices in power system is mandatory.

Several authors [1]-[3] have suggested different methods for congestion management. Minguez *et al.* [4] have propose a method of optimal placement of IPFC such that the load margin is maximized. Mandala *et al.* [5], proposed a method to determine the optimal location of thyristor controlled series compensators (TCSCs) for Congestion management. The optimal location is determined based on the real power

performance index and based on the reduction in total system active power and reactive power losses. Reddy *et al.* [6] has presented the optimal location of FACTS controllers considering branch loading (BL), voltage stability (VS) and loss minimization (LM) as objectives at once using Genetic Algorithm for management of congestion. Acharya *et al.* [7] propose two new methodologies for the placement of series FACTS devices for congestion management. The overall objective of FACTS device placement can be either to minimize the total congestion rent or to maximize social welfare. Zhang *et al.* [8] presented an optimal power flow (OPF) control in electric power systems incorporating IPFC with the minimum total capacity of converters of IPFC and minimizing the total active power loss of the system for reducing congestion in the lines. Mohamed *et al.* [9] has compared three variants of PSO namely basic PSO, Inertia weight approach PSO and constriction factor approach PSO considering a single objective i.e. to minimize the transmission line loss.

FACTS devices are preferred in modern power systems based on the requirement and are found to deliver good solution [10]. Out of all FACTS devices IPFC is considered to be most flexible, powerful and versatile as it employs at least two VSC's with a common DC link. Hence IPFC has the capability of compensating multi transmission line [11]. FACTS devices like TCSC and SSSC are also placed on the most congested line. However, IPFC is a device connected to multiple transmission lines. In its simplest form it has at least two converters placed on two transmission lines connected to a common bus. Proper placement of IPFC is therefore a subject to be analyzed. Location and tuning of FACTS devices in the power system is one of the important issues and hence optimal placement and tuning of IPFC has been proposed based on a previous study [12], [13]. Optimal tuning and placement of IPFC has been done to obtain various objectives [14], [15]. Nature inspired algorithms are among the most powerful algorithms for optimization [16]. Cuckoo Search is inspired from brooding parasitism of cuckoo species in nature. It has only two parameters p_a and population size. The convergence rate of the cuckoo search is considered to be insensitive to parameter p_a [17]. Thus it need not be fine-tuned for a specific problem Cuckoo Search Algorithm has been found to be superior to PSO and GA with almost exponential convergence rate [18], [19].

In this paper, a Line Utilization Factor (LUF) is used for the determination of congestion of a single transmission line. However, IPFC is the multiline FACTS device. Hence LUF is not a sufficient index for obtaining the location for placement of IPFC. The difference of Line Utilization Factors between two lines has been used for the determination of the optimal location of IPFC. It gives an estimate of the difference of the percentage of line being used for the power flow. Thus all the line pairs of a common bus are ranked in terms of line congestion. The IPFC is placed in the lines with maximum value of DLUF to reduce congestion and power loss in the system. A multi Objective optimization has been formulated for optimal tuning of IPFC using Cuckoo Search algorithm. The multi objective function comprises for the reduction of active power loss, minimization of total voltage deviations and minimization of security margin with the usage of minimum value of installed IPFC. Tuning of IPFC for the reduction of loss further reduces line congestion. The reduction of Voltage deviation and security margin ensure power quality and system security. The proposed method is implemented and tested on an IEEE 30 bus system with different loading conditions.

2. IPFC Modelling

IPFC consists of at least two back to back DC-AC converters connected by a common DC link [20]. V_i, V_j, V_k are complex voltages at bus i, j, k respectively. $V_l = V_l \angle \theta_l (l = i, j, k)$ and V_l, θ_l are the magnitude and angle of V_l . $V_{se_{in}}$ is the complex controllable, series injected voltage source. It shows the series compensation of the series converter. $V_{se_{in}}$ is given by $V_{se_{in}} = V_{se_{in}} \angle \theta_{se_{in}} (n = j, k)$. $V_{se_{in}}$ and $\theta_{se_{in}}$ are the magnitude and angle of $V_{se_{in}}$.

The basic model of IPFC, as shown in Fig. 1 consisting of three buses i, j and k . Two transmission lines are

connected with the bus i in common. The equivalent circuit of the IPFC with two converters is represented in Fig. 2. $Z_{se_{in}}$ is the series transformer impedance. $P_{se_{in}}$ is the active power exchange of each converter via the common DC link. P_i and Q_i has given in equations (1) and (2) are the sum of the active and reactive power flows leaving the bus i . The IPFC branch active and reactive power flows leaving bus n are P_{ni} and Q_{ni} and expressions are given in the equation (3) and (4). I_{ji} , I_{ki} are the IPFC branch currents of branch j - i and k - i leaving bus j and k , respectively [21].

$$P_i = V_i^2 g_{ii} - \sum_n V_i V_n [g_{in} \cos(\theta_i - \theta_n) + b_{in} \sin(\theta_i - \theta_n)] - \sum_n V_i V_{se_{in}} [g_{in} \cos(\theta_i - \theta_{se_{in}}) - b_{in} \sin(\theta_i - \theta_{se_{in}})] \quad (1)$$

$$Q_i = -V_i^2 b_{ii} - \sum_{n=j,k} V_i V_n [g_{in} \sin(\theta_i - \theta_n) - b_{in} \cos(\theta_i - \theta_n)] - \sum_{n=j,k} V_i V_{se_{in}} [g_{in} \sin(\theta_i - \theta_{se_{in}}) - b_{in} \cos(\theta_i - \theta_{se_{in}})] \quad (2)$$

$$P_{ni} = V_n^2 g_{nn} - V_i V_n [g_{in} \cos(\theta_n - \theta_i) + b_{in} \sin(\theta_n - \theta_i)] + V_n V_{se_{in}} [g_{in} \sin(\theta_n - \theta_{se_{in}}) - b_{in} \cos(\theta_n - \theta_{se_{in}})] \quad (3)$$

$$Q_{ni} = -V_n^2 b_{nn} - V_i V_n [g_{in} \sin(\theta_n - \theta_i) - b_{in} \cos(\theta_n - \theta_i)] + V_n V_{se_{in}} [g_{in} \sin(\theta_n - \theta_{se_{in}}) - b_{in} \cos(\theta_n - \theta_{se_{in}})] \quad (4)$$

$$g_{in} + jb_{in} = 1/z_{se_{in}} = y_{se_{in}}, g_{nn} + jb_{nn} = 1/z_{se_{in}} = y_{se_{in}}, g_{ii} = \sum_{n=j,k} g_{in}, b_{ii} = \sum_{n=j,k} b_{in}$$

Assuming lossless converter, the active power supplied by one converter equals the active power demanded by the other, if there are no underlying storage systems

$$\text{Re}(V_{se_{ij}} I_{ji}^* + V_{se_{ik}} I_{ki}^*) = 0 \quad (5)$$

where the superscript * denotes the complex conjugate.

Fig. 1. Basic model of IPFC.

Fig. 2. Equivalent circuit of IPFC.

3. Disparity Line Utilization Factor

Line Utilization Factor is an index used for determining the congestion of the transmission lines.

It is given by equation (6)

$$LUF_{ij} = \frac{MVA_{ij}}{MVA_{ij\max}} \quad (6)$$

where,

LUF_{ij} : The Line utilization factor (LUF) of the line connected to bus i and bus j .

$MVA_{ij(\max)}$: Maximum MVA rating of the line between bus i and bus j .

MVA_{ij} : The Actual MVA rating of the line between bus i and bus j .

LUF gives an estimate of the percentage of the line being utilized and is an efficient method to estimate the congestion in a line. For placement of IPFC, there should be at least two lines connected to a common bus. Therefore LUF is not sufficient for Placement of IPFC. Taking into consideration, the fact that IPFC can directly transfer real power via the common DC link, it has the capability to transfer power demand from overloaded to under loaded lines. Hence a new index Disparity Line Utilization Factor is hereby proposed for the optimal placement of an IPFC. DLUF indicates the difference between the utilization of the lines. It gives an estimate of the difference of the percentage of the line being used for the power flow. All the lines are first ranked in descending order of their line utilization factors. The line which has the first rank is considered to be the most congested line. DLUF is calculated for all the lines connected to the line with the highest congestion. All the line pairs connected to the same bus are ranked on the basis of DLUF. The line set that has the highest value of DLUF is considered to be the optimal location of IPFC for Congestion Management. Assuming both lines of same rating:

$$DLUF_{(ij)-(ik)} = \left| \frac{MVA_{ij} - MVA_{ik}}{MVA_{\max}} \right| \quad (7)$$

where,

$DLUF_{(ij)-(ik)}$ is the Disparity line utilization factor ($DLUF$) of the line set $i-j$ and $i-k$ connected to bus i and bus j .

MVA_{ij} is the MVA rating of the line between bus i and bus j .

$MVA_{\max}$ is the maximum MVA rating of line.

MVA_{ik} is the actual MVA rating of the line between bus i and bus k .

Step by Step Procedure:

Step 1: Read line data and bus data.

Step 2: Calculate power flow and LUF of all lines.

Step 3: Calculate DLUF values for all lines in pair with lines ranking highest in congestion.

Step 4: Place IPFC on the lines having the highest value of DLUF.

Step 5: Perform load flow analysis and calculate the LUF of all lines.

4. Optimal Tuning of IPFC

An objective function is formulated to find the optimal size of IPFC which minimizes the active power loss, total voltage deviations, and security margin with the usage of minimum value of installed IPFC.

4.1. Objective Function

A multi objective function formulated is given in equation (8)

$$\min F = \min \sum_{i=1/\text{to}4} w_i f_i \quad (8)$$

where, w_1, w_2, w_3, w_4 are weighting factors.

$$w_1 + w_2 + w_3 + w_4 = 1 \quad (9)$$

$$w_1 = w_2 = w_3 = w_4 = 0.25$$

4.1.1. Reduction of loss

The expression for the reduction of active power loss is given in the equation (10) and (11),

$$\min f_1(x) = \sum_{n=j,k}^{lk} P_{\text{loss}} \quad (10)$$

$$P_{\text{loss}} = \left(|V_i|^2 G_{in} - |V_i| |V_n| [G_{in} \cos \theta_{in} + B_{in} \sin \theta_{in}] - |V_i| |V_{seij}| [G_{in} \cos \theta_{seij} + B_{in} \sin \theta_{seij}] \right) \\ + \left(|V_n|^2 G_{in} - |V_i| |V_n| [G_{in} \cos \theta_{ni} + B_{in} \sin \theta_{ni}] - |V_n| |V_{seik}| [G_{in} \cos \theta_{seik} + B_{in} \sin \theta_{seik}] \right) \quad (11)$$

where, lk is the number of transmission lines,

$V_i = V_i \angle \theta_i$ and $V_n = V_n \angle \theta_n$ are the voltages at the end buses i and n ($n = j, k$).

$V_{seij} = V_{seij} \angle \theta_{seij}$ ($n = j, k$) is the series injected voltage source of n^{th} line, se stands for series, G_{in} and B_{in} are the transfer conductance and susceptance between bus i and n ($n = j, k$) respectively. The magnitude and phase angle of the series injected voltage of V_{seij} and V_{seik} are determined optimally

4.1.2. Minimization of voltage deviation

To have a good voltage performance, the voltage deviation at each bus must be made as small as possible. The Voltage Deviation (VD) can be expressed by the equation (12):

$$f_2(x) = \min(VD) = \min \left(\sum_{k=1}^{N_{bus}} |V_k - V_k^{\text{ref}}|^2 \right) \quad (12)$$

V_k is the voltage magnitude at bus k .

4.1.3. Minimization of security margin

The security rate of a system according to the critical state can be expressed as follows in the equation (13).

$$SM = \frac{\sum_{j \in J_L} S_j^{\text{lim}} - \sum_{j \in J_L} S_j^{\text{initial}}}{\sum_{j \in J_L} S_j^{\text{lim}}} \quad (13)$$

where, $J_L = A$ set contains all load buses.

SM takes a value between zero and one for a system with normal operating condition. A negative value of SM means the system cannot provide the initial load, and the voltage will definitely collapse. Since it is intended to minimize the function, the objective function in the equation (13) is rewritten in the equation (14).

$$f_3(x, u, z) = 1 - SM = \frac{\sum_{j \in J_L} S_j^{\text{initial}}}{\sum_{j \in J_L} S_j^{\text{lim}}} \quad (14)$$

4.1.4. Minimization of total capacity of installed IPFC

The total capacity of the installed IPFC is required for solving the overload on the transmission lines formulated as in the equation (15).

$$f_4(x) = \min(PQ_1^2 + PQ_2^2) \quad (15)$$

where, PQ : the capacity of each VSCs of IPFC.

$$PQ_1^2 + PQ_2^2 = \left(Vse_{ij} \left(\frac{V_i - Vse_{ij} - V_j}{Z_{ij}} \right) \right)^2 + \left(Vse_{ik} \left(\frac{V_i - Vse_{ik} - V_k}{Z_{ik}} \right) \right)^2 \quad (16)$$

4.2. Equality Constraints

$$P_{gi} + P_i - P_{Di} = \sum_{j=1}^n V_i V_j Y_{ij} \cos(\theta_{ij} + \delta_j - \delta_i) \quad \forall i \quad (17)$$

$$Q_{gi} + Q_i - Q_{Di} = \sum_{j=1}^n V_i V_j Y_{ij} \sin(\theta_{ij} + \delta_j - \delta_i) \quad \forall i \quad (18)$$

4.3. Inequality Constraints

$$V_i^{\min} \leq V_i \leq V_i^{\max} \quad \forall i \in loadbus \quad (19)$$

$$S_{in}(V, \delta) \leq S_{in}^{\max} \quad (20)$$

4.3.1. IPFC constraints

$$V_{se}^{\min} \leq V_{se} \leq V_{se}^{\max} \quad (21)$$

$$\theta_{se}^{\min} \leq \theta_{se} \leq \theta_{se}^{\max} \quad (22)$$

where, S_{in} is the power injected by the IPFC converters.

5. Cuckoo Search

This algorithm is based on the brood parasitic behavior of some cuckoo species along with the Lévy flight behavior of some birds and fruit flies. Some species of cuckoos lay their eggs in common nests while others lay their eggs in the nests of other host birds.

Cuckoo Search considers three rules:

- 1) Each cuckoo lays one egg at a time, and puts its egg in the randomly chosen nest;
- 2) The best nests for good quality of eggs will be taken forward to the next generations;
- 3) The number of available host nests is fixed. The probability of discovery of the cuckoo egg by the host bird is considered as $Pa \in [0, 1]$.

In this case, the host bird can either throw the egg away or abandon the nest, to build a new nest. For simplicity, this last assumption can be approximated by the fraction Pa of the n nests are replaced by new nests (with new random solutions).

For simplicity, it can be assumed that each egg in a nest represents a solution, and a cuckoo egg represent a new solution. The aim is to use the new and potentially better solutions (cuckoos) to replace a not-so good solution in the nests.

Flow Chart of Cuckoo Search Algorithm:

6. Results and Discussion

An IEEE 30 bus test system is considered and shown in Fig. 3. In the IEEE 30 bus system bus no. 1 is considered as a slack bus and bus nos. 2, 5, 8, 11, 13 are considered as PV buses while all other buses are load bus. This system has 41 interconnected lines. The IEEE 30 bus test system load flow is obtained using MATLAB Software and the results have been presented. Only load buses are considered for IPFC placement. Equal weights of 0.25 have been considered for all objectives. The results have been analyzed for normal loading, 110% loading and 125% loading condition.

LUF values of all the lines without and with Optimal placement of IPFC has been presented in Table 1 and shown in Fig. 4. It is established that line 3-4 is the most congested line connected between the load buses.

All possible DLUF index calculation for line 3-4 has been shown in Table 2 as test cases. The parameters of Cuckoo Search algorithm used for tuning the IPFC have been mentioned in Table 3. The untuned and the optimally tuned values of IPFC using Cuckoo Search algorithm is given in Table 4. Table 5 compares the real power loss, Voltage deviation, security margin with a smaller capacity of installed IPFC. In Table 6 both active power loss and reactive power loss are compared without IPFC, with untuned IPFC and optimally tuned IPFC. The results for 110% load and 125% load have also been presented and analyzed.

Fig. 3. IEEE 30 bus test system with IPFC installed at the line connected between buses 3-4 and 4-12.

Table 1. LUF Values of All Lines in 30 Bus System

Line No.	From Bus (SB No)	To Bus (RB No.)	LUF without IPFC (p.u.)	LUF with un tuned IPFC (p.u.)	LUF with optimal tuning of IPFC using cuckoo (p.u.)
1	1	2	1.8029	1.7979	1.7597
2	1	3	0.9483	0.9039	0.8870
3	2	4	0.4939	0.4768	0.4604
4	3	4	0.8415	0.8334	0.8240
5	2	5	0.8532	0.8451	0.8362
6	2	6	0.6473	0.6279	0.6096
7	4	6	0.7173	0.7439	0.6918
8	5	7	0.2539	0.236	0.2339
9	6	7	0.3866	0.3835	0.3898
10	6	8	0.397	0.4899	0.4406
11	6	9	0.3273	0.3042	0.3044
12	6	10	0.2479	0.233	0.2329
13	9	11	0.4704	0.5146	0.5074
14	9	10	0.6789	0.6806	0.6765
15	4	12	0.5284	0.5028	0.4988
16	12	13	0.6929	0.7521	0.7377
17	12	14	0.1645	0.1642	0.1641
18	12	15	0.3858	0.3861	0.3861
19	12	16	0.2122	0.2133	0.2136
20	14	15	0.0317	0.0323	0.0325

21	16	17	0.0868	0.0889	0.0893
22	15	18	0.1481	0.1485	0.1485
23	18	19	0.037	0.0378	0.0378
24	19	20	0.0651	0.0644	0.0641
25	10	20	0.1622	0.16	0.1594
26	10	17	0.1002	0.0978	0.0972
27	10	21	0.2525	0.2509	0.2500
28	10	22	0.1296	0.1308	0.1305
29	21	23	0.0571	0.0564	0.0557
30	15	23	0.0924	0.0954	0.0958
31	22	24	0.0545	0.0555	0.0553
32	23	24	0.0305	0.0328	0.0327
33	24	25	0.0356	0.0318	0.0318
34	25	26	0.0434	0.0433	0.0432
35	25	27	0.078	0.074	0.0740
36	28	27	0.3122	0.3013	0.3003
37	27	29	0.1158	0.1147	0.1144
38	27	30	0.089	0.0882	0.0879
39	29	30	0.0426	0.0427	0.0424
40	8	28	0.0799	0.0969	0.0870
41	6	28	0.2166	0.2021	0.2023

Table 2. IPFC Placement on the Basis of DLUF

Case	Line 1 SB No- RB No.	Line 2 SB No- RB No.	LUF Line1 (p.u.)	LUF Line 2 (p.u.)	DLUF (p.u.)
CASE-1	3-4	4-6	0.8415	0.7173	0.1242
CASE2	3-4	4-12	0.8415	0.5284	0.3131

Fig. 4. LUF of lines of 30 bus test system without IPFC and with optimally tuned IPFC.

It is observed from the Table 1, line connected between buses3-4 is the most congested line connected to load bus. In the 30 bus system, two lines have been connected to line 3-4. So, two test cases for IPFC placement have been considered, as shown in Table 2. DLUF has been calculated for each test case, and it is observed that DLUF is the maximum between lines connected to buses 3-4 and 4-12. Hence, lines between buses 3-4 and buses 4-12 have been selected for optimal placement of IPFC. It is observed that placement of IPFC at the location, reduces the congestion in line 3-4 from 0.8415 to 0.8334. The LUF values before and after placement of IPFC have been compared and shown in Fig. 4.

After optimal tuning of IPFC using Cuckoo Search algorithm, the congestion in the line reduces to 0.8240. Fig. 5-Fig. 7 shows the values of the objective functions namely, active power loss, security margin, installed IPFC capacity, and voltage deviation for the different values of P_a . It is observed that for increase in P_a beyond 0.25 the improvement in the value of objective function is very marginal. However, if the rejection of nests on the basis of considering it to be alien is very large, good nests also get rejected in the process. Hence the number of runs required to obtain good results increase if the value of P_a is very large, i.e. the rate of failure is more for a very large value of P_a . With the increase in the number of generations the computation time increases to a very large extent with only marginal improvement in objective function values. Hence, $P_a = 0.25$ and $n = 25$ have been chosen for Cuckoo Search Algorithm for optimal tuning of IPFC as listed in Table 4. Fig. 8 shows the Computation Time Required for different values of P_a and Fig. 9 shows the No. of runs for better solution.

Fig. 5. Security margin and total active power loss vs. probability switch.

Fig. 6. Installed IPFC capacity vs. probability switch.

Fig. 7. Voltage deviation vs. probability switch.

Fig. 8. Computation time required for different values of Pa.

Fig. 9. No. of runs for better solution.

Table 3. Comparative Analysis for Various Population Size

Pa = 0.75	No. of Nests 25	No. of Nests 50
Active Power Loss (MW)	21.189	20.7797
Security Margin (p.u.)	15.5767	15.7184
Voltage Deviation (p.u.)	2.311	2.1007
Installed IPFC Capacity (p.u.)	0.0112	6.5623e-8
Computation Time (sec)	234.579	552.800913

Table 4. Cuckoo Search Parameters for IPFC Tuning

Parameter	Value
No. of Nests (n)	25
Probability of finding alien nest (Pa)	0.25

6.1. Results for Normal Loading

Although series devices are primarily supposed to improve power flow in the system, a marked improvement in voltage profile of the buses with optimal placement of tuned IPFC in comparison to voltage profile of the system without IPFC is observed from Fig. 10. Thus, the Voltage Deviation of the overall system is reduced which is also established from Table 6. Table 6 also shows a reduction in the values of the other objective functions by optimal placement of IPFC. Thus, it is established that by Optimal tuning of IPFC Using Cuckoo Search algorithm the system loss, voltage deviation and also security margin is reduced with the use of minimum capacity of IPFC. The reduction in loss helps in congestion management of the system. The reduction in security margin protects the system against collapse. Lower the capacity of IPFC lower is the cost. Hence, the overall system performance has been improved at a minimum cost. Table 7

shows the effectiveness of IPFC in the reduction of active and reactive power loss. It also shows the importance of proper placement and tuning of IPFC to be able to completely utilize the IPFC. Fig. 11 shows the fast convergence of Cuckoo Search algorithm in just 10 generations.

Table 5. IPFC Parameters before and after Tuning of IPFC

IPFC parameters	Un tuned IPFC	Tuning of IPFC using CS
VSe1 (p.u.)	0.0050	0.0012
VSe2 (p.u.)	0.0100	0.0001
θ_{se1} (degree)	-140.1182	180
θ_{se2} (degree)	180	132.6977

Fig. 10. Voltage profile without and with CS tuned IPFC.

Fig. 11. Convergence characteristics of cuckoo search algorithm with normal loading.

Table 6. Real Power Loss, Voltage Deviation Security Margin and Total Capacity of Installed IPFC with Untuned and with CS Tuned IPFC

Parameters	Untuned IPFC	Tuning of IPFC using CS
Real Power losses (MW)	21.909	21.297
Voltage Deviation of all buses (p.u.)	2.3889	2.3459
Security Margin of all lines (p.u.)	18.2714	15.3364
The total capacity of installed IPFC (p.u.)	0.000406	0.0000044554

Table 7. Comparison of Total Real and Reactive Power Loss in the System without IPFC, with Untuned IPFC and with CS Tuned IPFC

	Real Power Losses (MW)	Reactive power losses (MVAR)
Without IPFC	22.941	107.370
Un tuned IPFC	21.909	101.334
Tuning of IPFC using CS	21.297	99.616

6.2. Results for 110% Loading

Table 8. IPFC Parameters before and after Tuning of IPFC

IPFC parameters	Un tuned IPFC	Tuning of IPFC using CS
VSe1 (p.u.)	0.0050	0.0012
VSe2 (p.u.)	0.0100	0.0169
θse1 (degree)	-159.8295	-161.8856
θse2 (degree)	180	-180

Table 9. Comparison of Total Real Power Loss, and Reactive Power Loss without IPFC, with Untuned and with CS Tuned IPFC

	Real Power Losses (MW)	Reactive power losses (MVAR)
Without IPFC	27.806	127.295
Un tuned IPFC	26.294	118.994
Tuning of IPFC using CS	25.863	117.277

Table 10. Comparison of Real Power Loss, Voltage Deviation Security Margin and Total Capacity of Installed IPFC with Untuned and with CS Tuned IPFC

Parameters	Untuned IPFC	Tuning of IPFC using CS
Real Power losses (MW)	26.294	25.8635
Voltage deviation (p.u.)	2.4609	2.4083
Security Margin (p.u.)	19.4269	16.6196
The total capacity of installed IPFC (p.u.)	0.0002437	5.2e-5

Fig. 12. Voltage profile without IPFC and with CS tuned IPFC under 110% load condition for IEEE 30 bus test system.

Fig. 13. Convergence characteristics of Cuckoo Search algorithm with 110% loading.

Simulation is carried for 110% load on the IEEE 30 bus test system. It is observed that with the increase in load the total real and reactive power loss increases. Optimal tuning and placement of IPFC has been done to reduce loss, voltage deviation Security Margin and capacity of installed IPFC and the results are presented in Tables 8-10. The voltage profile of the 30 bus system in Fig. 12 with optimally allocated IPFC shows a comparative improvement to that without IPFC. Fig. 13 shows the fast convergence of Cuckoo Search algorithm at 28 generations.

6.3. Results for 125% Loading

Table 11. IPFC Parameters before and after Tuning under 125% Load

	Untuned IPFC	Tuning of IPFC using CS
VSe1 (p.u.)	0.0050	0.0010
VSe2 (p.u.)	0.0100	0.0079
θ_{se1} (degree)	-167.9689	180
θ_{se2} (degree)	180	-174.9885

Table 12. Comparison of Real Power Loss, Voltage Deviation Security Margin and Total Capacity of Installed IPFC with Untuned and with CS Tuned IPFC under 125% Loading Condition

Parameters	Un tuned IPFC	Tuning of IPFC using CS
Real Power losses (MW)	34.115	33.933
Voltage deviation (p.u.)	2.5861	2.5612
Security Margin (p.u.)	21.2293	18.38
The total capacity of installed IPFC (p.u.)	0.000245	9.8008e-7

Table 13. Comparison of Total Real Power Loss, and Reactive Power Loss without IPFC, with Untuned and with CS Tuned IPFC under 125% Load Condition

	Real Power Losses (MW)	Reactive power losses (MVAR)
Without IPFC	36.074	160.733
Un tuned IPFC	34.115	149.791
Tuning of IPFC using CS	33.934	149.175

Fig. 14. Voltage profile without IPFC and with CS tuned IPFC under 125% load condition for the IEEE 30 bus test system.

Simulation Results for 125 % load have been presented in Tables 11-13. It is observed that the total real and reactive power loss further increases. Optimal tuning and placement of IPFC has been done to reduce loss, voltage deviation Security Margin and capacity of installed IPFC and results are presented in Tables 11-13. Fig. 14 shows improvement in voltage profile without and with IPFC. Convergence characteristics of cuckoo Search Algorithm shows a fast convergence at just 4 generations and shown in Fig.

15. In Fig. 16, real power loss under different loading conditions has been compared, without IPFC, with untuned IPFC and with optimally tuned IPFC. It is observed that real power loss increases with the increase of loading.

Fig. 15. Convergence characteristics of cuckoo search algorithm with 125% loading condition.

Fig. 16. Real power loss without IPFC with IPFC and with CS based tuned IPFC under normal, 110% and 125% loading condition.

7. Conclusion

In this paper, a Disparity Line Utilization Factor for the optimal placement of IPFC for congestion management has been implemented. The IPFC is accordingly placed in the lines with highest DLUF value. It has been established that the placement of IPFC using DLUF effectively reduces line congestion and power loss. A multi Objective function comprising of the reduction of active power loss, minimization of total voltage deviations, and minimization of security margin with the usage of minimum value of installed IPFC is considered for the optimal tuning of IPFC using Cuckoo Search algorithm. Effect and importance of the CS parameters for IPFC tuning has been carried. The proposed method is implemented for IEEE-30 bus test system. The results have been presented and analyzed under normal loading, 110% loading and 125% loading condition to ascertain the effectiveness of the proposed method on the power system performance. It is observed that placement of IPFC with the proposed methodology causes an effective reduction in congestion in the lines. Simulation results have demonstrated the effectiveness and accuracy of the Cuckoo Search algorithm technique to achieve multiple objectives and to determine the optimal parameters of the

IPFC under different loading conditions. A reduction in real power loss, voltage deviation, security margin has been achieved with much smaller capacity of installed IPFC. The reduction in loss helps in congestion management of the system. The reduction in security margin protects the system against collapse. Lower the capacity of IPFC lower is the cost. Hence, the overall system performance has been improved at a minimum cost.

References

- [1] Kumar, A., Srivastava, S. C., & Singh, S. N. (May 2005). Congestion management in competitive power market: A bibliographical survey. *Electric Power Systems Research*, 76, 153–164.
- [2] Singh, S. N., & David, A. K. (June 2001). Optimal location of FACTS devices for congestion management. *Electric Power Syst. Res.*, 58, 71–79.
- [3] Besharat, H., & Taher, S. A. (June 2008). Congestion management by determining optimal location of TCSC in deregulated power systems. *Electrical Power and Energy Systems*, 30, 563–568.
- [4] Minguez, R., Milano, F., Zarate-Minano, R., & Conejo, A. J. (Nov. 2007). Optimal network placement of SVC devices. *IEEE Trans. on Power Systems*, 22(4).
- [5] Mandala, M., & Gupta, C. P. (2010). Congestion management by optimal placement of FACTS device. *PEDES and Power India*, 1–7.
- [6] Reddy, S. S., Kumari, M. S., & Sydulu, M. (April 2010). Congestion management in deregulated power system by optimal choice and allocation of FACTS controllers using multi-objective genetic algorithm. *Transmission and Distribution Conference and Exposition*, 1-7.
- [7] Acharya, N., & Mithulananthan, N. (March 2007). Locating series FACTS devices for congestion management in deregulated electricity markets. *Electric Power Systems Research*, 77(3–4), 352–360.
- [8] Zhang, J. (2006). Optimal power flow control for congestion management by interline power flow controller (IPFC). *Proceedings of International Conference on Power System Technology* (pp. 1–6). Chongqing, China.
- [9] Mohamed, K. H., Rama-Rao, K. S., & Hasan, K. N. M. (2005). Application of particle swarm optimization and its variants to interline power flow controllers and optimal power flow. *Proceedings of Transmission and Distribution Conference and Exhibition: Asia and Pacific* (pp. 1–7). Dalian, China.
- [10] Abdel-Moamen, M. A., & Padhy, N. P. (2003). Optimal power flow incorporating FACTS devices-bibliography and survey. *Proceedings of IEEE PES Transmission and Distribution Conference and Exposition* (pp. 669-676).
- [11] Hingorani, N. G., & Gyugyi, L. (2000). *Understanding FACTS: Concepts and Technology of Flexible AC Transmission System*. IEEE Press.
- [12] Teerthana, S., & Yokoyama, A. (2004). An optimal power flow control method of power system using interline power flow controller (IPFC). *Proceedings of the 7th International Power Engineering Conference* (pp. 1075-1080).
- [13] Kargarian, A., & Falahati, B. (July 2012). Multiobjective optimal power flow algorithm to enhance multi-microgrids performance incorporating IPFC. *Proceedings of Power and Energy Society General Meeting* (pp. 1-6). San Diego, CA.
- [14] Ram, I. S., & Amarnath, J. (2013). Optimal setting of IPFC for voltage stability improvement using (GA-GSA) hybrid algorithm. *Proceedings of Nirma University International Conference on Engineering* (pp. 1-6).
- [15] Karthik, B., Alagarasan, I., & Chandrasekar, S. (2012). Optimal location of interline power flow controller for controlling multi transmission line: A new integrated technique. *Frontiers of Electrical and Electronic Engineering*, 7(4), 447-458.

- [16] Yang, X. S. *Engineering Optimization — An Introduction with Metaheuristic Applications*. John Wiley and Sons, Inc.
- [17] Yang, X. S., & Deb, S. (December 2009). Cuckoo search via Lévy flights. *Proceedings of World Congress on Nature & Biologically Inspired Computing* (pp. 210-214). India.
- [18] Yang, X. S. (2008). *Nature-Inspired Metaheuristic Algorithms*. Frome: Luniver Press.
- [19] Acha, E., Fuerte-Esquivel, C., Ambriz-Perez, H., & Angeles, C. (2004). *FACTS: Modelling and Simulation in Power Networks*. John Wiley & Sons.
- [20] Perez, M. A., Messina, A. R., & Fuerte-Esquivel, C. R. (July 2000). Application of FACTS devices to improve steady state voltage stability. *Proceedings of Power Engineering Society Summer Meeting* (pp.1115–1120).
- [21] Zhang, X. P. (May 2003). Modeling of the interline power flow controller and the generalized unified power flow controller in Newton power flow. *IEE Proceedings of Generation, Transmission and Distribution*, 150(3), 268-274.

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