Disparity Line Utilization Factor Based Optimal Placement of IPFC for Congestion Management

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DOI: 10.15598/aeee.v14i2.1546

Abstract. *Recently, due to the adoption of power reforms, there is a marked increase of contracted power that flows in the transmission line and also the spontaneous power exchanges leading to complex power transmission congestion problems. The appearance of Flexible AC Transmission Systems (FACTS) devices specifically Interline Power Flow Controller (IPFC) has opened up new opportunities to overcome the congestion problem by increasing the possible system load. Hence, the optimal placement of FACTS devices is deservedly an issue of great importance. 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 proposed method is implemented for IEEE–14 and IEEE-57 bus test system. The IPFC is placed in all possible line combinations of IEEE-14 bus system to check the validity of the proposed methodology. To confirm the generality of the proposed method, the technique is also implemented and verified for IEEE-57 bus test system. An increased load of 110 % and 125 % is applied, and the results are presented and analysed in detail to establish the effectiveness of the proposed methodology.*

Keywords

Congestion, interline power flow controller, line utilization factor, optimal placement.

1. Introduction

Lately, the deregulated electric power industries have changed the way of operation, structure, ownership and management of the utilities. There is a huge enhancement of spontaneous power exchanges. More power is scheduled or flows across the transmission lines and transformers than the physical limits of those lines, which is the primary cause of congestion in transmission lines [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. It is, therefore, necessary to improve power delivery of system by reducing power loss in the interconnected electric power system. Many attempts have been made by researchers recently to improve the power transfer capability of the existing network [2], [3].

The concept of Flexible AC Transmission Systems (FACTS) devices was introduced by Hingorani [4] and they have been found very successful in solving various power system issues [5]. Several authors [6], [7] have proposed a sensitivity based approach for optimizing the location of FACTS devices for congestion management by controlling the device parameters. Kumar et al. [8] have used a sensitivity based approach for zonal/cluster-based congestion management. Acharya et al. [9] have proposed two new methodologies for the placement of series FACTS devices for congestion management. The overall objective of FACTS device placement can be minimization of the total congestion rent or maximization of social welfare.

Samimi et al. [10] have proposed a method to determine optimal location and best setting of Thyristor Controlled Series Compensator (TCSC). Seeking the best place is performed using the sensitivity analysis and optimum setting of TCSC is managed using the genetic algorithm. Yousufi et al. [11] have proposed a combination of Demand Response (DR) and Flexible Alternating Current Transmission System (FACTS) devices for congestion management. Esmaili et al. [12] have proposed optimization of total operating cost, voltage and transient stability margins for optimal placement and sizing of FACTS devices for congestion management. Hooshmand et al. [13] considered non-smooth fuel cost-function and penalty cost of emission for optimal placement of TCSC to manage congestion. Esmaili et al. [14] have used Real Power Performance Index (RPPI) and reduction of total system VAR power losses for optimal placement of TCSC. Ushasurendra et al. [15] have proposed Line Utilization Factor (LUF) for optimal placement of FACTS devices for congestion management. RPPI is based only on the real power flowing through a line, whereas, LUF takes into consideration the apparent power that flows in the line. Hence, LUF is chosen for the study. Line Utilization Factor has been used for the determination of congestion of a single transmission line. FACTS devices are placed on the transmission line with maximum LUF value. However, IPFC is a multiline series FACTS device [16]. In its simplest form it consists of at least two converters required to be placed on two transmission lines with a common bus. The 1st converter of IPFC can be placed on the line with maximum LUF. But the placement of the other converter is an issue which becomes more and more complex with the increase in the size of the system, number of IPFC's and the complexity of IPFC. Hence, LUF is not a sufficient index for obtaining the location for placement of IPFC.

In this paper, the difference of Line Utilization Factors between two lines has been used for determination of the optimal location of IPFC. The IPFC is placed in the lines with a maximum value of DLUF to reduce congestion. The effect of IPFC placement on the active and reactive power of the power system is also studied under different loading conditions. The proposed method is implemented and tested on IEEE-14 and IEEE-57 bus system for different loading conditions.

2. Modelling of IPFC

An IPFC consists of at least two back to back DC-AC converters connected by a common DC link [17], [18]. V_i, V_j, V_k are complex voltages at bus-i, j, k respectively. $V_l = V_l \llcorner \Theta_l$ ($l = i, j, k$) and V_l, Θ_l are the magnitude and angle of V_l. Vse_{in} is the complex controllable, series injected voltage source. It shows the series compensation of the series converter. Vse_{in} is given by $Vse_{in} = Vse_{in} \llcorner \Theta se_{in}$ ($n = j, k$). Vse_{in} and Θse_{in} are the magnitude and angle of Vse_{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. Zse_{in} is the series transformer impedance. Pse_{in} is the active power exchange of each converter via the common DC link. P_i and, Q_i as given in equations Eq. (1) and Eq. (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 equation Eq. (3) and Eq. (4). I_{ji}, I_{ki} are the IPFC branch currents of branch $j - i$ and $k - i$ leaving bus-j and k, respectively.

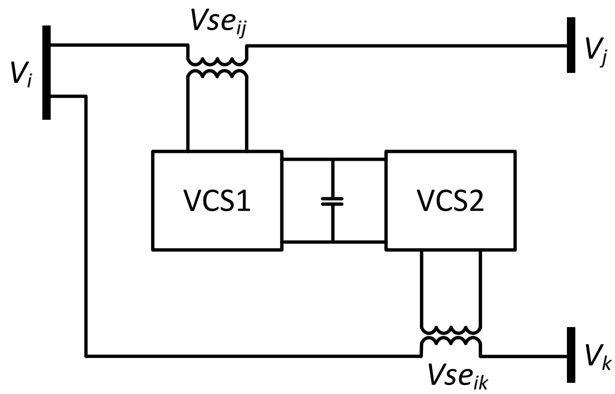

Fig. 1: Basic model of IPFC.

In Eq. (1), Eq. (2), Eq. (3) and Eq. (4) are:

- $n = j, k$,
- $g_{in} + jb_{in} = \dfrac{1}{zse_{in}} = yse_{in}$,
- $g_{nn} + jb_{nn} = \dfrac{1}{zse_{in}} = yse_{in}$,
- $g_{ii} = \sum\limits_{n=j,k} g_{in}$,
- $b_{ii} = \sum\limits_{n=j,k} b_{in}$.

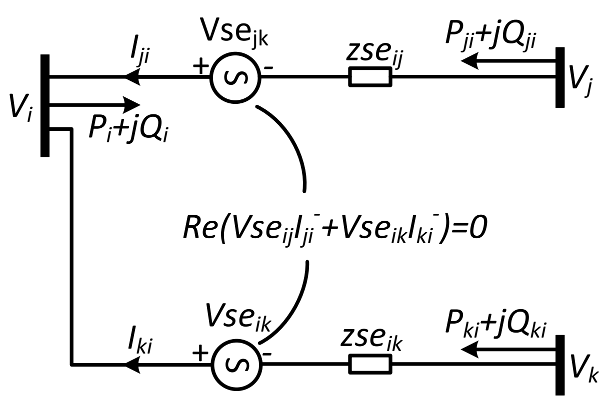

Fig. 2: Equivalent circuit of IPFC.

$$\begin{aligned}P_i &= V_i^2 b_{ii} - \sum_n V_i V_n \left[g_{in}\cos\left(\Theta_i - \Theta_n\right) + b_{in}\sin\left(\Theta_i - \Theta_n\right)\right] \\ &- \sum_n V_i Vse_{in}\left[g_{in}\cos\left(\Theta_i - \Theta se_{in}\right) + b_{in}\sin\left(\Theta_i - \Theta se_{in}\right)\right].\end{aligned} \quad (1)$$

$$\begin{aligned}Q_i &= -V_i^2 b_{ii} - \sum_{n=j,k} V_i V_n \left[g_{in}\sin\left(\Theta_i - \Theta_n\right) - b_{in}\cos\left(\Theta_i - \Theta_n\right)\right] \\ &- \sum_{n=j,k} V_i Vse_{in}\left[g_{in}\sin\left(\Theta_i - \Theta se_{in}\right) - b_{in}\cos\left(\Theta_i - \Theta se_{in}\right)\right].\end{aligned} \quad (2)$$

$$\begin{aligned}P_{ni} &= V_n^2 g_{nm} - V_i V_n \left[g_{in}\cos\left(\Theta_n - \Theta_i\right) + b_{in}\sin\left(\Theta_n - \Theta_i\right)\right] \\ &+ V_n Vse_{in}\left[g_{in}\sin\left(\Theta_n - \Theta se_{in}\right) - b_{in}\cos\left(\Theta_n - \Theta se_{in}\right)\right].\end{aligned} \quad (3)$$

$$\begin{aligned}Q_{ni} &= -V_n^2 b_{nm} - V_i V_n \left[g_{in}\sin\left(\Theta_n - \Theta_i\right) - b_{in}\cos\left(\Theta_n - \Theta_i\right)\right] \\ &+ V_n Vse_{in}\left[g_{in}\sin\left(\Theta_n - \Theta se_{in}\right) - b_{in}\cos\left(\Theta_n - \Theta se_{in}\right)\right].\end{aligned} \quad (4)$$

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

$$Re\left(Vse_{ij} I_{ji}^* + Vse_{ik} I_{ki}^*\right) = 0, \quad (5)$$

where the superscript $*$ denotes the complex conjugate.

3. Disparity Line Utilization Factor

Line Utilization Factor is an index used for determining the congestion of the transmission lines. It is given by Eq. (6):

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

where LUF_{ij} - 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} - 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.

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 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 highest congestion. All the line pairs connected to the same bus are ranked on the basis of DLUF. The line set that has highest value of DLUF is considered to be the optimal location of IPFC for Congestion Management. Assuming both lines of same rating:

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

where $DLUF_{(ij)-(ik)}$ - Disparity Line Utilization Factor (DLUF) of the line set ij and ik, MVA_{ij} - MVA rating ofthe line between bus-i and bus-j, $MVA_{\max}$ - maximum MVA rating of line, MVA_{ik} - actual MVA rating of the line between bus-i and bus-k.

Step by Step Procedure:

- STEP I – Read the line data and bus data.
- STEP II – Calculate the power flow and LUF of all lines
- STEP III – Calculate the DLUF values for all lines in pair wit the lines ranking highest in congestion.
- STEP IV – Place IPFC on the lines having highest value of DLUF.

Tab. 1: DLUF value calculation for line 4-5 of 14 bus test system.

Case	Line 1, SB No., RB No.	Line 2, SB No., RB No.	LUF Line1	LUF Line 2	DLUF	LUF of Line 1 with IPFC
1	4-5	4-7	0.5951	0.2851	0.1313	0.8374
2	4-5	4-9	0.5951	0.1849	0.3511	0.8370

- STEP V – Perform the load flow analysis and calculate the LUF of all lines.

4. Results and Discussion

4.1. IEEE-14 Bus System

An IEEE-14 bus test system has 4 generator buses, 9 load buses and 20 transmission lines. Bus 1 is the slack bus. Bus number 2, 3, 6, 8 are the generator buses as shown in Fig. 3. The remaining buses are the load buses. System base MVA is 100. An IPFC consisting of two converters has been used in the study. The inductive reactance and resistance of the coupling transformers are assumed to be 0.001 p.u. The voltage magnitude of the two converters of the IPFC is taken in the range $0 \leq V_{se} \leq 0.1$ and the angle is taken in the range $-\Pi \leq \Theta_{se} \leq \Pi$. Only load buses have been considered for IPFC placement.

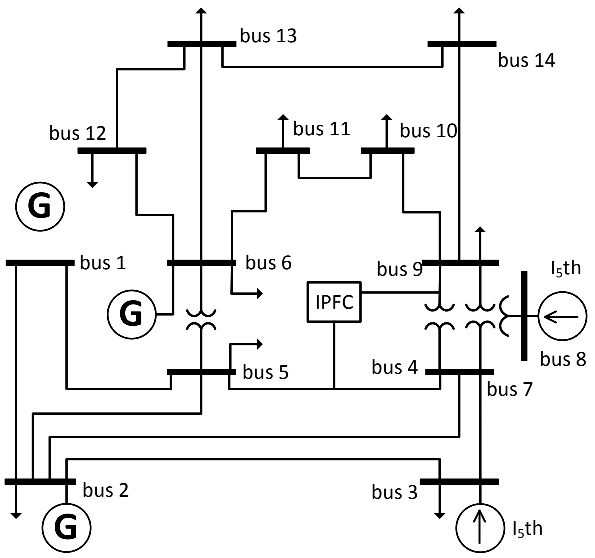

Fig. 3: IEEE-14 bus test system with IPFC installed at line connected between buses 4–5 and 4–9.

Table 2 displays the LUF values of all lines without IPFC and with IPFC. It is observed that the line connected between buses 4 and 5, with highest value of LUF is the most congested line. The line connected between buses 4–7 and buses 4–9 have been connected to the line 4-5 through a common bus. In Tab. 1 the value of DLUF has been calculated for the two possible options of IPFC placement. It is observed from Tab. 1 that the line pair (4–5) and (4–9) have the maximum value of DLUF. Hence, the IPFC is proposed to be located at line 4–5 and 4–9. In order to prove that the proposed location is the best location for the placement of IPFC, the device is placed in all possible locations of the transmission system and the results have been presented in Tab. 3. It is observed from Tab. 3 and Fig. 4 that congestion in the line 4–5 is reduced most effectively when IPFC is placed on line 4–5 and 4–9 which is the location being proposed for optimal placement. Thus, it is verified that for reduction of congestion, the 1st converter of IPFC has to be placed on the most congested line (maximum LUF) while the 2nd converter has to be placed on the line that has maximum DLUF value with respect to the 1st line. The active power loss is also reduced at this location, although it may

Tab. 2: LUF values of all lines without and with IPFC.

From Bus	To Bus	LUF without IPFC	LUF with IPFC at proposed location
2	5	0.4601	0.4417
3	4	0.3001	0.2623
4	5	0.5951	0.5787
4	7	0.2851	0.2802
4	9	0.1849	0.1598
5	6	0.5338	0.5713
6	11	0.2661	0.2908
6	12	0.2562	0.257
6	13	0.7323	0.7380
7	8	0.3724	0.4481
7	9	0.4853	0.4729
9	10	0.0763	0.0925
9	14	0.3556	0.3331
10	11	0.1326	0.1550
12	13	0.1159	0.1184
13	14	0.2405	0.2546

Tab. 3: Placement of IPFC at all possible locations in the IEEE-14 bus test system.

S. No.	Location of IPFC on Line Pair	LUF of line 7	Total Active power loss
1.	7, 8	0.5820	22.313
2.	7, 9	0.5787	20.140
3.	8, 9	0.5980	22.368
4.	9, 16	0.8020	20.376
5.	9, 17	0.8020	20.383
6.	15, 16	0.8030	21.923
7.	15, 17	0.8030	21.929
8.	16, 18	0.7690	22.540
9.	17, 20	0.8050	21.929
10.	19, 20	0.8400	21.539

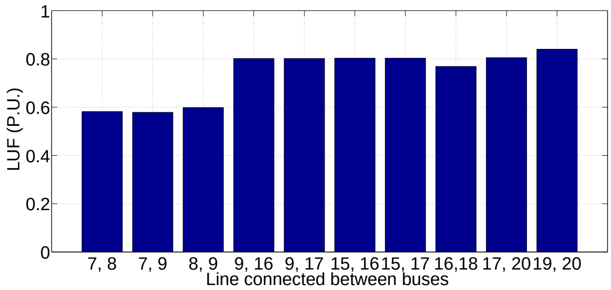

Fig. 4: LUF of line connected between buses 4–5 after placement of IPFC at all feasible locations of IEEE-14 bus test system.

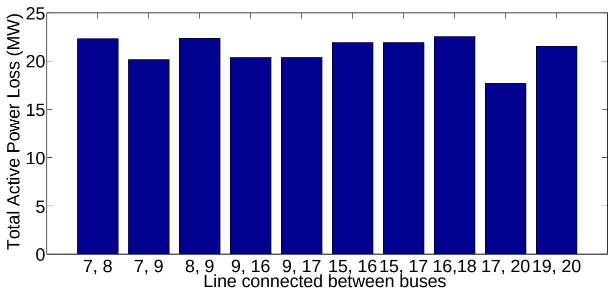

Fig. 5: Active power loss in IEEE-14 bus system after placement of IPFC at all feassible locations.

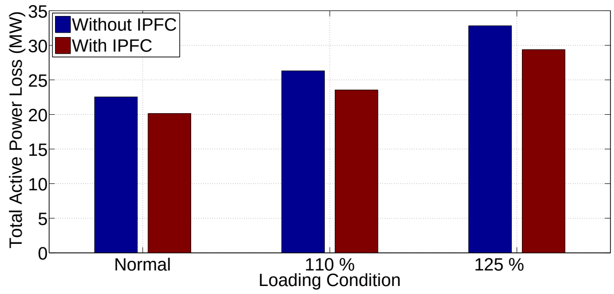

Fig. 6: Real power loss without and with IPFC for normal, 110 % and 125 % load.

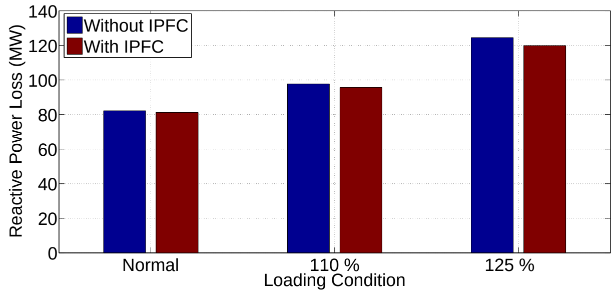

Fig. 7: Reactive power loss without and with IPFC for normal, 110 % and 125 %.

not achieve its minimum value as observed from Fig. 5. The next best location for IPFC placement, in terms of reduction of congestion, is line 4–5 and 4–7 where the value of DLUF is smaller in comparison to the proposed location.

Next, the load on the transmission system has been increased by 10 % and 25 % and the results have been presented in Tab. 4. It shows the improvement in active and reactive power loss with placement of IPFC at the proposed location at both normal and increased loading condition. The total active and reactive power loss for different loading conditions have been shown in Fig. 6 and Fig. 7 respectively.

Tab. 4: Active power loss and reactive power loss without and with optimally placed IPFC for normal, 110 % and 125 % loading condition.

Loading cond.	Real power loss		Reactive power loss	
	Without IPFC	With IPFC	Without IPFC	With IPFC
Normal	22.545	20.140	82.171	81.171
110 %	26.313	23.533	97.658	95.650
125 %	32.828	29.385	124.490	119.850

4.2. IEEE-57 Bus System

From the results obtained for IEEE-14 bus system, it is clear that the 1st converter of the IPFC has to be placed on the most congested line while the location of the 2nd converter of the IPFC should be on the line with maximum DLUF with respect to the most congested line to obtain maximum LUF reduction. In order to confirm the validity and generality of the proposed method, the concept of optimal placement of IPFC using DLUF is verified again for an IEEE-57 bus test system. An IEEE-57 bus test system is considered. In an IEEE-57 bus system 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 as shown in Fig. 8. LUF values of all the lines without and with Optimal placement of IPFC has been presented in Tab. 5. It is established that line connected between buses 14–46 (line 59) is the most congested line. All possible DLUF index calculations for line 14–46 have been shown in Tab. 6 as test cases. It is observed from Tab. 5, line 14–46 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 have been considered, as shown in Tab. 6 DLUF has been calculated for each test case and it is observed that congestion in line 14–46 is reduced most when the line-2 used for IPFC placement is Line 13–14 where the DLUF value is maximum. Hence, lines 14–46 and 13–14 have been selected for optimal placement of IPFC. It is observed from Tab. 6 that placement of IPFC at the location where DLUF is maximum causes a maximum reduction in congestion in line 14–46.

It is observed from Fig. 9 that optimal placement of IPFC reduces congestion in line 14–46 (line no. 59)

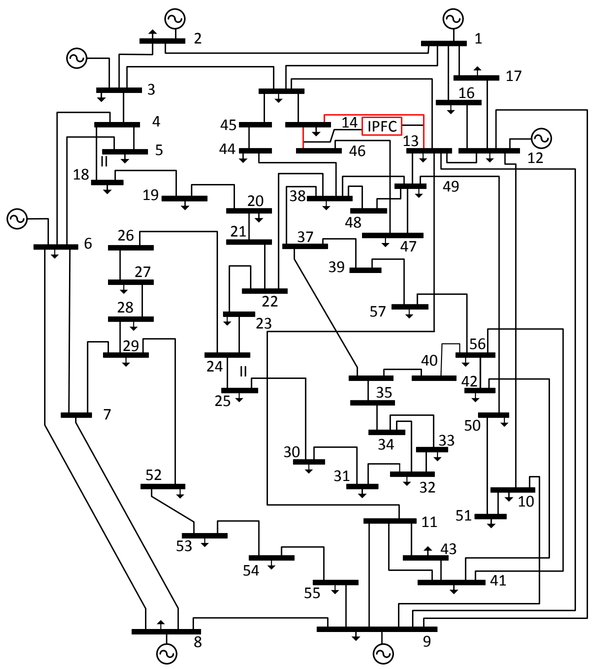

Fig. 8: IEEE-57 Bus test system with IPFC installed at line connected between buses 14–46 and 13–14.

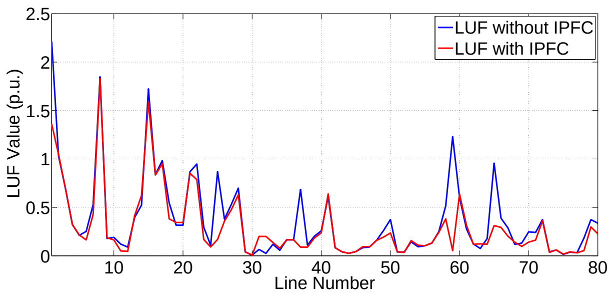

Fig. 9: Comparison of LUF values with and without IPFC with normal load.

and in the other lines in the system. Fig. 10 shows a marked improvement in voltage profile of the buses. It is observed from Tab. 7 that after the placement of IPFC using DLUF, line losses are considerably reduced.

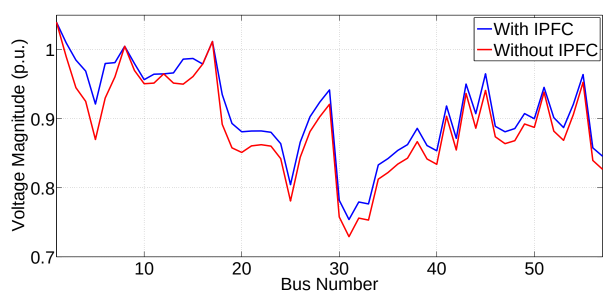

Fig. 10: Voltage profile without and with IPFC.

Simulation has been performed for 110 % and 125 % load on IEEE-14 and 57 bus test system. It is observed from Tab. 7 and Fig. 11 and Fig. 12 that with increase in load the total real and reactive power loss increases. Placement of IPFC by the proposed method seems to be an effective method for reduction of the above parameters even in increased loading condition.

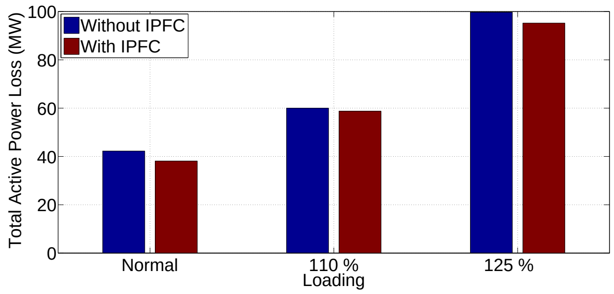

Fig. 11: Real power loss without and with IPFC for normal, 110 % and 125 % load.

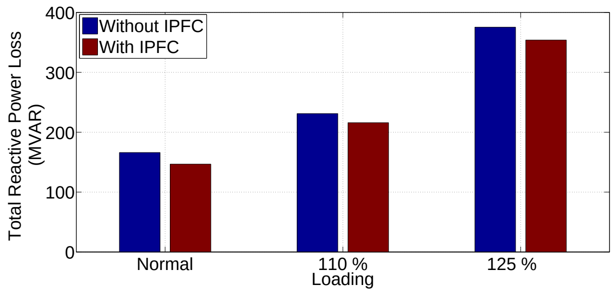

Fig. 12: Reactive power loss without and with IPFC for normal, 110 % and 125 % load.

5. Conclusions

In this paper, a Disparity Line Utilization Factor for the optimal placement of IPFC for congestion management has been implemented. The IPFC is being placed in the lines with highest DLUF value. It has been established that placement of IPFC using DLUF effectively reduces line congestion and active and reactive power loss simultaneously. The proposed method has been verified and implemented for IEEE-14 and IEEE-57 bus test system using MATLAB Software. It is observed that the placement of IPFC by the proposed methodology causes an effective reduction in congestion in the lines. The result of LUF value before and after placement of IPFC shows reduction of loading in congested line. Comparison of results with other locations ensures that placement of IPFC at the proposed location is a healthy location for the placement of IPFC in terms of reduction of congestion. A reduction in Real and reactive power loss has also been observed. Hence, the overall system performance has been studied under different loading conditions and the results are found to be favourable.

Tab. 5: Comparison of 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	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	41.	7	29	0.6102	0.639
2.	2	3	1.0286	1.047	42.	25	30	0.0840	0.083
3.	3	4	0.6947	0.693	43.	30	31	0.0415	0.041
4.	4	5	0.3229	0.322	44	31	32	0.0257	0.026
5.	4	6	0.2115	0.214	45.	32	33	0.0430	0.043
6.	6	7	0.2522	0.164	46.	34	32	0.0834	0.094
7.	6	8	0.5275	0.427	47.	34	35	0.0913	0.093
8.	8	9	1.8483	1.830	48.	35	36	0.1591	0.159
9.	9	10	0.1792	0.186	49.	36	37	0.2597	0.193
10.	9	11	0.1904	0.164	50.	37	38	0.3742	0.235
11.	9	12	0.1205	0.050	51.	37	39	0.0395	0.041
12.	9	13	0.0897	0.046	52.	36	40	0.0389	0.035
13.	13	14	0.3954	0.415	53.	22	38	0.1433	0.157
14.	13	15	0.5226	0.624	54.	11	41	0.0930	0.109
15.	1	15	1.7232	1.585	55.	41	42	0.1034	0.104
16.	1	16	0.8385	0.834	56.	41	43	0.1302	0.133
17.	1	17	0.9834	0.950	57.	38	44	0.2488	0.241
18.	3	15	0.5463	0.382	58.	15	45	0.5156	0.381
19.	4	18	0.3160	0.344	59.	14	46	1.2301	0.053
20.	4	18	0.3160	0.344	60.	46	47	0.6038	0.636
21.	5	6	0.8674	0.852	61.	47	48	0.2786	0.316
22.	7	8	0.9475	0.787	62.	48	49	0.1220	0.119
23.	10	12	0.2954	0.168	63.	49	50	0.0755	0.123
24.	11	13	0.1092	0.091	64.	50	51	0.1785	0.120
25.	12	13	0.8694	0.169	65.	10	51	0.9562	0.312
26.	12	16	0.3787	0.358	66.	13	49	0.3884	0.293
27.	12	17	0.5314	0.477	67.	29	52	0.2874	0.202
28.	14	15	0.6985	0.629	68.	52	53	0.1184	0.14
29.	18	19	0.0391	0.040	69.	53	54	0.1310	0.097
30.	19	20	0.0079	0.006	70.	54	55	0.2471	0.141
31.	21	20	0.0655	0.200	71.	11	43	0.2405	0.162
32.	21	22	0.0249	0.200	72.	44	45	0.3737	0.362
33.	22	23	0.1188	0.138	73.	40	56	0.0415	0.035
34.	23	24	0.0565	0.078	74.	56	41	0.0595	0.061
35.	24	25	0.1653	0.165	75.	56	42	0.0148	0.017
36.	24	25	0.1653	0.165	76.	39	57	0.0376	0.041
37.	24	26	0.6851	0.089	77.	57	56	0.0320	0.030
38.	26	27	0.1095	0.089	78.	38	49	0.1835	0.054
39.	27	28	0.2021	0.183	79.	38	48	0.3734	0.298
40.	28	29	0.2578	0.237	80.	9	55	0.3367	0.227

Tab. 6: DLUF value calculation for line 14–46 of 57 bus test system.

Case	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
1	14–46	46–47	1.230	0.603	0.627	0.166
2	14–46	14–15	1.230	0.698	0.532	0.160
3	14–46	13–14	1.230	0.395	0.834	0.053

Tab. 7: Active power loss and reactive power loss without and with optimally placed IPFC for normal, 110 % and 125 % loading condition.

Loading condition	Real power loss		Reactive power loss	
	Without IPFC	With IPFC	Without IPFC	With IPFC
Normal	42.258	38.110	166.112	146.724
110 %	59.989	58.736	231.139	215.918
125 %	99.721	95.216	375.397	353.829

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