Congestion Management of Power System with Interline Power Flow Controller Using Disparity Line Utilization Factor and Multi-objective Differential Evolution

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***Abstract*—The restructuring of the electric power market has led to complex power transmission congestion problems. Additionally, scheduled power flows in the transmission line, as well as spontaneous power exchanges have also risen sharply in recent years. The proper placement of IPFC can improve the transmission line congestion problem to a great extent. 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 percentages of Mega Volt Ampere utilization of each line connected to the same bus. The IPFC is placed in the lines with maximum DLUF. A multi-objective function consisting of reduction of active power loss, minimization of total voltage deviations, minimization of security margin and minimization of installed IPFC capacity is considered for the optimal tuning of IPFC using differential evolution algorithm. The proposed method is implemented for IEEE-30 bus test system under different loading conditions and the results are presented and analyzed to establish the effectiveness on the reduction of congestion.**

***Index Terms*—Congestion, differential evolution algorithm, interline power flow controller, line utilization factor, optimal placement, optimal tuning.**

NOMENCLATURE

n	Bus j, k.
$\boldsymbol{V}_n$	Complex voltage at bus (j, k).
V_n, θ_n	Magnitude and angle of V_n respectively.
$\boldsymbol{V}se_{in}$	Complex controllable series injected voltage source.
$Vse_{in}, \theta se_{in}$	Magnitude and angle of $\boldsymbol{V}\text{se}_{in}$ respectively.
$\boldsymbol{V}_i$	Complex voltage at bus i.
V_i, θ_i	Magnitude and angle of $\boldsymbol{V}_i$ respectively.
P_i ,Q_i	Sum of active and reactive power leaving bus i.
P_{ni} , Q_{ni}	IPFC branch active and reactive powers leaving bus n.
I_{ji}, I_{ki}	Current in line j–i and k–i respectively.
$\boldsymbol{Z}se_{in}$	Series transformer impedance of line i–n.
g_{in}	Series transformer conductance of line i–n.
b_{in}	Series transformer susceptance of line i–n.

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I. INTRODUCTION

POWER system operation problems increase with size, loading, and the complexity of the network. Restructuring in the electric power industry has further enhanced the problems of power systems related to power delivery and power quality. The deregulated electric power industry, for example, has changed its operations, structure, ownership, and management models. The issue of transmission congestion is particularly prominent in deregulated and competitive markets, thus requiring an appropriate management strategy [1]. In the new competitive electric market, it is now mandatory for the electric utilities to operate in ways that make better use of existing transmission facilities, and in conjunction with maintaining the security, stability, and reliability of the supplied power.

In the literature, FACTS devices have been used for several purposes including congestion management. It is a well-recognized fact that the performance of FACTS devices in a power system mainly depends on its placement and tuning. Gitizadeh and Kalantar [2] investigated a simulated annealing based optimization method for placement of flexible AC transmission systems (FACTS) devices in order to relieve congestion in the transmission lines while increasing static security margin and voltage profile of a given power system. Qian *et al.* [3] used sensitivity analysis and extended equal area criterion to find the optimal location and capability of FACTS in a power system for enhancing static voltage and transient stability. P. Ye *et al.* [4] proposed an algorithm for optimal congestion dispatch calculation with UPFC control. A decomposition control method was introduced to solve this optimal power flow problem. Mandala and Gupta [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 real power performance index and also on 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 using genetic algorithm for management of congestion. Acharya and Mithulananthan [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 the 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 the 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 solutions [10]. Out of all FACTS devices, IPFC is considered to be the most flexible, powerful, and versatile as it employs at least two VSCs with a common DC link. Hence, IPFC has the capability of compensating multi-transmission lines. FACTS devices, such as 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 [11]. Proper placement of IPFC is, therefore, a subject to be analyzed.

Location and tuning of FACTS devices in the power system is an important issue, and hence optimal placement and tuning of IPFC has been proposed based on a previous study [10], [12]. Differential evolution is a heuristic approach for minimizing nonlinear and non-differentiable continuous functions. It has very fast convergence, requires few control variables, and is robust and easy to use [14], [15]. It is also considered as good alternative evolutionary algorithms for power system applications [16]. Several authors have reported placement and tuning of IPFC and other FACTS devices using various conventional and heuristic methods.

Line utilization factor (LUF) is used for determining congestion of a single transmission line. Single-line FACTS devices can be placed on the transmission line with maximum LUF value. However, IPFC is a multiline series FACTS device. In its simplest form it consists of at least two converters placed on two transmission lines with a common bus. The first converter of IPFC can be placed on the line with maximum LUF. However, the placement of the other converter is an issue that becomes more and more complex with increases in system size, number of IPFCs, and the complexity of the IPFC. Hence, LUF is not a sufficient index for obtaining IPFC location placement.

In this paper, the difference of line utilization factors between two lines has been used for determining the optimal location of IPFC. LUF gives an estimate of the difference of the percentage of line being used for the power flow. First, all lines are ranked in terms of line congestion. Then, DLUF is calculated for all the lines that share a common bus with the most congested line. 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 is formulated for optimal tuning of IPFC using differential evolution algorithm. The multi-objective function comprises 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 reduction of loss further reduces line congestion. Reduction of voltage deviation and security margin ensures power quality and system security. The proposed method is implemented and tested on an IEEE 30 bus system with different loading conditions.

II. IPFC MODELING

IPFC consists of at least two back-to-back DC-AC converters connected via a common DC link. V_i, V_j, and V_k are complex voltages at buses i, j, and k, respectively. $\boldsymbol{V_1} = V_1\angle\theta_1$ ($1 = i, j, k$) and V_1, θ_1 are the magnitude and angle of $\boldsymbol{V}_1$. $\boldsymbol{V}se_{in}$ is the complex controllable series injected voltage source, which represents the series compensation of the series converter. $\boldsymbol{V}se_{in}$ is defined as $\boldsymbol{V}se_{in} = Vse_{in}\angle\theta\ se_{in}(n = j, k)$. Vse_{in} and θse_{in} are the magnitude and angle of $\boldsymbol{V}se_{in}$.

The basic model of IPFC, as shown in Fig. 1, consists of three buses i, j, and k [17], [18]. Two transmission lines are connected with the bus i in common. The equivalent circuit of the IPFC with two converters is represented with two series injected voltage sources, as shown in Fig. 2. Zse_{in} is the series transformer impedance. P_i and, Q_i as given in (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 the expressions are given in (3) and (4). I_{ji}, I_{ki} are the IPFC branch currents of branch j–i and k–i leaving buses j and k, respectively [19].

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

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

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

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

where $n = j, k$

$$g_{in} + jb_{in} = 1/\boldsymbol{Z}se_{in} = yse_{in}, g_{nn} + jb_{nn} = 1/\boldsymbol{Z}se_{in} = yse_{in}$$

$$g_{ii} = \sum_{n=j,k} g_{in}, b_{ii} = \sum_{n=j,k} b_{in}.$$

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

$$\mathrm{Re}(\boldsymbol{V}se_{ij}\boldsymbol{I}_{ji}^* + \boldsymbol{V}se_{ik}\boldsymbol{I}_{ki}^*) = 0 \quad (5)$$

where the superscript $*$ denotes the complex conjugate.

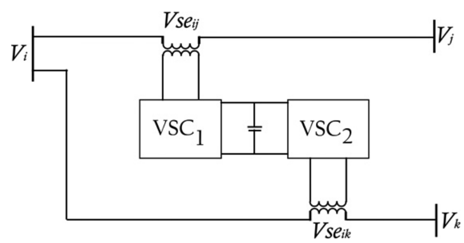

Fig. 1. Basic model of IPFC.

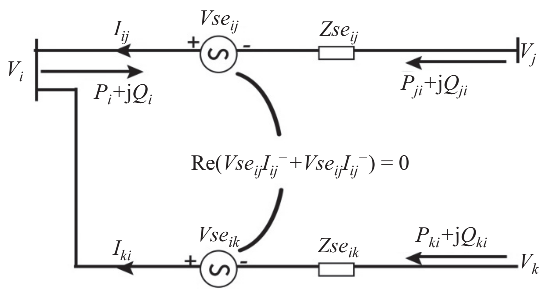

Fig. 2. Equivalent circuit of IPFC.

III. Disparity Line Utilization Factor

Line utilization factor (LUF) is an index used for determining the congestion of the transmission lines. It is given by

$$LUF_{ij} = \frac{MVA_{ij}}{MVA_{ij}^{\max}} \tag{6}$$

where LUF_{ij} is line utilization factor of the line connected to bus i and bus j, $MVA_{ij}^{\max}$ is maximum *MVA* rating of the line between bus i and bus j, and MVA_{ij} is actual *MVA* rating of the line between bus i and bus j.

LUF gives an estimate of the percentage of 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. Hence, a new index disparity line utilization factor is proposed for the optimal placement of an IPFC. The index provides an estimate of the difference of the percentage of line being used for the power flow. All the lines are first ranked in descending order of their line utilization factors. The line that is the first rank is considered as the most congested line. *DLUF* is calculated for the lines connected to the line with highest congestion. All the line pairs connected to the same bus are ranked based on *DLUF*. The line set that has highest value of *DLUF* is considered to be the optimal location for IPFC for congestion management. Assuming both lines of same rating

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

where, $DLUF_{(ij)-(ik)}$ is the disparity line utilization factor 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 the line, and MVA_{ik} is the actual *MVA* rating of the line between bus i and bus k.

The flow chart for placement of IPFC is given in Fig. 3.

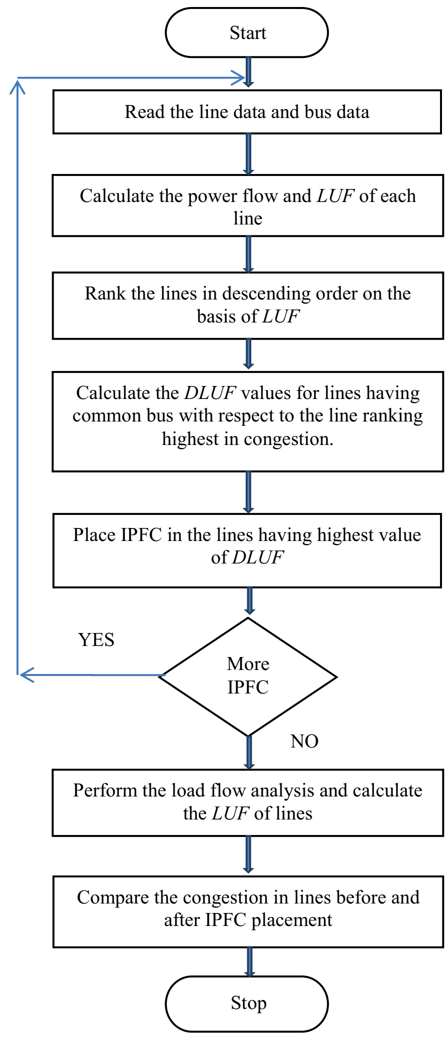

Fig. 3. Flow chart for placement of IPFC.

IV. 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 usage of minimum value of installed IPFC.

A. Objective Function

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

$$\min F = \min \sum_{i=1\ to\ 4} w_i f_i \tag{8}$$

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

$$\begin{aligned} w_1 + w_2 + w_3 + w_4 &= 1 \\ w_1 = w_2 = w_3 = w_4 &= 0.25. \end{aligned} \tag{9}$$

Weighting factors are used to reflect the relative importance of the objective functions. In this study, equal preference is given to all the objective functions. Hence, the value of each weight is taken as 0.25, such that the sum is equal to unity. These weights will not change with the optimization process.

1) Reduction of Loss: The expression for reduction of active power loss [9] is given in (10) and (11),

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

$$P_{\text{loss}} = \begin{pmatrix} |V_i|^2 G_{in} - |V_i|\,|V_n|\,[G_{in}\cos\theta_{in} + B_{in}\sin\theta_{in}] \\ -|V_i|\,|V_{sin}|\,[G_{in}\cos\theta_{sin} + B_{in}\sin\theta_{sin}] \end{pmatrix} + \begin{pmatrix} |V_n|^2 G_{in} - |V_i|\,|V_n|\,[G_{in}\cos\theta_{ni} + B_{in}\sin\theta_{ni}] \\ -|V_n|\,|V_{\text{sin}}|\,[G_{ik}\cos\theta_{sin} + B_{ik}\sin\theta_{sin}] \end{pmatrix} \tag{11}$$

where lk is the number of transmission lines, $\boldsymbol{V}_i = V_i\angle\theta_i$ and $\boldsymbol{V}_n = V_n\angle\theta_n$ are the voltages at the end buses i and n ($n = j,\,k$); $\boldsymbol{V}_{\text{sin}} = V_{\text{sin}}\angle\theta_{sin}$ ($n = j,\,k$) is the series injected voltage source of n^{th} line, s 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 $\boldsymbol{V}_{\text{s}ij}$ and $\boldsymbol{V}_{\text{s}ik}$ are determined optimally.

1) 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) [20] can be expressed by (12):

$$f_2(x) = \min(VD) = \min(\sum_{k=1}^{N\text{bus}} |V_k - V_k^{\text{ref}}|^2) \tag{12}$$

where V_k is the voltage magnitude at bus k.

2) Minimization of Security Margin: This function depends on the static voltage stability and shows whether the chance of voltage collapse is reduced. Voltage collapse is a situation when a system is unable to provide the load demand and is considered to be a critical state. By knowing this critical state, the system can be protected against voltage collapse. The security rate of a system according to the critical state can be expressed [21], [22] as follows in (13).

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

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

SM has a value between zero and one for a system with stable operating condition. $SM = 0$ at the voltage stability limit. A negative value of *SM* means the system cannot provide the initial load. Thus, nearer the value of *SM* is to one, the system is considered to be more stable. Hence, (13) is a maximization function. Since minimization is the aim of the multi-objective function rather than maximization, the objective function in (13) is rewritten in (14).

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

3) Minimization of Total Capacity of Installed IPFC: The total capacity of the installed IPFC [13] required for solving the overload on the transmission lines is formulated as in (15):

$$f_4(x) = \min(PQ_1^2 + PQ_2^2) \tag{15}$$

where PQ denotes capacity of each VSCs of IPFC

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

B. Equality Constraints

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

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

C. Inequality Constraints

$$V_i^{\min} \le V_i \le V_i^{\max} \quad \forall i \in \text{load bus} \tag{19}$$

$$S_{ij}(V,\delta)| \le S_{ij}^{\max} \quad \forall ij. \tag{20}$$

D. IPFC Constraints

$$Vse^{\min} \le Vse \le Vse^{\max} \tag{21}$$

$$\theta se^{\min} \le \theta se \le \theta se^{\max} \tag{22}$$

where V_{slk}, θ_{slk} are the injected voltage magnitude and angle, I_{lk} is line current magnitude through the series converter, and S_{slk} is power injected by VSC.

V. Results and Discussion

An IEEE 30 bus test system is considered as shown in Fig. 4, in which 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. Load flow analysis including IPFC is then performed. 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 and tuning of IPFC, are presented in Table I. 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 II as test cases. The parameters of differential evolution algorithm used for tuning the IPFC have been mentioned in Table III. The results for 110% load and 125% load have also been presented and analyzed.

It is observed from Table I that the line connected between buses 3–4 is the most congested line connected to the load bus.

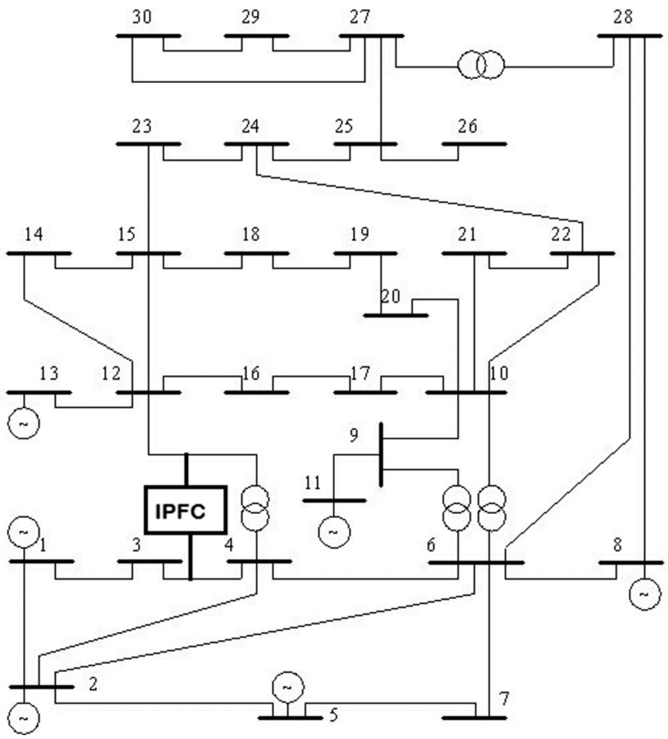

Fig. 4. IEEE 30 Bus Test System with IPFC installed at line connected between buses 3–4 and 4–12.

In the 30 bus system, two lines are connected to line 3–4. So, two test cases for IPFC placement are considered, as shown in Table II. For each test case, *DLUF* is calculated, and it is observed that *DLUF* is maximum between lines connected to buses 3–4 and 4–12. Hence, lines between buses 3–4 and buses 4–12 are 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 are compared in Fig. 5. After optimal tuning of IPFC using differential evolution algorithm the congestion in the line reduces to 0.8240.

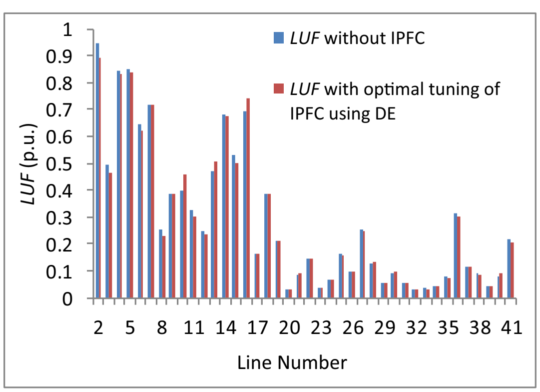

Fig. 5. *LUF* of all lines of IEEE 30 bus system.

Fig. 6, 7, and 8 show the objective function vs. crossover probability characteristics for step size = 0.1. It is observed that the objective minimization is better achieved with increase in CR. However, increase in CR beyond 0.3 does not affect the objective values much.

TABLE I
LUF VALUES OF IEEE 30 BUS TEST SYSTEM WITHOUT IPFC, WITH UNTUNED IPFC AND WITH DE TUNED IPFC

Line No.	From Bus (SB No)	To Bus (RB No.)	*LUF* Without IPFC	*LUF* with Untuned IPFC	*LUF* with DE Tuned IPFC
1	1	2	1.8029	1.7979	1.7767
2	1	3	0.9483	0.9039	0.8940
3	2	4	0.4939	0.4768	0.4667
4	3	4	0.8415	0.8334	0.8309
5	2	5	0.8532	0.8451	0.8408
6	2	6	0.6473	0.6279	0.6201
7	4	6	0.7173	0.7439	0.7190
8	5	7	0.2539	0.2360	0.2324
9	6	7	0.3866	0.3835	0.3848
10	6	8	0.3970	0.4899	0.4570
11	6	9	0.3273	0.3042	0.3050
12	6	10	0.2479	0.2330	0.2333
13	9	11	0.4704	0.5146	0.5097
14	9	10	0.6789	0.6806	0.6781
15	4	12	0.5284	0.5028	0.5034
16	12	13	0.6929	0.7521	0.7421
17	12	14	0.1645	0.1642	0.1642
18	12	15	0.3858	0.3861	0.3862
19	12	16	0.2122	0.2133	0.2136
20	14	15	0.0317	0.0323	0.0324
21	16	17	0.0868	0.0889	0.0892
22	15	18	0.1481	0.1485	0.1486
23	18	19	0.0370	0.0378	0.0378
24	19	20	0.0651	0.0644	0.0644
25	10	20	0.1622	0.1600	0.1597
26	10	17	0.1002	0.0978	0.0974
27	10	21	0.2525	0.2509	0.2505
28	10	22	0.1296	0.1308	0.1306
29	21	23	0.0571	0.0564	0.0559
30	15	23	0.0924	0.0954	0.0957
31	22	24	0.0545	0.0555	0.0554
32	23	24	0.0305	0.0328	0.0328
33	24	25	0.0356	0.0318	0.0318
34	25	26	0.0434	0.0433	0.0433
35	25	27	0.0780	0.0740	0.0740
36	28	27	0.3122	0.3013	0.3009
37	27	29	0.1158	0.1147	0.1146
38	27	30	0.0890	0.0882	0.0881
39	29	30	0.0426	0.0427	0.0426
40	8	28	0.0799	0.0969	0.0901
41	6	28	0.2166	0.2021	0.2030

TABLE II
IPFC PLACEMENT ON THE BASIS OF *DLUF*

Sl. No.	Line 1 SB No–RB No.	Line 2 SB No–RB No.	*LUF* Line 1	*LUF* Line 2	*DLUF*	*LUF* of Line 1 with IPFC
Case 1	3–4	4–6	0.8415	0.7173	0.1242	0.8365
Case 2	3–4	4–12	0.8415	0.5284	0.3131	0.8330

TABLE III
DIFFERENTIAL EVOLUTION PARAMETERS FOR IPFC TUNING

Sl. No.	Parameter	Value
1	Cross over probability (CR)	0.3
2	Step size (F)	0.1

It is observed from Fig. 9 that DE requires very less computation time, and computation time does not vary much with increase of CR. Fig. 10 compares the objective functions with respect to step size for CR = 0.1. It is observed that increase in step size increases the computation time without much improvement in objective function values. Hence, the

Crossover Probability is chosen to be 0.3 and step size is 0, as shown in Table III.

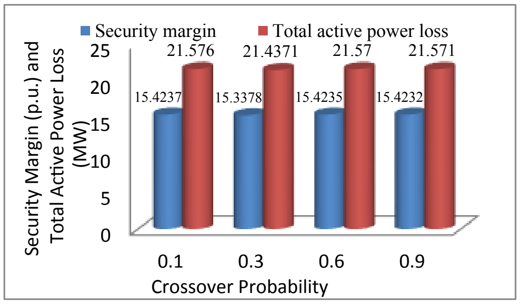

Fig. 6. Active power loss and security margin vs. CR for $F = 0.1$.

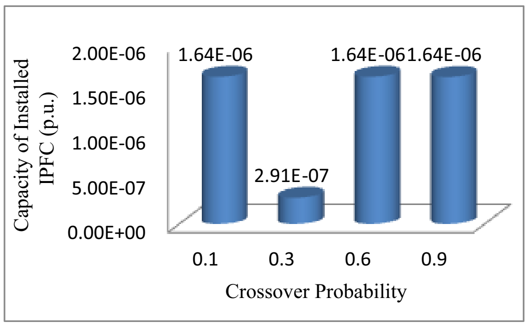

Fig. 7. Capacity of installed IPFC vs cross probability for step size = 0.1.

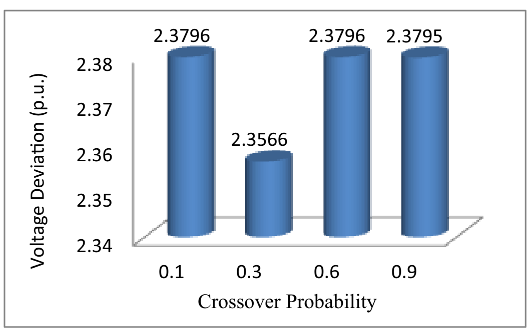

Fig. 8. Voltage deviation vs. crossover probability for step size = 0.1.

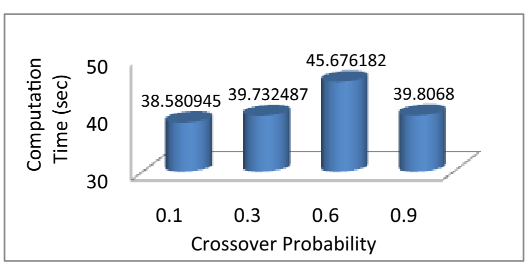

Fig. 9. Computation time vs. crossover probability for step size = 0.1.

A. Results for Normal Loading

The values of the IPFC parameters before and after tuning are mentioned in Table IV. Fig. 11 shows a marked improvement in voltage profile of the buses with optimally tuned IPFC.

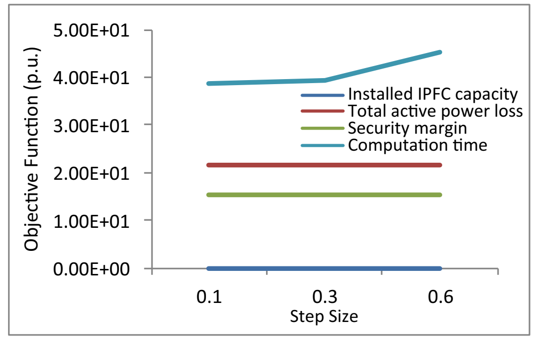

Fig. 10. Objective functions vs. step size for CR = 0.1.

Thus, the voltage deviation of the overall system is reduced. Table V shows a reduction in the values of all the objective functions by optimal placement of IPFC. Thus, it is established that by optimal tuning of IPFC using differential algorithm the system loss, voltage deviation, and security margin are reduced with the use of minimum capacity of IPFC. Reduction in loss helps in congestion management of the system. Reduction in security margin protects the system against collapse. The lower the capacity of IPFC the lower the cost is. Hence, the overall system performance is improved at a minimum cost. Table VI shows the effectiveness of IPFC in reduction of active and reactive power loss.

TABLE IV
IPFC PARAMETERS BEFORE AND AFTER TUNING FOR IEEE 30 BUS TEST SYSTEM UNDER NORMAL LOAD CONDITION

IPFC Parameters	Untuned IPFC	Tuning of IPFC Using DE
Vse_1 (p.u.)	0.0050	0.0011
Vse_2 (p.u.)	0.0100	0.0081
Θse_1 (degree)	−159.8295	180
Θse_2 (degree)	180	−174.1833

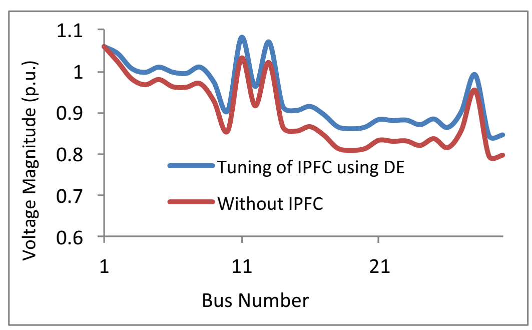

Fig. 11. Voltage profile without and with DE tuned IPFC.

B. Results for 110% Loading

Simulation has been performed for 110% load on IEEE 30 bus test system. It is observed that with 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; the results are presented in Table VII, VIII, and Table IX. Fig. 12 shows the improvement in voltage profile with optimal tuning and placement of IPFC.

TABLE V
REAL POWER LOSS, VOLTAGE DEVIATION SECURITY MARGIN AND TOTAL CAPACITY OF INSTALLED IPFC WITH UNTUNED AND WITH DE TUNED IPFC

Parameters	Untuned IPFC	Tuning of IPFC Using DE
Real power losses (MW)	21.909	21.4371
Voltage deviation of all buses (p.u.)	2.3889	2.3566
Security margin of all lines (p.u.)	18.2714	15.3378
Total capacity of installed IPFC (MVA)	0.000406	2.91e−7

TABLE VI
COMPARISON OF TOTAL REAL AND REACTIVE POWER LOSS IN THE SYSTEM WITHOUT IPFC, WITH UNTUNED IPFC AND WITH DE TUNED IPFC

Parameters	Without IPFC	Untuned IPFC	Tuning of IPFC Using Differential Algorithm
Real power losses (MW)	22.941	21.909	21.4371
Reactive power losses (MVar)	107.370	101.334	100.154

TABLE VII
IPFC PARAMETERS BEFORE AND AFTER TUNING FOR 110% LOAD CONDITION

IPFC Parameters	Untuned IPFC	Tuning of IPFC Using DE
Vse_1 (p.u.)	0.0050	0.0012
Vse_2 (p.u.)	0.0100	0.0033
Θse_1 (degree)	−140.1182	180
Θse_2 (degree)	180	−153.393

TABLE VIII
COMPARISON OF TOTAL REAL POWER LOSS AND REACTIVE POWER LOSS WITHOUT IPFC, WITH UNTUNED AND WITH DE TUNED

Parameters	Without IPFC	Untuned IPFC	Tuning of IPFC Using DE
Real power losses (MW)	27.806	26.294	26.079
Reactive power losses (MVar)	127.295	118.994	118.507

TABLE IX
COMPARISON OF REAL POWER LOSS, VOLTAGE DEVIATION SECURITY MARGIN AND TOTAL CAPACITY OF INSTALLED IPFC WITH UNTUNED AND WITH DE TUNED IPFC

Parameters	Untuned IPFC	Tuning of IPFC Using DE
Real power losses (MW)	26.294	26.079
Voltage deviation of all buses (p.u.)	2.4609	2.4557
Security Margin of all lines (p.u.)	19.4269	16.5855
Total capacity of installed IPFC (p.u.)	0.0002437	0.000157

C. Results for125% Loading

Simulation results for 125 % load on IEEE 30 bus system listed in Table X, XI, and XII show a marked reduction in the objective function values after optimal tuning of IPFC. It is observed that voltage deviation, security margin, capacity of installed IPFC, and real and reactive power loss further decreases. Comparisons of voltages are shown in Fig. 13, which shows that after incorporating the IPFC in the system, voltage profile is improved.

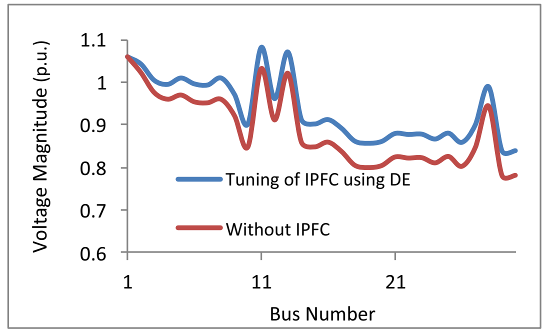

Fig. 12. Voltage profile without and with DE tuned IPFC under 110% load condition for IEEE 30 bus test system.

TABLE X
IPFC PARAMETERS BEFORE AND AFTER TUNING FOR 125% LOAD

IPFC Parameters	Untuned IPFC	Tuning of IPFC Using DE
Vse_1 (p.u.)	0.0050	0.0010
Vse_2 (p.u.)	0.0100	0.0079
Θse_1 (degree)	−167.9689	180
Θse_2 (degree)	180	−175.0117

TABLE XI
COMPARISON OF REAL POWER LOSS, VOLTAGE DEVIATION SECURITY MARGIN AND TOTAL CAPACITY OF INSTALLED IPFC WITH UNTUNED AND DE TUNED IPFC FOR 125% LOADING CONDITION

Parameters	Untuned IPFC	Tuning of IPFC Using DE
Real power losses (MW)	34.115	33.934
Voltage deviation of all buses (p.u.)	2.5861	2.5613
Security margin of all lines (p.u.)	21.2293	18.3804
Total capacity of installed IPFC (p.u.)	0.000245	0.00009827

TABLE XII
COMPARISON OF TOTAL REAL POWER LOSS AND REACTIVE POWER LOSS WITHOUT IPFC, WITH UNTUNED AND WITH DE TUNED IPFC

Parameters	Without IPFC	Untuned IPFC	Tuning of IPFC Using DE
Real power losses (MW)	36.074	34.115	33.934
Reactive power losses (MVar)	160.733	149.791	149.180

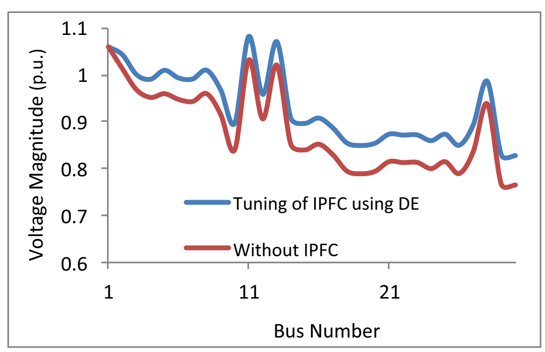

Fig. 13. Voltage profile without and with DE tuned IPFC.

VI. CONCLUSION

A disparity line utilization factor for the optimal placement of IPFC for congestion management has been proposed. The IPFC is accordingly placed in the lines with highest DLUF value. It is established that placement of IPFC using DLUF effectively reduces line congestion and power loss. A multi-objective function comprising 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 differential evolution algorithm. The proposed method is implemented for IEEE 30 bus test system. The results are presented and analyzed under normal loading, 110% loading, and 125% loading conditions to ascertain the effectiveness of the proposed method on the power system performance. It is observed that placement of IPFC by the proposed methodology causes an effective reduction in congestion in the lines.

The results of *LUF* calculation before and after the compensation process show reduction of loading in the congested line. Thus, it is found that placement of IPFC at the location where *DLUF* is maximum is the best location for the placement of IPFC in terms of reduction of congestion. Simulation results demonstrate the effectiveness and accuracy of the differential evolution algorithm technique to achieve the multiple objectives and to determine the optimal parameters of the IPFC under different loading conditions. A reduction in real power loss, voltage deviation, and security margin is achieved with much smaller capacity of installed IPFC. Reduction in loss helps in congestion management of the system. Reduction in security margin protects the system against collapse. The lower the capacity of IPFC, the lower is the cost. Hence, the overall system performance is improved at a minimum cost.

APPENDIX

CASE STUDY FOR IEEE 57 BUS TEST SYSTEM

An IEEE 57 bus test system is shown in Fig. A1 in which bus no. 1 is considered as a slack bus and bus nos. 2, 3, 6, 8, 9, 12 are considered as PV buses while all other buses are load buses. This system has 80 interconnected lines. *LUF* values of all the lines, without and with optimal placement of IPFC, are presented in Table AI. It is found that line connected between buses 14–46 (line 59) is the most congested line. All possible *DLUF* index calculation for line 14–46 are shown in Table AII as test cases.

Table AI shows that line 59 is the most congested line connected to load bus. In the 57 bus system, three lines have been connected to line 59. So, three test cases for IPFC placement are considered, as shown in Table AII. *DLUF* is calculated for each test case and it is observed that congestion in line 59 is reduced most when the second line used for IPFC placement is Line 13, and where the *DLUF* value is maximum. Hence, lines 59 and 13 have been selected for optimal placement of IPFC. It is observed from Table AII that placement of IPFC at the location where *DLUF* is maximum reduces the congestion in line 59 from 1.23 to 0.053. Table AIII shows that after the placement of IPFC using *DLUF*, line congestion, line losses, and voltage deviation and security margin are considerably reduced.

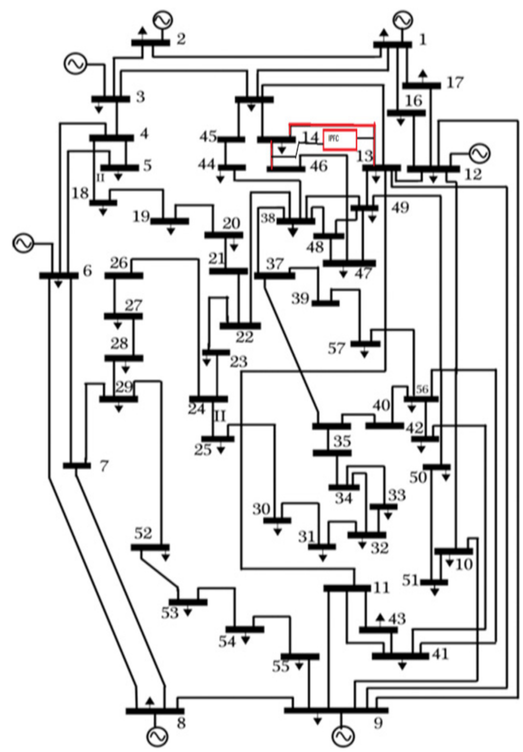

Fig. A1. IEEE 57 bus test system with IPFC installed at line connected between buses 14–46 and 13–14.

TABLE AI
LUF VALUES OF ALL LINES OF 57 BUS TEST SYSTEM WITHOUT AND WITH OPTIMALLY PLACED IPFC

Line No.	From Bus (SB No)	To Bus (RB No.)	*LUF* Without IPFC	*LUF* with Opt. Placed IPFC
1	1	2	2.2141	1.360
2	2	3	1.0286	1.047
3	3	4	0.6947	0.693
4	4	5	0.3229	0.322
5	4	6	0.2115	0.214
6	6	7	0.2522	0.164
7	6	8	0.5275	0.427
8	8	9	1.8483	1.830
9	9	10	0.1792	0.186
10	9	11	0.1904	0.164
11	9	12	0.1205	0.050
12	9	13	0.0897	0.046
13	13	14	0.3954	0.415
14	13	15	0.5226	0.624
15	1	15	1.7232	1.585
16	1	16	0.8385	0.834
17	1	17	0.9834	0.950
18	3	15	0.5463	0.382
19	4	18	0.3160	0.344
20	4	18	0.3160	0.344
21	5	6	0.8674	0.852
22	7	8	0.9475	0.787
23	10	12	0.2954	0.168
24	11	13	0.1092	0.091
25	12	13	0.8694	0.169
26	12	16	0.3787	0.358
27	12	17	0.5314	0.477
28	14	15	0.6985	0.629
29	18	19	0.0391	0.040
30	19	20	0.0079	0.006
31	21	20	0.0655	0.200
32	21	22	0.0249	0.200
33	22	23	0.1188	0.138

TABLE AI
(CONTINUED)

Line No.	From Bus (SB No)	To Bus (RB No.)	*LUF* Without IPFC	*LUF* with Opt. Placed IPFC
34	23	24	0.0565	0.078
35	24	25	0.1653	0.165
36	24	25	0.1653	0.165
37	24	26	0.6851	0.089
38	26	27	0.1095	0.089
39	27	28	0.2021	0.183
40	28	29	0.2578	0.237
41	7	29	0.6102	0.639
42	25	30	0.0840	0.083
43	30	31	0.0415	0.041
44	31	32	0.0257	0.026
45	32	33	0.0430	0.043
46	34	32	0.0834	0.094
47	34	35	0.0913	0.093
48	35	36	0.1591	0.159
49	36	37	0.2597	0.193
50	37	38	0.3742	0.235
51	37	39	0.0395	0.041
52	36	40	0.0389	0.035
53	22	38	0.1433	0.157
54	11	41	0.0930	0.109
55	41	42	0.1034	0.104
56	41	43	0.1302	0.133
57	38	44	0.2488	0.241
58	15	45	0.5156	0.381
59	14	46	1.2301	0.053
60	46	47	0.6038	0.636
61	47	48	0.2786	0.316
62	48	49	0.1220	0.119
63	49	50	0.0755	0.123
64	50	51	0.1785	0.120
65	10	51	0.9562	0.312
66	13	49	0.3884	0.293
67	29	52	0.2874	0.202
68	52	53	0.1184	0.140
69	53	54	0.1310	0.097
70	54	55	0.2471	0.141
71	11	43	0.2405	0.162
72	44	45	0.3737	0.362
73	40	56	0.0415	0.035
74	56	41	0.0595	0.061
75	56	42	0.0148	0.017
76	39	57	0.0376	0.041
77	57	56	0.0320	0.030
78	38	49	0.1835	0.054
79	38	48	0.3734	0.298
80	9	55	0.3367	0.227

TABLE AII
DLUF VALUE CALCULATION FOR LINE 59 OF 57 BUS TEST SYSTEM

Sl. No.	Line 1 SB No–RB No.	Line 2 SB No–RB No.	*LUF* Line 1	*LUF* Line 2	*DLUF*	*LUF* Line 1 with IPFC
Case 1	14–46	46–47	1.230	0.603	0.627	0.166
Case 2	14–46	14–15	1.230	0.698	0.532	0.160
Case 3	14–46	13–14	1.230	0.395	0.834	0.053

TABLE AIII
REAL AND REACTIVE POWER LOSS, VOLTAGE DEVIATION SECURITY MARGIN WITHOUT AND WITH IPFC FOR NORMAL LOADING

Parameters	Without IPFC	Optimal Placement of IPFC
Real power losses (MW)	42.258	38.11
Voltage deviation of all buses (p.u.)	6.4029	5.06
Security margin of all lines (p.u.)	25.0588	24.83
Reactive power loss (MVar)	166.112	146.724

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