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Research Article

A UPFC based Optimal Power Flow of an Integrated Power System

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Abstract:

The geopolitical landscape of the world has made it abundantly evident how important energy resources are and how best to use them on Earth. The ultimate consumers of electrical energy benefit from an additional benefit of lower costs due to resource optimization. In this paper a multi-objective optimal power flow (OPF) for an integrated power system in the presence of FACTS devices has been proposed. The selection of the multi-objective function makes this paper unique. Minimizing Negative Social Welfare (NSW) voltage variation and power loss are part of the objective function. Lower loss and NSW's guarantee of lower electricity costs per unit at the customer's end result in higher customer satisfaction. The Unified Power Flow Controller (UPFC) is the FACTS device utilised to solve the issue. An IEEE 57 bus system has been used to test the hypothesis. The objective function has been optimized by applying the Mouth Flame Optimisation Algorithm.

1. Introduction

India is an over populated country with rising energy needs. The country's transmission routes are under more strain now that the power business has been deregulated. As a result, optimizing power flow has become crucial in the power industry. To get HVDC efficiency FACTS Devices can be included in the AC Transmission System. To get around congestion in hydrothermal systems, M.O. Lawal and colleagues [1] proposed an optimal power flow method. It is possible to increase power plant output as a form of punishment by tracking power flows to determine which plants are causing line congestion. It is required to correct the utmost power of affected generators to relieve congestion. I. Batra et al. [2] included the TECM-PSO method's enhanced twin extremity mapping of the chaotic map to solve the congestion management problem in derestricted Power systems. The problem has been resolved. For their consideration of emergency wind and heat generator use, Teeparthi et al. [3] utilized the PSO-APO method. FACTS devices have proven effective in resolving power system issues [4]. Visakha et al. suggested a technique in [5] for installing a UPFC at the appropriate location even though planning for contingencies. Nusair et al. [6] have optimised the power flow of a power system with renewable systems in the presence of TCSC. Authors have carried out OPF in the presence of FACTS devices in order to cut costs [7]. In order to reduce expenses, optimal power flow for an integrated system with FACTS Devices Thyristor Controlled Series Compensator and Unified Power Flow Controller present has been carried out by the authors [8].

Appropriate FACTS device deployment and calibration are necessary to meet the different power system issues. With IPFC, power system congestion and backup problems have been effectively addressed [9, 10]. An IPFC has several terminals, therefore each IPFC converter needs to have its appropriate location planned [11]. In [12], a contingency analysis based on a voltage index has been developed. Kumar et al. [13] have proposed an IPFC placement strategy based on cat swarm optimisation with the aim of improving voltage stability. Verma et al. [14] recommended location of FACTS devices for voltage stability.

Integrated power systems have been the subject of research on FACTS device control. Apart from technical issues such as voltage enhancement, recommendations have been made in the placement and dimensions of FACTS devices to maximise social welfare, reduce load shedding costs, and construct more branches. It has been observed that applying optimisation is more appropriate in the case of boosting social welfare. [15,16] created and effectively examined a combination of ideal power flow, FACTS placement and tuning for a objective function.

An integrated power system overall power function with numerous objectives is presented in this study. Wind turbines, solar panels, and conventional generators create the transmission network. Optimization maximizes societal welfare while decreasing losses and voltage volatility. Since the goal function minimizes, social welfare has declined. The goals have been achieved using three methods. OPFs were originally built to serve the integrated system's multi-objective purpose. The next stage is finding the optimum index-based power system UPFC placement. Using an index the optimal location for the Unified Power Flow Controller has been identified in the power system.

The UPFC is being adjusted to its best potential to meet the goals. Integrated system has been optimized once more to evaluate the system's power and conduct a contingency analysis. The data given and analysed highlights the system's robustness under unstable operation conditions. For the purpose of the study, an IEEE 57 test bus system and Moth Flame optimization (MFO) Algorithm were implemented.

Moth Flame Optimization

Nature served as the inspiration for this optimization concept. An algorithm based on the moths' nocturnal navigation approach was developed. A constant tilt toward the moon governs the moths' movement. The moths will often spin around the lights as well. Presumably, the moths represent the answer to the multi-objective function. Moth location is one among the factors in the problem. The catalogue of mathematical models that have been applied to the study of moth behavior.

$$M_i = S(M_i, F_j) \quad (1)$$

M_i is the symbol for the i-th moth, Fj is the expression for the j-th flame, and S is the symbol for the spiral function. In light of these considerations, we offer the following definition for the logarithmic spiral that is utilized by the MFO algorithm

$$S(M_i, F_I) = D_i . e^{bt} . \cos(2\pi t) + F_j \quad (2)$$

b specifies the logarithmic spiral, D_i represents the distance between the i-th moth and the j-th falme, and t is a random value between -1 and 1. All variables are described by this equation. M_i is the ith flame, while D_i is the distance between flames and the moth.

2. Proposed Methodology

Multi Objective Function

The following research objectives are included in the multi-objective function that is being minimized.

Objective 1- Negative Social Welfare

Negative Social Welfare in power systems is used to highlight the importance of avoiding actions or policies that reduce the overall economic well-being of society. By focusing on optimizing market efficiency, accounting for externalities, and ensuring equitable resource allocation, power system operators and policymakers aim to maximize social welfare, thereby ensuring that the benefits of electricity generation and consumption are maximized for society. Minimizing a negative value means it maximizes social welfare.

$$NSW = \sum_{i=1}^{NG} C_i(P_{Gi}) - \sum_{j=1}^{ND} B_j(P_{Dj}) \quad (3)$$

$$C(P_g) = \sum_{i=1}^{n} a_{gi}P_{gi}^2 + b_{gi}P_{gi} + c_{gi} \quad (4)$$

$$B(P_d) = \sum_{i=1}^{n} a_{di}P_{di}^2 + b_{di}P_{di} + c_{di} \quad (5)$$

Objective 2- Minimization of Power Loss

$$F_2 = \sum_{k=1}^{NT} G_{k(i,j)}[V_i^2 + V_j^2 - 2V_iV_j\cos(\delta_{ij})] \quad (6)$$

Where, V_i, V_j= i,j voltage in p.u.

Objective 3- Minimization of Voltage deviation:

Only by continuously monitoring the voltage profile and minimising the voltage collapse that causes significant voltage spikes can an appropriate voltage profile be achieved.

The objective of the function for reducing voltage deviation is:

$$F_3 = \sum_{i=1}^{N_B} \| V_m - 1 \| \quad (7)$$

V_m- Voltage at bus m and N_b – Number of buses

Constraints:

$$\sum_{i=1}^{NG} P_{Gi} + WP - P_{Loss} - P_L = 0 \quad (8)$$

$$P_{Loss} = \sum_{j=1}^{N_{TL}} G_j[|V_i|^2 + |V_j|^2 - 2|V_i||V_j|\cos(\delta_i - \delta_j)] \quad (9)$$

7.

$$P_i - \sum_{k=1}^{N_b} |V_i V_k Y_{ik}| \cos(\theta_{ik} - \delta_i + \delta_k) = 0 \quad (10)$$

$$Q_i - \sum_{k=1}^{N_b} |V_i V_k Y_{ik}| \sin(\theta_{ik} - \delta_i + \delta_k) = 0 \quad (11)$$

Inequality Constraints:

$$V_i^{\min} \le V_i \le V_i^{\max} \quad (12)$$

$$\phi_i^{\min} \le \phi_i \le \phi_i^{\max} \quad (13)$$

$$TL_1 \le TL_1^{\max} \quad (14)$$

$$P_{Gi}^{\min} \le P_{Gi} \le P_{Gi}^{\max} \quad (15)$$

$$Q_{Gi}^{\min} \le Q_{Gi} \le Q_{Gi}^{\max} \quad (16)$$

Proposed Methodology

Optimal Power Flow (OPF) problem is solved with multi objectives stepwise as following:

1. Renewable energy sources Solar and Wind are placed at bus numbers 9 & 12 instead of thermal generators
2. The optimal power flow is performed for the multi objective function.
3. The Placement of Unified Power Flow Controller is done based on L-Index
4. The L-Index calculate the factual state of stability of the system with refer to its stability limit. It calculates the whole system stability.

$$L = \max_{j\varepsilon\alpha_l}\{L_j\} = \max_{j\varepsilon\alpha_l}\left|1 - \frac{\sum_{i\varepsilon\alpha G} E_{ji}V_i}{V_j}\right| \quad (17)$$

Where α_L- Load bus & α_G - generator bus.

The L-Index value will be in between 0 to 1.

At no load L = 0 while at a point near voltage collapse it is 1.

5. optimal power flow and UPFC tuning Were carried out for the multi-objective function.
6. The strength of the system is examined under line-outage conditions.

3. Results and Discussions

IEEE 57 Bus System

In the following IEEE 57 Test bus system: number of transmission lines- 80, number of generator buses-6, slack bus -1 and number of load buses-50 represented in figure 1. For the placement of UPFC Only load buses have been considered. Renewable energy sources Solar and Wind are placed at bus numbers 9 &12 instead of thermal generators. In the table 1, Test bus system generation reallocation Values and Multi Objective function Parameters are shown. Negative Social welfare is represented with OF_1, Voltage Deviation is represented with OF_2, Active power loss is represented with OF_3 and Multi-objective Optimization is represented with OF4. Table-1 shows that OF1 obtains the optimum value of NSW; OF2 obtains the least voltage deviation of 1.2 p.u; and OF3 achieves the smallest active power loss of 4.24 MW, four objectives have been reasonably optimized. Each of the study's objectives has been given equal weight, though this can be altered based on needs.

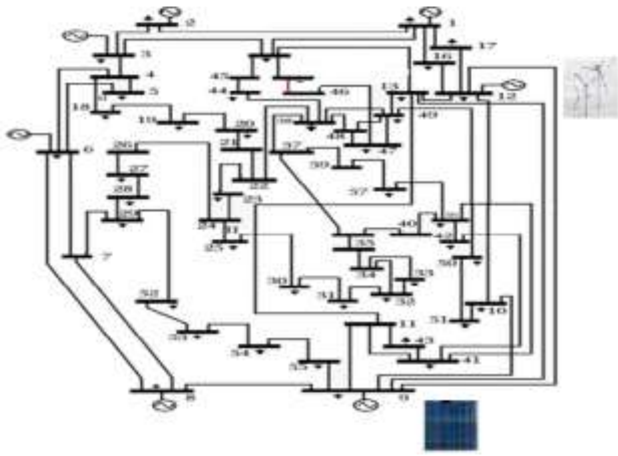

Figure 1. *IEEE 57 Bus System Modified*

According to table 2, Bus 33 has the second weak L-index after Bus 31. Tables 3 show the results after UPFC was implemented at bus 31.

Figure 2 compares L-index without and with UPFC. The L-index of severe lines has lowered with UPFC installation. For the mentioned system, a contingency analysis is performed. Table 4 shows the most severe cases and the lines most affected by the earlier situations. The most severe contingencies are on lines 24-26, 26-27, and 15-45, affecting 31 buses. Table 5 compares the line power flows under each of these contingency conditions. The OPF for the line 24-26 under contingency is shown in table 6.

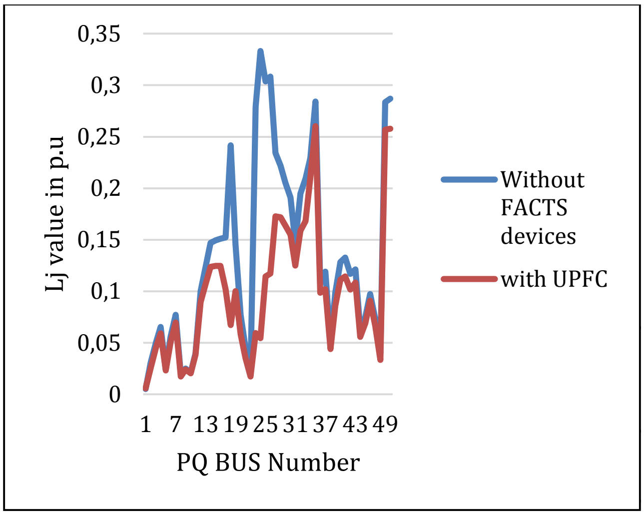

Figure 2. *Comparison of L-index without and with UPFC.*

Table 7 presents the results of the UPFC installed on bus 31 for each situation mentioned above. It has been noted that the loss of power has decreased to 15.64 MW from 18.20 MW. Figure 3 shows system voltage changes without and with FACTS devicesThe multi-objective function's convergence with and without UPFC is shown in Figure 4. Figure 5 shows without and with UPFC system topologies reduce societal welfare.

4. Conclusions

A robust electrical structure is critical for attracting industry and foreign investment. To increase the stability and dependability of present power systems, FACTS devices can be used along with solar and wind renewable energy sources are viable alternatives to traditional power systems.

When renewable energy is present, the OPF efficiently enhances the system's power flow capacity.

Optimal UPFC tuning and location leads to increased system efficiency.

Implementing UPFC in the desired location leads to improved social welfare outcomes.

- Moth flame optimisation is effective for multi-objective problems. Compared to other FACTS devices, UPFC is a cost-effective and viable option. Power system is studied and reported in the literature [17-19].

Table 1. *MFO technique for IEEE 57 bus generation reallocation without UPFC*

S. No	Parameters		OF_1	OF_2	OF_3	OF_4
1	Real power generation (MW)	P_{G1}	127.5378	124.2723	195.4962	134.4906
		P_{G2}	100.0000	100.0000	1.1332	100.0000
		P_{G3}	40.5278	140.0000	117.0720	45.0145
		P_{G6}	0.9233	30.9781	100.0000	12.6634
		P_{G8}	417.2525	288.7562	268.6933	393.2302
		P_{Gs}	180.0000	180.0000	180.0000	180.0000
		P_{Gw}	350.0000	350.0000	350.0000	350.0000
2	Total Active power generation (MW)		1216.2414	1214.0066	1212.3947	1215.3987
3	Total real power generation cost ($/hr)		21383	24445	24663	21422
4	Active power Loss (MW)		20.4413	18.2066	16.5947	19.5986
5	Valve point effect ($/hr)		21437	24508	24715	21470
6	Voltage deviation (p.u.)		4.7973	4.7143	4.7326	4.7848
7	Carbon Emission(ton/hr)		0.7303	0.4797	0.5428	0.6729
8	FPL		4462.8	4462.8	4462.8	4462.8
9	FPG		21383	24445	24663	21422
10	NSW		16920.2	19982.2	20200.2	16959.2
11	Objective function		16920	4.7143	16.5947	19397

Table 2. *Values of the Severity Index for each bus of the IEEE 57 bus system*

Rank	Bus Number	Lj
1	31	0.3332
2	33	0.3083

3	32	0.3037
4	57	0.2871
5	42	0.2843
6	56	0.2836
7	30	0.2791
8	25	0.2415
9	34	0.2341
10	41	0.2291
11	35	0.2217
12	40	0.2093
13	36	0.2053
14	39	0.1948
15	37	0.191

Table 3. *The MFO method with UPFC reallocates generation on IEEE 57 system at BUS 31.*

S.No	Parameters		OF_1	OF_2	OF_3	OF_4
1	Real power generation (MW)	P_{G1}	130.6627	164.8613	51.3093	126.9777
		P_{G2}	30.0000	107.3134	150.0000	32.7627
		P_{G3}	36.9251	0.2241	58.1959	44.0992
		P_{G6}	0.5265	100.0000	100.0000	10.7416
		P_{G8}	386.2318	209.8010	222.7368	369.0287
		P_{Gs}	220.0000	220.0000	220.0000	220.0000
		P_{Gw}	410.0000	410.0000	410.0000	410.0000
2	Total Active power generation (MW)		1214.3461	1212.1998	1212.2420	1213.6099
3	Total real power generation cost ($/hr)		17385	20090	20123	17426
4	Active power Loss (MW)		18.5461	16.3998	16.4419	17.8098
5	Valve point effect ($/hr)		17420	20118	20181	17477
6	Voltage deviation (p.u.)		3.4017	3.3772	3.3794	3.3976
7	Carbon Emission (Ton/hr)		0.6079	0.3825	0.3326	0.5598
8	PQ_{send}		0.1244	0.1213	0.1222	0.1242
9	PQ_{rec}		0.1174	0.1167	0.1169	0.1174
10	Size	V_{cr}	0.0350	0.0350	0.0350	0.0350
		T_{cr}	-87.1236	-87.1236	-87.1236	-87.1236
		V_{vr}	1.0227	1.0225	1.0225	1.0227
		T_{vr}	-17.6231	-20.4587	-19.2199	-17.7540
11	FPL		4462.8	4462.8	4462.8	4462.8
12	FPG		17385	20090	20123	17426
13	NSW		12922.2	15627.2	15660.2	12963.2
14	Objective function		12922	3.3772	16.4419	15084

Table 4. *Various line outages cause severe lines, presented in descending order of Lj*

	Line outage		Severity line		Severity bus	
S. No	SEB	REB	FVSI Max Value	Line no with FVSI Max	Lj Max Value	BUS No with Lj Max
1	24	26	0.5217	41-43	0.4580	31
2	26	27	0.5218	41-43	0.4577	31
3	15	45	0.5777	41-43	0.4420	31
4	11	41	1.0996	41-43	0.4409	42
5	41	42	0.4564	41-43	0.4393	42
6	24	25	0.5071	41-43	0.4383	31
7	24	25	0.5062	41-43	0.4291	31
8	13	14	0.5644	41-43	0.4261	32
9	38	44	0.5621	41-43	0.4194	31
10	31	32	0.4914	41-43	0.4043	31

11	29	52	0.4997	41-43	0.4023	52
12	46	47	0.5479	41-43	0.4018	31
13	14	46	0.5476	41-43	0.4011	31
14	22	23	0.4931	41-43	0.3867	31
15	13	49	0.5360	41-43	0.3852	31

Table 5. *Variations between conventional line flows and line outages*

SEB	REB	Power flow in line limit (MVA)	Line flows under normal condition	Line flow under Line outage of 24-26	Line flow under Line outage of 26-27	Line flow under Line outage of 15-45
1	2	100	-0.5059 - 0.2326i	-0.5163 - 0.2361i	-0.5161 - 0.2360i	-0.4889 - 0.2009i
2	3	100	0.4614 - 0.1126i	0.4510 - 0.1158i	0.4512 - 0.1157i	0.4787 - 0.0819i
3	4	100	0.3659 - 0.1180i	0.3278 - 0.1403i	0.3280 - 0.1402i	0.3991 - 0.1555i
4	5	100	0.0435 - 0.0013i	0.0245 - 0.0083i	0.0245 - 0.0082i	0.0472 - 0.0053i
4	6	100	-0.0004 + 0.0072i	-0.0285 + 0.0017i	-0.0283 + 0.0017i	0.0039 + 0.0009i
6	7	100	-0.2256 - 0.1647i	-0.2790 - 0.1271i	-0.2791 - 0.1272i	-0.1667 - 0.1782i
6	8	100	-0.4849 - 0.0644i	-0.4831 - 0.0638i	-0.4831 - 0.0638i	-0.4525 - 0.0551i
8	9	100	1.0867 + 0.0082i	1.1590 - 0.0069i	1.1588 - 0.0070i	1.1498 - 0.0683i
9	10	100	0.3999 + 0.0482i	0.4206 + 0.0494i	0.4206 + 0.0494i	0.4251 + 0.0433i
9	11	100	0.4688 - 0.1718i	0.4994 - 0.1836i	0.4994 - 0.1836i	0.4925 - 0.2207i
9	12	100	0.2217 + 0.1462i	0.2344 + 0.1520i	0.2343 + 0.1520i	0.2210 + 0.1597i
9	13	100	0.3598 + 0.0260i	0.3867 + 0.0211i	0.3866 + 0.0211i	0.3714 - 0.0014i
13	14	100	0.4575 - 0.3148i	0.5013 - 0.3453i	0.5012 - 0.3453i	0.6125 - 0.4523i
13	15	100	-0.4153 + 0.2327i	-0.4261 + 0.2511i	-0.4262 + 0.2510i	-0.6248 + 0.3337i
1	15	100	0.3422 - 0.2085i	0.3499 - 0.2192i	0.3500 - 0.2192i	0.3091 - 0.1397i
1	16	100	0.3853 - 0.0561i	0.3888 - 0.0181i	0.3889 - 0.0181i	0.4333 - 0.0505i
1	17	100	0.5266 - 0.0886i	0.5299 - 0.0651i	0.5299 - 0.0651i	0.5746 - 0.0831i
3	15	100	0.1290 + 0.0595i	0.1653 + 0.0780i	0.1651 + 0.0780i	0.0264 + 0.1280i
4	18	100	0.1402 - 0.0692i	0.1442 - 0.0731i	0.1442 - 0.0731i	0.1510 - 0.0799i
4	18	100	0.1809 - 0.0877i	0.1861 - 0.0943i	0.1861 - 0.0943i	0.1949 - 0.1031i
5	6	100	-0.0866 + 0.0132i	-0.1056 + 0.0061i	-0.1055 + 0.0062i	-0.0829 + 0.0093i
7	8	100	-0.8423 + 0.0744i	-0.7676 + 0.0241i	-0.7676 + 0.0241i	-0.8448 + 0.1106i
10	12	100	-0.0287 + 0.2301i	-0.0283 + 0.2421i	-0.0284 + 0.2421i	-0.0673 + 0.2650i
11	13	100	0.2191 + 0.2349i	0.2397 + 0.2390i	0.2396 + 0.2390i	0.2154 + 0.2317i
12	13	100	-0.0335 - 0.5927i	-0.0144 - 0.6412i	-0.0144 - 0.6412i	0.0193 - 0.7381i
12	16	100	0.0511 + 0.0193i	0.0477 + 0.0386i	0.0476 + 0.0386i	0.0046 + 0.0064i
12	17	100	-0.0999 + 0.0298i	-0.1031 + 0.0342i	-0.1032 + 0.0342i	-0.1463 + 0.0171i
1	15	100	0.5968 - 0.3526i	0.6110 - 0.3684i	0.6112 - 0.3683i	0.5313 - 0.2478i
18	19	100	0.0491 - 0.0310i	0.0583 - 0.0363i	0.0583 - 0.0363i	0.0739 - 0.0481i
19	20	100	0.0144 - 0.0225i	0.0230 - 0.0268i	0.0230 - 0.0268i	0.0370 - 0.0363i
21	20	100	0.0088 + 0.0119i	0.0005 + 0.0159i	0.0005 + 0.0159i	-0.0131 + 0.0240i
21	22	100	-0.0088 - 0.0119i	-0.0005 - 0.0159i	-0.0005 - 0.0159i	0.0131 - 0.0240i
22	23	100	0.0681 - 0.0537i	0.1984 - 0.1150i	0.1984 - 0.1150i	0.0202 - 0.0355i
23	24	100	0.0050 - 0.0325i	0.1347 - 0.0929i	0.1347 - 0.0929i	-0.0429 - 0.0145i
24	25	100	0.0719 - 0.0500i	0.0656 - 0.0457i	0.0656 - 0.0457i	0.0742 - 0.0538i
24	25	100	0.0691 - 0.0480i	0.0631 - 0.0439i	0.0631 - 0.0439i	0.0713 - 0.0517i
24	26	100	-0.1363 + 0.0593i	-	0.0000 + 0.0000i	-0.1889 + 0.0858i
26	27	100	-0.1363 + 0.0606i	0.0000 + 0.0000i	-	-0.1889 + 0.0887i
27	28	100	-0.2339 + 0.0729i	-0.0930 + 0.0050i	-0.0930 + 0.0050i	-0.2920 + 0.1093i
28	29	100	-0.2842 + 0.1025i	-0.1396 + 0.0289i	-0.1396 + 0.0289i	-0.3453 + 0.1435i
7	29	100	0.6150 - 0.2580i	0.4866 - 0.1686i	0.4866 - 0.1686i	0.6768 - 0.3093i
25	30	100	0.0780 - 0.0432i	0.0657 - 0.0354i	0.0657 - 0.0354i	0.0826 - 0.0458i
30	31	100	0.0404 - 0.0228i	0.0284 - 0.0155i	0.0284 - 0.0155i	0.0446 - 0.0248i
31	32	100	-0.0187 + 0.0079i	-0.0303 + 0.0145i	-0.0303 + 0.0145i	-0.0150 + 0.0066i
32	33	100	0.0381 - 0.0191i	0.0381 - 0.0191i	0.0381 - 0.0191i	0.0381 - 0.0191i
34	32	100	0.0732 - 0.0457i	0.0855 - 0.0589i	0.0855 - 0.0589i	0.0694 - 0.0449i
34	35	100	-0.0732 + 0.0457i	-0.0855 + 0.0589i	-0.0855 + 0.0589i	-0.0694 + 0.0449i
35	36	100	-0.1337 + 0.0743i	-0.1464 + 0.0880i	-0.1464 + 0.0880i	-0.1300 + 0.0738i

36	37	100	-0.1618 + 0.1106i	-0.1703 + 0.1204i	-0.1703 + 0.1204i	-0.1457 + 0.0974i
37	38	100	-0.1976 + 0.1531i	-0.2028 + 0.1604i	-0.2028 + 0.1604i	-0.1710 + 0.1299i
37	39	100	0.0343 - 0.0406i	0.0307 - 0.0378i	0.0307 - 0.0378i	0.0239 - 0.0308i
36	40	100	0.0266 - 0.0357i	0.0221 - 0.0312i	0.0221 - 0.0312i	0.0142 - 0.0226i
22	38	100	-0.0769 + 0.0418i	-0.1988 + 0.0991i	-0.1988 + 0.0991i	-0.0072 + 0.0116i
11	41	100	0.0981 - 0.1712i	0.1020 - 0.1766i	0.1020 - 0.1766i	0.1093 - 0.1890i
41	42	100	0.0965 - 0.0310i	0.1005 - 0.0352i	0.1005 - 0.0352i	0.1080 - 0.0443i
41	43	100	-0.1250 + 0.1835i	-0.1302 + 0.1877i	-0.1302 + 0.1877i	-0.1400 + 0.1970i
38	44	100	-0.2749 + 0.2180i	-0.3154 + 0.2419i	-0.3154 + 0.2419i	0.1206 - 0.0165i
15	45	100	0.4154 - 0.3001i	0.4614 - 0.3402i	0.4615 - 0.3402i	-
14	46	100	0.3482 - 0.2580i	0.3911 - 0.2856i	0.3911 - 0.2856i	0.4994 - 0.3824i
46	47	100	0.3482 - 0.2430i	0.3911 - 0.2667i	0.3911 - 0.2667i	0.4994 - 0.3497i
47	48	100	0.0465 - 0.1132i	0.0881 - 0.1358i	0.0881 - 0.1358i	0.1921 - 0.2059i
48	49	100	-0.0444 + 0.0718i	-0.0631 + 0.0806i	-0.0631 + 0.0806i	-0.1066 + 0.1114i
49	50	100	0.0247 - 0.0042i	0.0064 - 0.0001i	0.0064 - 0.0001i	-0.0327 + 0.0176i
50	51	100	-0.1854 + 0.1009i	-0.2036 + 0.1049i	-0.2036 + 0.1050i	-0.2428 + 0.1228i
10	51	100	0.3726 - 0.1779i	0.3923 - 0.1855i	0.3923 - 0.1855i	0.4356 - 0.2135i
13	49	100	0.3079 - 0.2939i	0.3390 - 0.3229i	0.3390 - 0.3229i	0.4190 - 0.4191i
29	52	100	0.1565 - 0.0939i	0.1761 - 0.0950i	0.1761 - 0.0950i	0.1549 - 0.0935i
52	53	100	0.1024 - 0.0653i	0.1211 - 0.0652i	0.1211 - 0.0652i	0.1008 - 0.0649i
53	54	100	-0.0989 + 0.0364i	-0.0805 + 0.0369i	-0.0806 + 0.0369i	-0.1005 + 0.0368i
54	55	100	-0.1424 + 0.0534i	-0.1233 + 0.0530i	-0.1233 + 0.0530i	-0.1441 + 0.0540i
11	43	100	0.1450 - 0.2348i	0.1502 - 0.2421i	0.1502 - 0.2421i	0.1600 - 0.2585i
44	45	100	-0.3993 + 0.2449i	-0.4413 + 0.2701i	-0.4413 + 0.2701i	0.0000 + 0.0028i
40	56	100	0.0266 - 0.0356i	0.0220 - 0.0311i	0.0220 - 0.0311i	0.0141 - 0.0225i
56	41	100	-0.0603 - 0.0106i	-0.0649 - 0.0081i	-0.0649 - 0.0081i	-0.0732 - 0.0023i
56	42	100	-0.0222 - 0.0146i	-0.0259 - 0.0111i	-0.0259 - 0.0111i	-0.0324 - 0.0035i
39	57	100	0.0342 - 0.0404i	0.0306 - 0.0377i	0.0306 - 0.0377i	0.0239 - 0.0307i
57	56	100	-0.0328 - 0.0153i	-0.0364 - 0.0132i	-0.0364 - 0.0132i	-0.0431 - 0.0075i
38	49	100	-0.0562 + 0.1019i	-0.0856 + 0.1159i	-0.0856 + 0.1159i	-0.1544 + 0.1609i
38	48	100	-0.0890 + 0.1821i	-0.1480 + 0.2116i	-0.1480 + 0.2116i	-0.2890 + 0.3028i
9	55	100	0.2149 - 0.1002i	0.1948 - 0.0974i	0.1948 - 0.0974i	0.2167 - 0.1011i

Table 6. *Optimization of power flows for various objective functions including renewable energy sources and line 24-26 contingencies, without UPFC*

S.No	Parameter		OF_1	OF_2	OF_3	OF_4
1	Real power generation (MW)	P_{G1}	141.8056	81.2680	197.9313	136.3244
		P_{G2}	78.7302	100.0000	0.6324	100.0000
		P_{G3}	42.9910	140.0000	124.3493	45.8422
		P_{G6}	5.6449	100.0000	100.0000	12.2361
		P_{G8}	418.5566	263.5079	261.0891	392.6158
		P_{Gs}	180.0000	180.0000	180.0000	180.0000
		P_{GW}	350.0000	350.0000	350.0000	350.0000
2	Total Active power generation (MW)		1217.7283	1214.7759	1214.0021	1217.0185
3	Total real power generation cost ($ /hr)		21420	25750	25109	21491
4	Active power Loss (MW)		21.9283	18.9760	18.2022	21.2186
5	Valve point effect ($ /hr)		21467	25792	25159	21538
6	Voltage deviation (p.u.)		5.2943	5.2067	5.2246	5.2802
7	Carbon Emission(ton/hr)		0.7388	0.4296	0.5408	0.6740
8	FPL		4462.8	4462.8	4462.8	4462.8
9	FPG		21420	25750	25109	21491
10	NSW		16957.2	21287.2	20646.2	17028.2
11	Objective function		16958	5.2067	18.2022	19678

Table 7. *Lines 24-26: UPFC based renewable energy source contingency and optimal power flows for various objective functions*

S.No	Parameters		OF_1	OF_2	OF_3	OF_4
1	Real power generation (MW)	P_{G1}	124.1946	119.9534	173.6509	149.9027
		P_{G2}	30.0000	150.0000	30.0000	81.9120
		P_{G3}	38.9489	0.0241	60.7528	32.6227
		P_{G6}	0.0041	100.0000	100.0000	0.1630
		P_{G8}	392.5310	286.4327	217.0364	319.6634
		P_{GS}	220.0000	148.0620	220.0000	220.0000
		P_{GW}	410.0000	410.0000	410.0000	410.0000
2	Total Active power generation (MW)		1215.6786	1214.4722	1211.4401	1214.2638
3	Total real power generation cost ($/hr)		17421	22391	19644	17772
4	Active power Loss (MW)		19.8786	18.6724	15.6401	18.4639
5	Valve point effect ($/hr)		17452	22447	19674	17815
6	Voltage deviation (p.u.)		3.4868	3.4628	3.4646	3.4708
7	Carbon Emission(ton/hr)		0.6170	0.4956	0.3764	0.4942
8	PQ_{send}		0.1343	0.1342	0.1342	0.1341
9	PQ_{rec}		0.1214	0.1207	0.1207	0.1209
10	Size	V_{cr}	0.0350	0.0350	0.0350	0.0350
		T_{cr}	-87.1236	-87.1236	-87.1236	-87.1236
		V_{vr}	1.0252	1.0251	1.0251	1.0251
		T_{vr}	-20.8943	-23.1973	-22.6031	-22.3639
11	FPL		4462.8	4462.8	4462.8	4462.8
12	FPG		17421	22391	19644	17772
13	NSW		12958.2	17928.2	15181.2	13309.2
14	Objective function		12958	3.4628	15.6401	15503

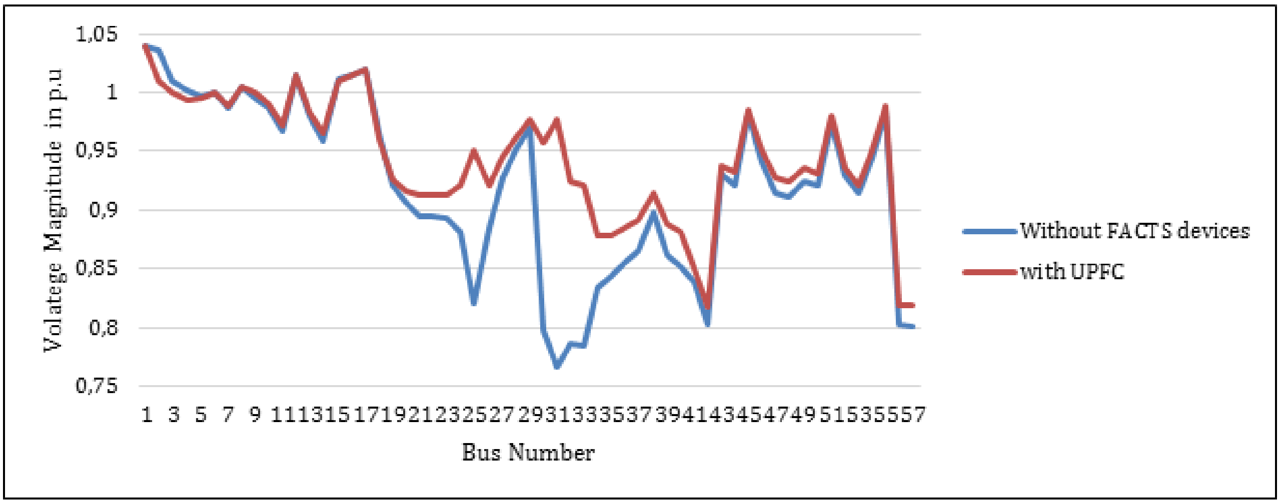

Figure 3. *Voltage profile of multi-objective function.*

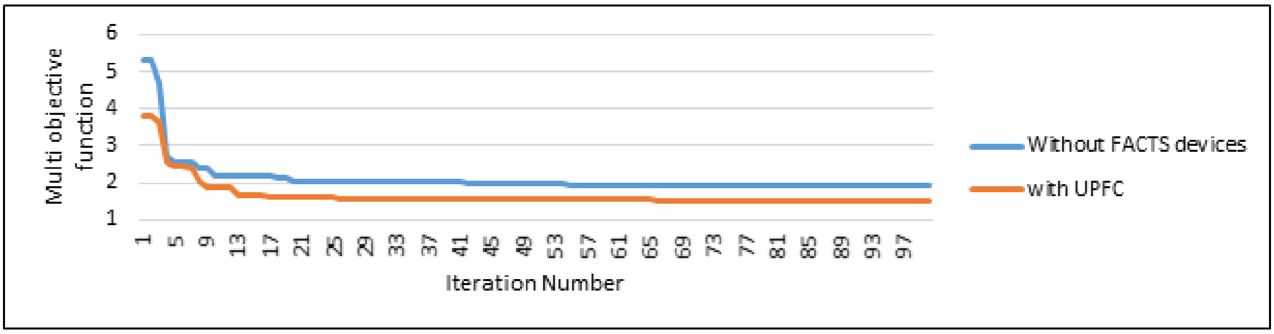

Figure 4. *Multi-objective function convergence*

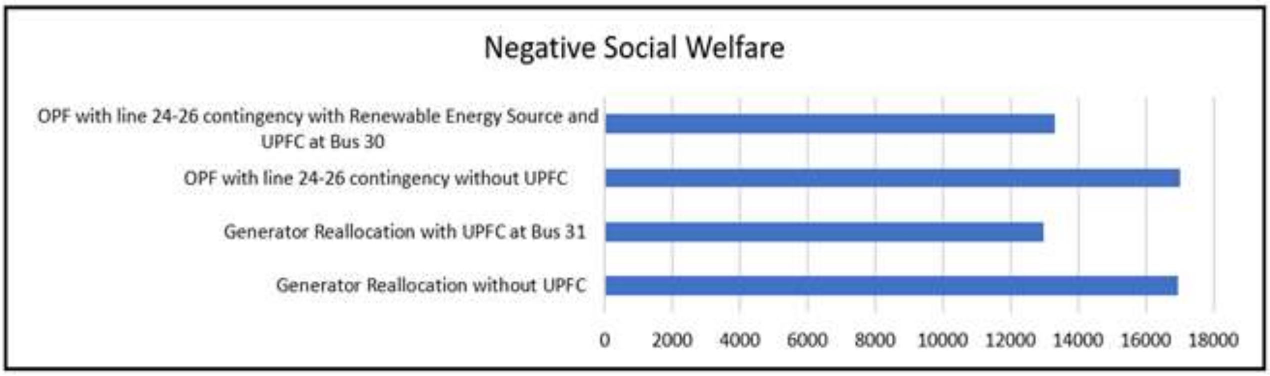

Figure 5. *Negative Social Welfare without and with UPFC: A Comparison.*

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- **Ethical approval:** The conducted research is not related to either human or animal use.
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