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Increasing the Loadability of Power System through Optimal Placement of GUPFC using UDTPSO

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This paper concentrates on increasing the loadability of power system. The most powerful multi-line FACTS controller, Generalized Unified Power Flow Controller (GUPFC) is considered using power injection model. While finding the optimal installation location for GUPFC, transmission line thermal limits and bus voltage limits are taken into consideration. The overall system and area wise loadability is enhanced in the presence of GUPFC with static and dynamic loads under normal and contingency conditions. A novel optimization algorithm based on uniform distribution of control variables and two-stage initialization processes included in conventional Particle Swarm Optimization (PSO) to start the convergence of problem with good initial value and reaches best final value in less number of iterations. The proposed methodology is tested on standard IEEE-30 bus test system and the obtained results are quite encouraging and will be useful for power system restructuring.

Keywords: Loadability Index; GUPFC; UDTPSO; Optimal Location; Dynamic LBI curves

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1. Introduction

Under the effect of contingencies and emergency conditions, the power system needs to operate at its maximum limits, which means effective utilization of the existing transmission network capacity to power transfer. Various types of Flexible AC Transmission Systems (FACTS) controllers are available to maximize the transfer capability of transmission network [1-2].

In [3], a method based on technical concerns by placing different types of FACTS devices on different locations to identify the increase of Loading Margin (LM). This method is not reliable, to identify the suitable device and its optimal control settings in an optimal location, as it takes many man hours. A method to calculate LM and Static var compensator (SVC) settings under contingency conditions are proposed in [4]. A method [5] based on GA was proposed, to identify the locations and control settings of various types of FACTS devices for LM enhancement. Certain power system conditions like, unexpected load increase, loss of important transmission lines, transformers, or generators, and inappropriate operation of the control devices effects the voltage stability, which leads to violation of reactive power generation limits [6]. Certain continuation methods [7-10] are implemented to calculate the loading margins in voltage collapse analysis, however these methods has good numerical accuracy, reliable and traces the path from any operating point to voltage collapse point. But these methods are time consuming and needs more expertise for larger systems. One of the regular processes, to find the loadability of a given system is to use a conventional load flow and to gradually increase loads until the convergence is no longer obtained [11, 12]. As this method needs manual intervention, and often suffers from

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convergence in the presence of operating constraints. Optimal location of SVC for enhancing the system loadability using GA and PSO methods are given in [13-15].

In this paper, one of the advanced multi-line FACTS controllers known for Generalized Unified Power Flow Controller (GUPFC) is proposed with its power injection model, mismatch equations and its incorporation procedure in conventional Newton Raphson (NR) load flow. An optimal location strategy based on transmission line loadings and bus voltage magnitude variations is proposed to enhance the system security by minimizing severity of the system. A novel optimization method by considering two-stage initialization and uniform distribution of problem control variables along with conventional Particle Swarm Optimization (PSO) is proposed. In this paper, both active and reactive load is increased by a common factor known as Loadability Index (LBI), and is optimized using the proposed method while satisfying equality, in equality and device operating constrains. The zonal loadability concept by dividing the standard IEEE-30 bus system in to 3 zones and the individual zonal LBI variations without and with GUPFC for normal, contingency and dynamic load variations are analyzed with supporting results.

2. GUPFC Modeling

Normally GUPFC consist two/more series converters and one shunt converter. To show the effectiveness of the control operation of GUPFC, two series converters are coordinated with one shunt converter is shown in Fig.1.

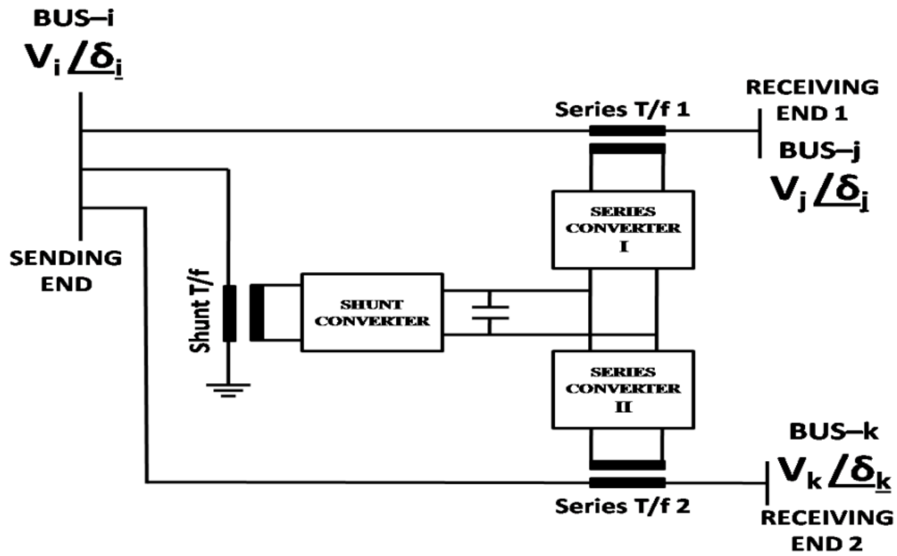

Figure.1: Basic configuration of two series converter GUPFC

In this paper, the following rules are considered, to identify the proper device location so as to reduce the number of possible locations.

1. It should be located between two PQ buses and there should not be any shunt capacitors.
2. It should not be placed in a line where tap changing transformer exists.

The final steady state power injection model of GUPFC is shown in Fig.2.

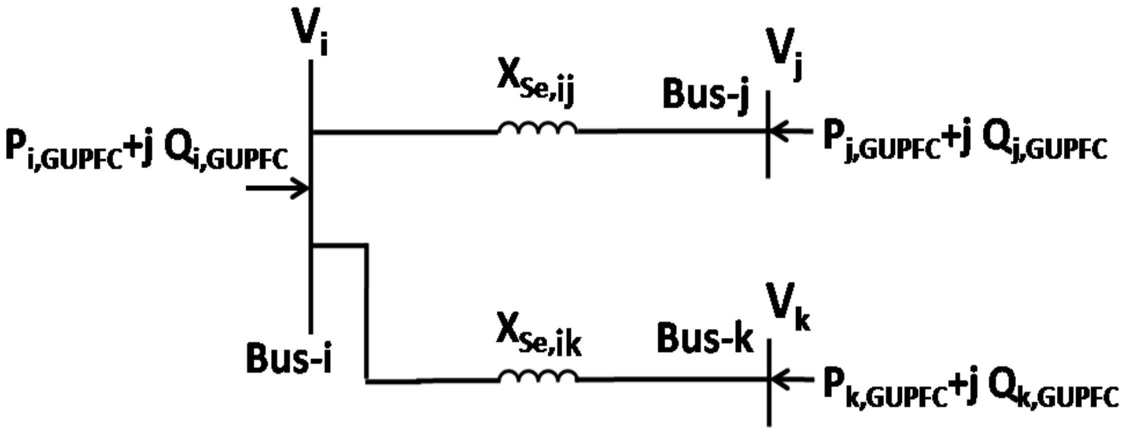

Figure.2. Injection model of two series converter GUPFC

The injected active and reactive powers can be expressed as

$$P_{i,GUPFC} = -V_i^2\left[\sum_{q=j,k} r_{iq}B_{se,iq}\sin\gamma_{iq}\right] - 1.03\left(\sum_{q=j,k} r_{iq}V_iV_qB_{se,iq}\sin\left(\delta_{iq}+\gamma_{iq}\right) - r_{iq}V_i^2B_{se,iq}\sin\gamma\right) \quad (1)$$

$$Q_{i,GUPFC} = -V_i^2\left[\sum_{q=j,k} r_{iq}B_{se,iq}\cos\gamma_{iq}\right] + Q_{sh} \quad (2)$$

$$P_{p,GUPFC} = r_{ip}V_iV_pB_{se,ip}\sin(\delta_{ip}+\gamma_{ip}) \;\; \forall \;\; p=j,k \quad (3)$$

$$Q_{p,GUPFC} = r_{ip}V_iV_pB_{se,ip}\cos(\delta_{ip}+\gamma_{ip}) \;\; \forall \;\; p=j,k \quad (4)$$

The coefficient 1.03 represents the converter switching loss factor.

where 'r' and 'γ' are respective per unit magnitude and phase angles of the series voltage sources operating within the limits $0 \leq r \leq r_{max}$ and $0 \leq \gamma \leq \gamma_{max}$.

2.1. GUPFC power mismatch equations

The power mismatch equations in Newton Raphson (NR) method can be modified by using the following equations.

$$\Delta P_{i,new} = \Delta P_{i,old} + P_{i,GUPFC} \quad (5)$$

$$\Delta Q_{i,new} = \Delta Q_{i,old} + Q_{i,GUPFC} \quad (6)$$

where, $\Delta P_{i,old}$ and $\Delta Q_{i,old}$ are the power mismatches without device. Similar modifications can be obtained for the remaining GUPFC buses.

2.2. GUPFC Jacobian elements

The Jacobian elements can be modified in the NR iterative process using the following equations $\left(H^{new} = H^{old} + H^{'}\right)$.

$$H^{'}_{ii} = \frac{\partial P_{i,GUPFC}}{\partial \delta_i} = -1.03\left[\sum_{q=j,k} r_{iq}V_iV_qB_{se,iq}\cos\left(\delta_{iq}+\gamma_{iq}\right)\right] \quad (7)$$

$$H^{'}_{qq} = -r_{iq}V_iV_qB_{se,iq}\cos(\delta_{iq}+\gamma_{iq}) = -Q_{q,GUPFC} \quad \forall \quad q=j,k \quad (8)$$

$$H^{'}_{iq} = 1.04\left[r_{iq}V_iV_qB_{se,iq}\cos(\delta_{iq}+\gamma_{iq})\right] = 1.04Q_{q,GUPFC} \quad \forall \quad q=j,k \quad (9)$$

$$H^{'}_{qi} = r_{iq}V_iV_qB_{se,iq}\cos(\delta_{iq}+\gamma_{iq}) = Q_{q,GUPFC} \quad \forall \quad q=j,k \quad (10)$$

where H^{old} is the Jacobian element without device. Similar modifications can be obtained for the remaining elements.

2.3. GUPFC incorporation procedure

The overall computational procedure of Newton-Raphson power flow method with device can be described in the following steps.

Step.1: Read bus data, line data and GUPFC data.
Step.2: Assume flat voltage profile and set iteration count k=0.
Step.3: Compute active and reactive power mismatch from the scheduled and calculated powers.
Step.4: Determine Jacobian matrix using power flow equations.
Step.5: Modify power mismatch and Jacobian with respective device elements to Incorporate GUPFC in load flow.
Step.6: Solve the NR method equations to find the voltage magnitude and angles correction vector.
Step.7: Update the solution using correction vector.
Step.8: Increase the iteration count, k=k+1 and repeat steps from 5 to 7.
Step.9: Stop the process, if the maximum mismatch is less than given tolerance.

2.4. Optimal location

A severity function is formulated based on transmission line loadings and bus voltage magnitude violations under contingency conditions. The proposed severity function ($F_{Severity}$) can be expressed as [16]

$$F_{Severity} = \sum_{i=1}^{N_{line}} \left(\frac{S_i}{S_i^{\max}} \right)^{2q} + \sum_{j=1}^{N_{bus}} \left(\frac{V_{j,ref} - V_j}{V_{j,ref}} \right)^{2r} \tag{11}$$

where N_{line}, N_{bus} are the total number of lines and buses in a given system. S_i and $S_i^{\max}$ are the present and maximum apparent powers of i^{th} line. $V_{j,ref}$ and V_j are the nominal voltage and present voltage values at j^{th} bus. 'q' and 'r' are two coefficients used to penalize more or less over loads and voltage violations. These are considered to be equal to 2.

With this, the system security has been enhanced under contingency conditions by placing GUPFC in a proper location. After performing contingency analysis, one of the highest critical line is identified and also its corresponding total Number of Voltage Violation Buses (NVVB) and total Number of Over Loaded Lines (NOLL) are identified. After this the performance index is calculated by adding NOLL and NVVB for the respective contingencies. Now, remove this critical line from the system and identify the possible device installation locations for a given system. Place the GUPFC in one of these locations and minimize the severity function. Repeat this process for all possible locations and identify the severity function values. Finally select the location which has the least severity function value in the presence of GUPFC under contingency conditions as the best GUPFC installation location. Finally system security has been enhanced with this location in the presence of GUPFC.

3. OPF Problem formulation

Optimal Power Flow (OPF) problem optimizes the power system objectives, includes non-linearities and complexities. Finally a set of control variables are obtained as a solution for the problem while satisfying equality, in equality and device operating constraints. Conventionally economic load dispatch problem includes generation fuel cost as an objective is optimized, but for the loadability problem, the system active and reactive power loadability index (LBI) is optimized. The LBI is increased step by step from its base load until the transmission line and bus voltages violates.

The problem can be formulated mathematically as a constrained nonlinear objective optimization problem as follows:

$$LBI = Max\ [\ \lambda\ ] \tag{12}$$

Subjected to g(x,u)=0; h(x,u)≤0.

where 'g' and 'h' are the equality and inequality constraints respectively and 'x' is a control vector of dependent variables like slack bus active power generation ($P_{g,slack}$), load bus voltage magnitudes (V_L) and generator reactive powers (Q_G) and vector 'u' consist control variables such as active powers (P_G) and voltage (V_G) of generators, transformer tap ratios (T) and shunt compensation (Q_{Sh}) and device control parameters. The considered objective is formulated as follows:

3.1. Loadability Index

In real time power system, the active and reactive powers are increased by an indexed factor (λ) known as Loadability Index to analyze the system capability. This analysis has a great significant in designing and planning of the power system. This can be modeled using the following expressions

$$\sum_{i=1}^{N_G}\left(P_{G_i}\right)-(1+\lambda)\sum_{i=1}^{N_{bus}}P_{Demand}=P_{Loss}\ ;\sum_{i=1}^{N_G}\left(Q_{G_i}\right)+\sum_{i=1}^{n_c}Q_{sh,i}-(1+\lambda)\sum_{i=1}^{N_{bus}}Q_{Demand}=Q_{Loss}$$

Where, 'N_G' is the total number of generating units, 'n_c' is the total number of VAr sources.

3.2. Non-convex fuel cost objective

The fuel input-power output cost function of the ith unit with valve point loadings is given as

$$F_i\left(P_i\right)=a_iP_i^2+b_iP_i+c_i+\left|e_i\times\sin\left(f_i\times\left(P_i^{\min}-P_i\right)\right)\qquad \$/h\right| \tag{13}$$

Where, a_i, b_i, c_i are the fuel cost-coefficients of the ith unit and e_i, f_i are the fuel cost-coefficients of the i^{th} unit with valve-point effects. This function is evaluated for the 'N_G' number of generating units.

3.3. Emission objective

While minimizing fuel cost of generating units, may produce high levels of SO_2 and NO_2 emissions. These environmental concerns are because of using fossil fuels in electric generators, and global warming etc. The total ton/h atmospheric pollutants such as Sulpher oxides SO_X and Nitrogen oxides NO^X emitted by $E(P_{Gi})$ [17, 18] is

$$E\left(P_{G_i}\right)=\sum_{i=1}^{N_G}\alpha_i+\beta_iP_{G_i}+\gamma_iP_{G_i}^2+\xi_i\exp^{\left(\lambda_iP_{G_i}\right)}\qquad ton/h \tag{14}$$

Where, $\alpha_i,\beta_i,\gamma_i,\xi_i$ and λ_i are emission coefficients of the i^{th} generator.

3.4. Total power loss

In power system, the active power loss should be minimized to enhance power delivery performance and can be calculated using

$$TPL = \sum_{i=1}^{N_{line}} g_i \left[V_i^2 + V_j^2 - 2V_iV_j \cos(\delta_i - \delta_j)\right] \quad MW \tag{15}$$

Where, g_i is the conductance of i[th] line which connects buses i and j. V_i, V_j and δ_i, δ_j are voltage magnitude and angle of i[th] and j[th] buses.

3.5. Constraints

The above problem is optimized by satisfying the following equality, in-equality, practical and also device limits.

3.5.1 Equality Constraints

These constraints are typically load flow equations.

$$\sum_{i=1}^{N_G} P_{G_i} - P_{Demand} - P_{Loss} = 0 \quad ; \sum_{i=1}^{N_G} Q_{G_i} + Q_{sh} - Q_{Demand} - Q_{Loss} = 0$$

3.5.2 In-equality Constraints

Generator bus voltage limits: $V_{G_i}^{min} \le V_{G_i} \le V_{G_i}^{max}; \quad \forall i \in N_G$

Active Power Generation limits: $P_{G_i}^{min} \le P_{G_i} \le P_{G_i}^{max}; \quad \forall i \in N_G$

Transformers tap setting limits: $T_i^{min} \le T_i \le T_i^{max}; \quad i = 1,2,..., n_t$

Capacitor reactive power generation limits: $Q_{Sh_i}^{min} \le Q_{Sh_i} \le Q_{Sh_i}^{max}; \quad i = 1,2,....,n_C$

Transmission line flow limit: $S_{l_i} \le S_{l_i}^{max}; \quad i = 1,2,....,N_{line}$

Reactive Power Generation limits: $Q_{G_i}^{min} \le Q_{G_i} \le Q_{G_i}^{max}; \quad \forall i \in N_G$

Bus voltage magnitude limits: $V_i^{min} \le V_i \le V_i^{max} \quad i = 1,2,...., N_{load}$

where n_t total number of taps, n_c total number of VAr sources, N_{load} total number of VAr sources.

The above mentioned problem can be generalized using penalty factors as follows:

$$A_{m,aug}(x,u) = A_m(x,u) + R_1\left(P_{g,slack} - P_{g,slack}^{lim}\right)^2 + R_2 \sum_{i=1}^{N_{Load}} \left(V_i - V_i^{lim}\right)^2 + R_3 \sum_{i=1}^{N_G} \left(Q_{G_i} - Q_{G_i}^{lim}\right)^2 + R_4 \sum_{i=1}^{N_{line}} \left(S_{l_i} - S_{l_i}^{max}\right)^2$$

where R_1, R_2, R_3 and R_4 are the penalty quotients having large positive value. The limit values are defined as

$$x^{lim} = \begin{cases} x^{max}, & x > x^{max} \\ x^{min}, & x < x^{min} \end{cases}$$

Here ‘x’ is the value of $P_{g,slack}, V_i \; and Q_{G_i}$

3.6. GUPFC limits

The following device operating limits are considered for GUPFC.

$$r_{iq}^{\min} < r_{iq} < r_{iq}^{\max} \quad ; \quad \forall \quad q = j,k$$

$$\gamma_{iq}^{\min} < \gamma_{iq} < \gamma_{iq}^{\max} \quad ; \quad \forall \quad q = j,k$$

$$B_{se,iq}^{\min} < B_{se,iq} < B_{se,iq}^{\max} \quad ; \quad \forall \quad q = j,k$$

4. Uniformly Distributed Particle Swarm Optimization (UDTPSO)

In conventional PSO, initial control variables, initial velocities for all populations and the random numbers ‘rand1’ and ‘rand2’ during the iterative process are generated randomly between their minimum and maximum limits. This needs more number of iterations to identify an optimal solution. Processing the total generated population in the iterative process does not start with good solution value. Similarly, global search starts with a large weight value and then decreases towards minimum weight in local search to identify the solution, sometime it leads to inaccurate solution.

To overcome these problems, UDTPSO is proposed. In this method, problem initial control variables are uniformly distributed between its boundaries in equal intervals. Because of this, the global search starts with good solution value. All generated initial population is processed using two stage initialization methodology [19], to decrease the number of population for PSO iterative process. The inertia weight (W) and acceleration coefficients (C1 and C2) used to update velocity in iterative process are calculated dynamically using the methodology implemented in [18]. Hence the final global solution is achieved in less number of iterations when compared to conventional PSO. The velocity (V) and position (X) of the ith particle in the next iteration (k) are calculated using the procedure given in [20]. The complete flow chart of the proposed method is shown in Fig.3.

5. Case study

IEEE-30 bus system with 41 transmission lines is considered [21-23]. The total control variables in this system are 18, which include 6 active power generations and voltage levels of 6 generators, 4 tap settings of tap-changing transformers and 2 shunt VAr sources. The area wise system diagram is shown in Fig.4. The total analysis is divided into three scenarios, explained as follows

5.1. Scenario-1

This scenario gives the validation of the proposed method with the existing PSO method. The Optimal Power Flow (OPF) results of Loadability Index (LBI) maximization for without FACTs controllers, with UPFC and with GUPFC are analyzed.

Initially, the formulated severity function given in Eq.11 is optimized. The optimal location to install GUPFC is identified by performing the procedure described in section-III. The result of contingency analysis for this system is given in Table.1. To maintain the continuity either in supplying/receiving the power, the contingency analysis is not performed on lines between buses 9-11, 12-13, and 25-26. Hence, for this system only 38 transmission line contingencies out of 41 are considered. The result of only top most contingency is tabulated.

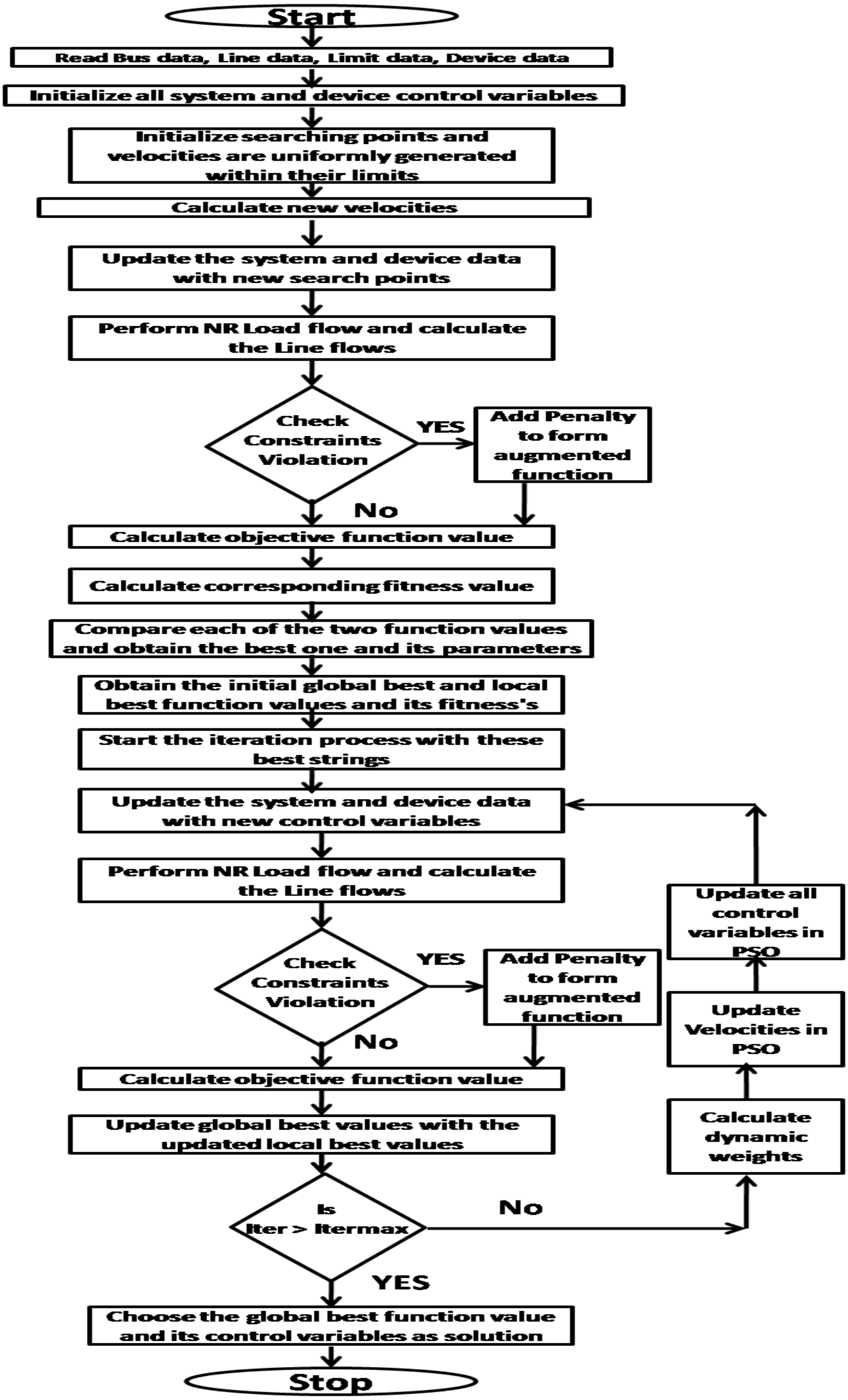

Figure.3. Flow chart of the proposed UDTPSO method

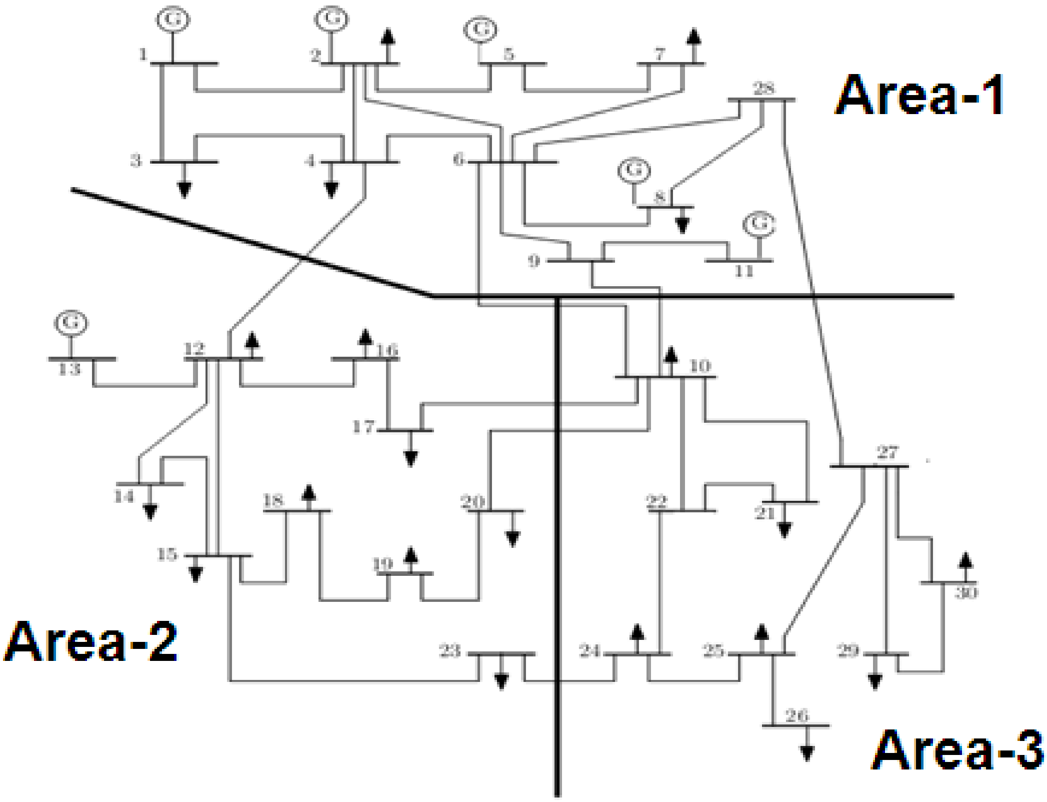

Figure.4. Area wise connections of IEEE-30 bus test system

Table 1: Result of contingency ranking

S. No.	Line No	Outage Line	Over loaded Lines (Line flow/ MVA limit)	NOLL	Voltage Violated Buses	NVVB	PI	Rank
1	5	2-5	(1-2) (171.399/130) (2-4) (77.671/65) (2-6) (105.434/65) (4-6) (121.418/90) (5-7) (110.190/70) (6-8) (35.828/32)	6	-	0	6	1

From Table.1, it is very clear that, the line connected between buses 2 and 5 is the most critical one. By following above rules given in section-II, the possible UPFC installation locations are 38. Severity function is evaluated in all locations with UPFC and the top 5 least severe function valued locations are tabulated in Table.2 under rank-1 contingency.

Table 2: Severity function values under rank-1 contingency with UPFC

S.No.	UPFC LOCATION		Severity function
	Sending end bus	Receiving end bus	value
1	12	14	1.608
2	30	27	1.6479
3	15	14	1.6484
4	27	25	1.6503
5	6	4	1.6573

Similarly, total possible installation locations for GUPFC are 23. Corresponding top 5 severity function values are tabulated in Table.3.

Table 3: Severity function values under rank-1 contingency with GUPFC

S.No.	GUPFC LOCATION			Severity function value
	Sending end bus	Receiving end buses		
1	12	14	15	1.517
2	12	14	16	1.6164
3	12	15	16	1.6492
4	15	12	23	1.6505
5	15	14	18	1.6668

From tables 2 and 3, it is observed that, first location is the best location for placing the UPFC and GUPFC, because it has least severity function value. The further analysis is performed by placing devices in these locations.

The obtained OPF results of overall system loadability for without, with UPFC and GUPFC are tabulated in Table.4. The result of proposed UDTPSO method is compared with the result of existing PSO method. From this table, it is observed that, the proposed method enhances the loadability and takes less time when compared to existing method. Further the loadability is enhanced using UPFC and GUPFC and the corresponding results are tabulated in Table.4. The loadability index of 0.04298 and 0.109856 are enhanced with UPFC and GUPFC when compared to without device. The corresponding generation cost, emission and transmission power losses are tabulated.

Table 4: OPF results for overall system LBI without and with FACTS devices

Control variables	Without FACTS		With UPFC	With GUPFC
	PSO	UDTPSO		
PG1, MW	195.5617	194.4278	194.2783	194.5196
PG2, MW	80	79.79048	80	80
PG5, MW	48.21005	50	50	50
PG8, MW	23.06917	15.85078	31.52635	35
PG11, MW	10	30	23.73142	30
PG13, MW	39.8575	28.54801	32.44336	40
VM1, p.u.	1.013422	1.042904	1.024332	1.001089
VM2, p.u.	0.991835	1.02521	0.920102	0.982703
VM5, p.u.	1.05	1.023755	0.991865	1.048183
VM8, p.u.	1.046305	1.032033	0.983621	1.021915
VM11, p.u.	0.979412	1.05	1.018171	1.041704
VM13, p.u.	1.046612	0.98507	0.994537	1.05
Tap, 6-9, p.u.	1.035488	0.97835	0.996017	0.969529
Tap, 6-10, p.u.	1.014571	0.914994	1.063003	1.051905
Tap, 4-12, p.u.	0.971288	1.022011	0.975031	0.991746
Tap, 28-27, p.u.	0.948309	0.924593	1.075271	0.980354

Qc, 10, p.u.	19.04474	22.10758	18.46608	28.29045
Qc, 24, p.u.	7.534689	6.856569	18.63414	21.06246
rij, p.u.	-	-	0.034294	0.002293
rik, p.u.	-	-	-	0.01204
γij, deg.	-	-	256.1717	186.3114
γik, deg.	-	-	-	314.3751
Xse,ij, p.u.	-	-	0.011433	0.018183
Xse,ik, p.u.	-	-	-	0.000422
Qsh, p.u.	-	-	0.029473	0.01689
LBI (λ)	0.34354	0.35502	0.398001	0.464876
Cost, $/h	1356.271	1366.184	1414.187	1491.611
Emission, ton/h	0.418312	0.411126	0.409386	0.407019
TPL, MW	15.93915	14.60439	15.78595	16.17532
PGEN, MW	399.7536	401.7089	411.9794	429.5196
PLOAD, MW	380.7592	384.0127	396.1935	415.1459
Computational time (Sec)	230.6718	195.8292	248.4771	270.0231

The convergence characteristics of the loadability maximization for the above cases are shown in Fig.5. From this figure, it is observed that, with the proposed UDTPSO, the iteration starts with good initial value and reaches the best final value in less number of iterations when compared to existing PSO method. Similarly with GUPFC, better convergence characteristics are obtained when compared to without and with UPFC.

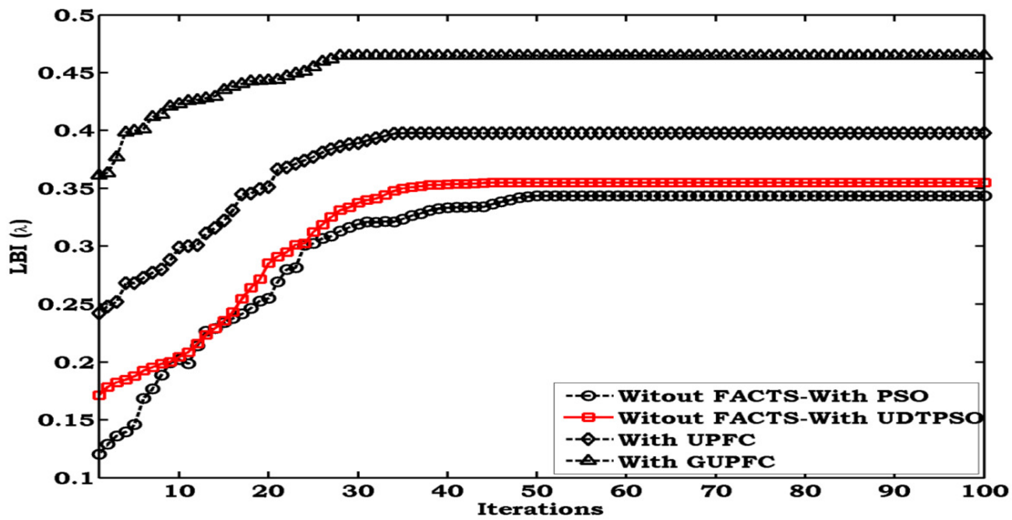

Figure 5: Convergence characteristics of LBI without and with FACTS

The individual area wise loadability values for without and with GUPFC are tabulated in Table.5. From this table, it is observed that, with GUPFC the loadability enhances more when compared to without FACTS. It is also observed that, in area-1, LBI value of 0.1333 is enhanced more when compared to other areas without device. The power flows through tie-lines with GUPFC are tabulated in Table.6.

Table 5: OPF results for area wise system LBI without and with FACTS devices

Area	Case	LBI (λ)	Cost ($/h)	Emission (ton/h)	TPL, MW	PGEN, MW	PLOAD, MW
A1	Without	0.32405	1193.204	0.308477	11.21159	355.5753	341.3077
	GUPFC	0.45739	1354.91	0.27896	10.4513	378.5927	365.1356
A2	Without	0.39871	1193.257	0.222619	7.431708	316.214	305.8075
	GUPFC	0.45256	1212.721	0.216765	6.230903	317.9298	308.8339
A3	Without	0.32372	1117.067	0.246813	8.958255	311.0444	299.1004
	GUPFC	0.45419	1204.525	0.215104	6.197547	314.5347	305.4282

Table 6: Tie-line power flows with GUPFC

S.	Tie	Power Flow (MVA)			
No	Line	AREA (A)	A1	A2	A3
1	4-12	13.9810 -10.1722i	6.8688 - 5.5104i	11.5271 +17.3014i	12.5559 +11.2455i
2	6-10	46.3115 +14.7404i	31.8802 - 7.3447i	37.5190 - 6.8386i	29.6927 -11.3271i
3	9-10	30.5022 -11.1745i	21.5204 +27.1815i	22.4764 - 7.1631i	20.4191 +20.3254i
4	27-28	11.7057 + 5.7898i	7.3941 - 0.2589i	12.2724 + 3.2880i	5.6832 + 2.3240i
5	10-17	5.1667 + 6.6926i	2.6948 - 1.3984i	7.1017 + 4.4538i	-1.0343 + 2.8546i
6	10-20	5.3756 - 3.0358i	4.2800 + 0.0998i	2.0312 - 3.4688i	7.6016 - 1.4076i
7	23-24	23.5688 + 7.7608i	16.2044 + 6.9445i	17.5398 + 4.5225i	20.2292 + 6.3560i

5.2. Scenario-2

In this scenario, the loadability index values with GUPFC under tie-line contingency conditions are tabulated in Table.7. From this table, it is observed that, tie-lines between buses 27-28 and 23-24 are most critical and no loadability is obtained in these contingency cases. Similarly, tie-line between buses 6-10 is critical and less loadability is obtained when compared to remaining contingencies.

Table 7: Overall system and area-wise LBI values under tie-line contingencies

S.No	Tie-Line	A	A1	A2	A3
1	4-12	0.43808	0.45203	0.4151	0.36473
2	6-10	0.32311	0.35428	0.32665	0.33993
3	9-10	0.45147	0.44811	0.44637	0.43257
4	27-28	0.0000	0.0000	0.0000	0.0000
5	10-17	0.45299	0.44412	0.44716	0.44274
6	10-20	0.46079	0.45351	0.42193	0.45212
7	23-24	0.0000	0.0000	0.0000	0.0000

5.3. Scenario-3

In this scenario, area-wise loadability curves are shown in figures 6, 7 and 8. This curve consist, four time slots and the variation of LBI from its base load is shown in the respective zonal LBI curves. The further enhancement of LBI in the respective time zones is tabulated in Table.8. From this table, it is observed that, in 4th time slot, the actual load on the system is high when compared to remaining time slots. Even though, LBI is further enhanced using GUPFC.

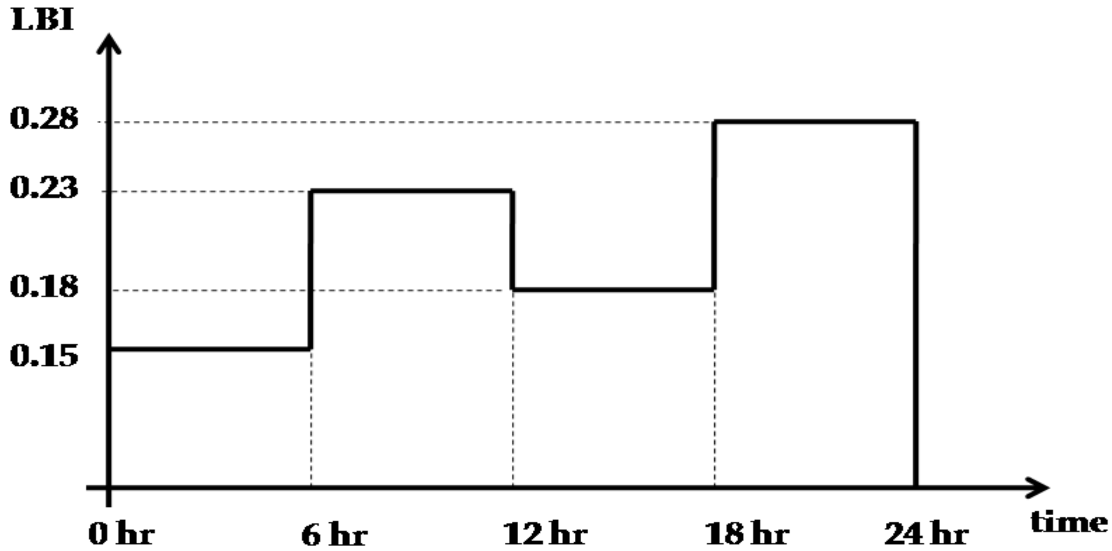

Figure 6: Dynamic LBI curve for area-1

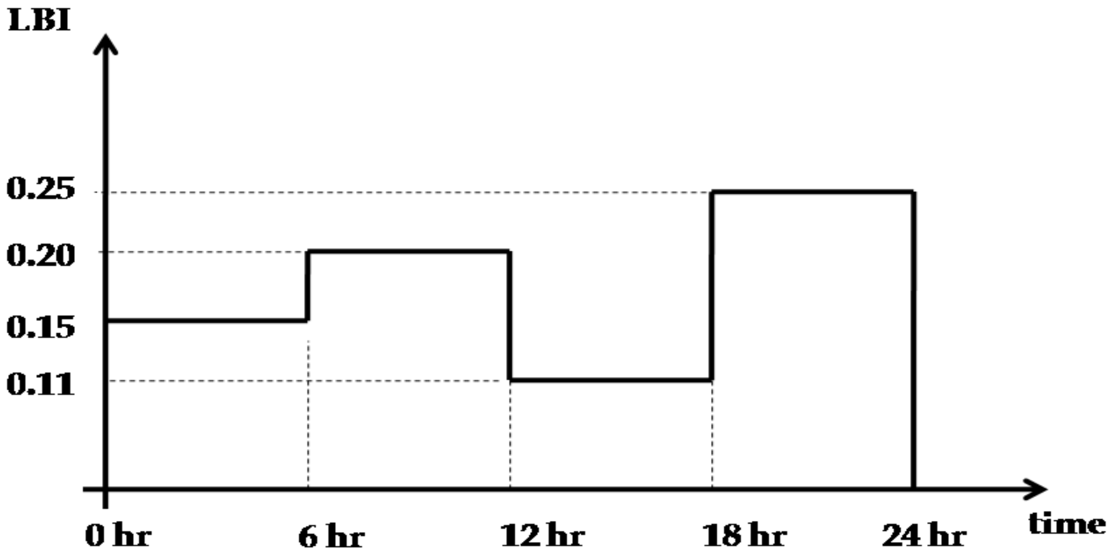

Figure.7. Dynamic LBI curve for area-2

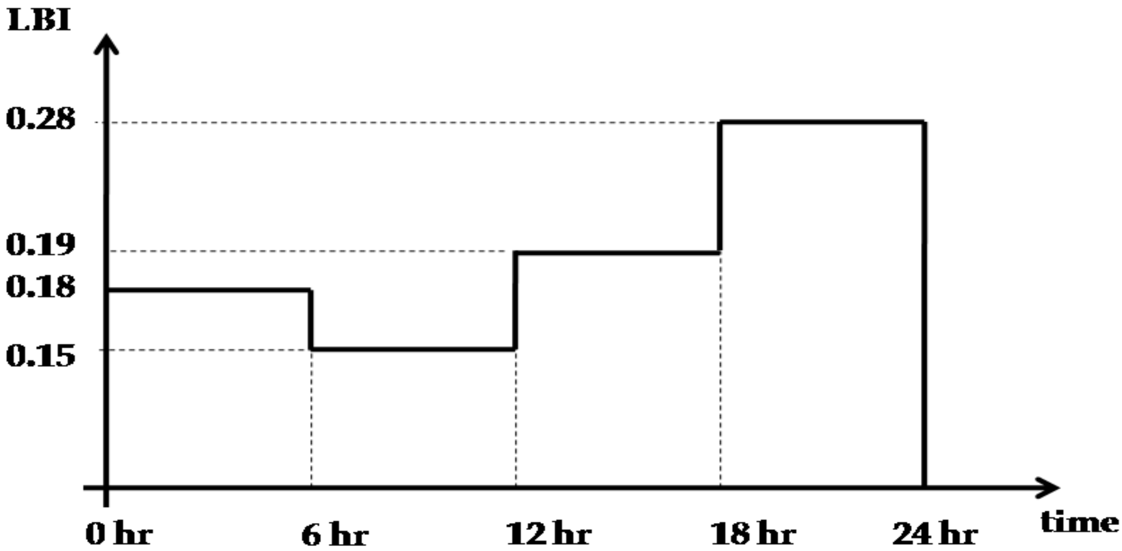

Figure 8: Dynamic LBI curve for area-3

Table 8: Overall system and area-wise LBI values under dynamic load condition

Time slot	Area	LBI (λ)	Cost, $/h	Emission, ton/h	TPL, MW	PGEN, MW	PLOAD, MW
0-6 hr	A	0.25512	1476.654	0.407835	15.24719	429.2185	410.8824
	A1	0.26012	1398.425	0.310649	12.36829	396.13	380.821
	A2	0.26395	1298.43	0.247385	7.71303	355.175	344.4241
	A3	0.2185	1258.117	0.262652	9.501567	352.4214	339.8698
6-12 hr	A	0.19631	1482.548	0.395314	15.67361	429.0771	410.3535
	A1	0.20312	1411.765	0.325367	11.44385	402.1476	387.662
	A2	0.18381	1321.238	0.272055	10.11589	368.5457	355.4121
	A3	0.20408	1327.4	0.262217	9.775274	367.1975	354.3986
12-18 hr	A	0.22582	1458.382	0.401016	15.26869	424.0717	405.7011
	A1	0.24758	1404.117	0.315104	12.22373	398.4781	383.1692
	A2	0.24549	1305.454	0.250775	8.790348	358.1694	346.2772
	A3	0.22534	1295.063	0.252017	8.881927	355.8052	343.9685
18-24 hr	A	0.13759	1486.44	0.400239	16.77808	430.5732	410.7451
	A1	0.13969	1428.288	0.344581	13.46826	409.4779	393.0181
	A2	0.14185	1372.133	0.290731	11.62466	385.5894	371.031
	A3	0.13795	1368.894	0.288853	11.80998	384.315	369.6299

Finally from all these scenarios, it is observed that, with GUPFC the system and area wise LBI can be enhanced more when compared to without FACTS. It is also observed that, the generation fuel cost, emission and TPL increases as LBI increases.

5. Conclusion

In this paper, power injection model of GUPFC with its incorporation procedure in conventional NR load flow is presented. The loadability index (LBI) values for overall system and sub areas are evaluated for static and dynamic loads under normal and contingency cases. The formulated LBI objective is optimized while satisfying equality, in equality and device limits. From the analysis, it is observed that, with GUPFC, LBI value is enhanced more when compared to without and with UPFC. The critical tie-lines are identified and the corresponding system and area-wise LBI values are calculated. Finally, it is concluded that, if the system LBI is increased the non-convex generation fuel cost, emission and total transmission power losses gets increased.

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