Strategy based PSO for Dynamic Control of UPFC to Enhance Power System Security

B. Mahdad, T. Bouktir, and K. *Srairi*

Abstract—Penetration and installation of a new dynamic technology known as Flexible AC Transmission Systems (FACTS) in a practical and dynamic network requires and force expert engineer to develop robust and flexible strategy for planning and control. Unified Power Flow Controller (UPFC) is one of the recent and effective FACTS devices designed for multi control operation to enhance the power system security. This paper presents a dynamic strategy based on Particle Swarm Optimization (PSO) for optimal parameters setting of UPFC to enhance the system loadability. Firstly, we perform a multi power flow analysis with load incrementation to construct a global database to determine the initial efficient bounds associated to active power and reactive power target vector. Secondly a PSO technique applied to search the new parameters setting of the UPFC within the initial new active power and reactive power target bounds. The proposed approach is implemented with Matlab program and verified with IEEE 30-Bus test network. The results show that the approach proposed can converge to the near optimum solution with accuracy, and confirm that flexible multi-control of this device coordinated with efficient location enhance the system security of power system by eliminating the overloaded lines and the bus voltage violation.

Key Words—Dynamic control, System loadability, FACTS, UPFC, PSO, Optimal power flow, Parameters setting, Multi control, Planning and control.

I.   INTRODUCTION

Optimal placement, sizing and control of multi new dynamic compensators known as FACTS devices is a well-researched subject which in recent years interests many expert engineers. Efficient coordination control of unified power flow controller (UPFC) installed in practical networks can result in minimizing operational costs, environmental protection, improved voltage regulation, power factor correction, and power loss reduction [1].

The global optimization techniques known as genetic algorithms (GA), simulated annealing (SA), tabu search (TS), and evolutionary programming (EP), which are the forms of probabilistic heuristic algorithm have been successfully used to overcome the non-convexity problems of the constrained economic dispatch (ED) [2].

Recently, Eberhart and Kennedy suggested a particle swarm optimization (PSO) based on the analogy of swarm of bird and school of fish [3].This new stochastic evolutionary computation technique, based on the movement and intelligence of swarms, has been shown in certain instances to

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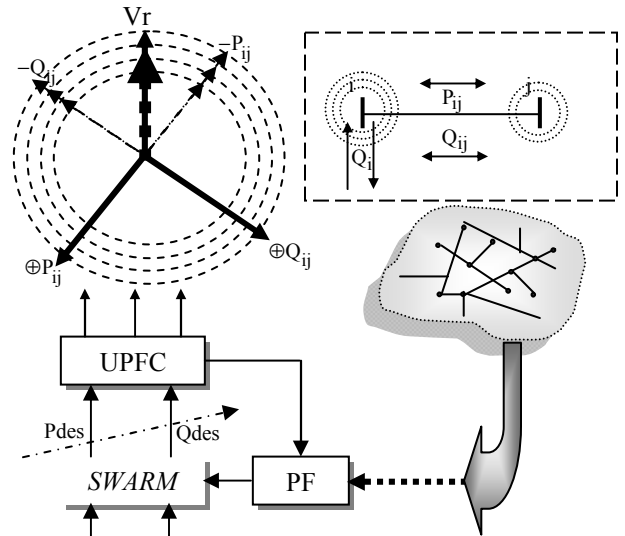
Fig. 1 Strategy based PSO for dynamic control of UPFC

outperform of optimization like genetic algorithms (GA).

The main advantages of the PSO algorithm are summarized as: simple concept, easy implementation, robustness to control parameters, and computational efficiency when compared with mathematical algorithm and other heuristic optimization techniques. Fig. 1 shows the strategy proposed for dynamic control of the UPFC installed at a practical network.

In this paper an approach based PSO proposed as a searching technique for finding the optimal parameters setting of UPFC to enhance the system security. The problem can be separated into two linked parts. The first stage is a PSO for active power planning to minimize the overload in transmission lines while the second stage is the reactive power planning to adjust the voltage deviations.

II.   UNIFIED POWER FLOW CONTROLLER (UPFC) MODELIZATION

An equivalent circuit of the UPFC as shown in Fig. 4 can be derived based on the operation principle of the UPFC [4 -5]. In the equivalent, the UPFC is represented by the following voltage sources:

$$E_{vR} = V_{vR}\left(\cos(\delta_{vR}) + j\sin(\delta_{vR})\right) \qquad (1)$$

$$E_{cR} = V_{cR}\left(\cos(\delta_{cR}) + j\sin(\delta_{cR})\right) \qquad (2)$$

Where V_{vR} and V_{cR} are the controllable magnitude

$V_{vR}^{\min} \leq V_{vR} \leq V_{vR}^{\max}$, and phase angle

$0 \leq \delta_{vR} \leq 2\pi$ of the voltage source representing the shunt converter. The magnitude V_{cR} and phase angle δ_{cR} of the voltage source representing the series converter are controlled between limits:

$V_{cR}^{\min} \leq V_{cR} \leq V_{cR}^{\max}$, and $0 \leq \delta_{cR} \leq 2\pi$.

For the series converter:

$$P_{cR} = V_{cR}^2 G_{mm} + V_{cR}V_k[G_{km}\cos(\delta_{cR}-\theta_k)+B_{km}\sin(\delta_{cR}-\theta_k)] \\ + V_{cR}V_m[G_{mm}\cos(\delta_{cR}-\theta_m)+B_{mm}\sin(\delta_{cR}-\theta_m)],$$ (3)

$$Q_{cR} = -V_{cR}^2 B_{mm} + V_{cR}V_k[G_{km}\sin(\delta_{cR}-\theta_k)-B_{km}\cos(\delta_{cR}-\theta_k)] \\ + V_{cR}V_m[G_{mm}\sin(\delta_{cR}-\theta_m)-B_{mm}\cos(\delta_{cR}-\theta_m)],$$ (4)

- For the shunt converter:

$$P_{vR} = -V_{vR}^2 G_{vR} + V_{vR}V_k[G_{vR}\cos(\delta_{vR}-\theta_k)+B_{vR}\sin(\delta_{vR}-\theta_k)],$$ (5)

$$Q_{vR} = V_{vR}^2 B_{vR} + V_{vR}V_k[G_{vR}\sin(\delta_{vR}-\theta_k)-B_{vR}\cos(\delta_{vR}-\theta_k)].$$ (6)

and assuming loss-less converter: $P_{vR} + P_{cR} = 0$

The active and reactive power flow equations are:
At bus k:

$$P_k = V_k^2 G_{kk} + V_k V_m[G_{km}\cos(\theta_k-\theta_m)+B_{km}\sin(\theta_k-\theta_m)] \\ + V_k V_{cR}[G_{km}\cos(\theta_k-\delta_{cR})+B_{km}\sin(\theta_k-\delta_{cR})] \\ + V_k V_{vR}[G_{vR}\cos(\theta_k-\delta_{vR})+B_{vR}\sin(\theta_k-\delta_{vR})]$$ (7)

$$Q_k = -V_k^2 B_{kk} + V_k V_m[G_{km}\sin(\theta_k-\theta_m)-B_{km}\cos(\theta_k-\theta_m)] \\ + V_k V_{cR}[G_{km}\sin(\theta_k-\delta_{cR})-B_{km}\cos(\theta_k-\delta_{cR})] \\ + V_k V_{vR}[G_{vR}\sin(\theta_k-\delta_{vR})-B_{vR}\cos(\theta_k-\delta_{vR})]$$ (8)

At bus m:

$$P_m = V_m^2 G_{mm} + V_m V_k[G_{mk}\cos(\theta_m-\theta_k)+B_{mk}\sin(\theta_m-\theta_k)] \\ + V_m V_{cR}[G_{mm}\cos(\theta_m-\delta_{cR})+B_{mm}\sin(\theta_m-\delta_{cR})],$$ (9)

$$Q_m = -V_m^2 B_{mm} + V_m V_k[G_{mk}\sin(\theta_m-\theta_k)-B_{mk}\cos(\theta_m-\theta_k)] \\ + V_m V_{cR}[G_{mm}\sin(\theta_m-\delta_{cR})-B_{mm}\cos(\theta_m-\delta_{cR})],$$ (10)
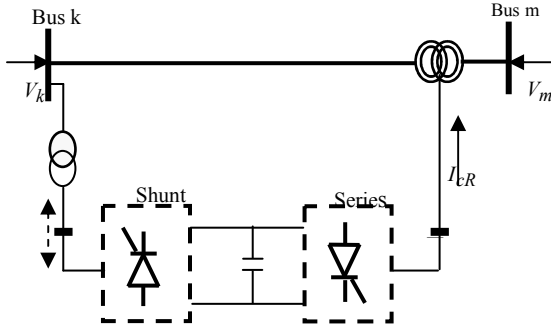
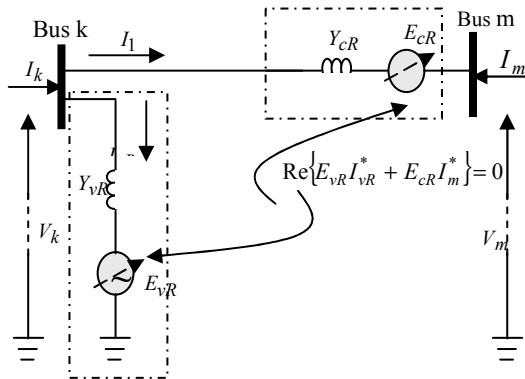

Fig. 3 UPFC Operation principales.

Fig. 4 Equivalent circuit based on solid-state voltages sources.

A. Multi Function Control

The objective function of the multi control functional operation of FACTS devices is the combination from the prescribed control targets:

$$FMC = \alpha_1|P-P^{des}| + \alpha_2|Q-Q^{des}| + \alpha_3|V-V^{des}| \quad (11)$$

Where: FMC the objective function of the multi control;

P^{des}, Q^{des}, and V^{des} are the control targets of active and reactive power flow along line, and voltage of bus K, respectively.

Coefficients α_1, α_2, and α_3 can take 1 or 0 based in the control strategy adopted.

For a power system with N_{UPFC} devices integrated in practical network to enhance the power system security, the optimization objective is:

$$Min\ F \quad (12)$$

Fig. 5 shows the three control modes representation. The mathematical descriptions of the three control modes of the UPFC Compensators are presented as follows.

Target 1: Bus Voltage Control
The bus Voltage control constraint is given by

$$V_m - V_m^{des} = 0 \quad (13)$$

where V_m^{des} is the desired bus voltage control

Target 2: The active Power Flow Control

$$P_{mk} - P_{mk}^{des} = 0 \quad (14)$$

where P_{mk}^{des} is the desired active power control

Target 3: The Reactive Power Flow Control

$$Q_{mk} - Q_{mk}^{des} = 0 \quad (15)$$

where Q_{mk}^{des} is the desired reactive power control.
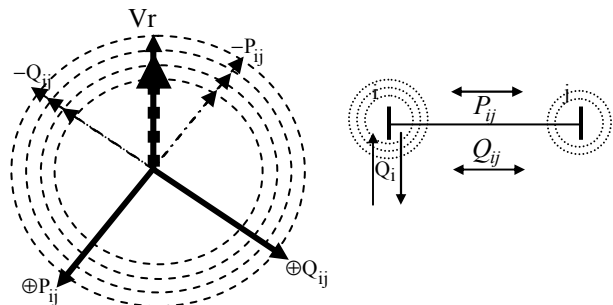
Fig. 5 Three control mode: voltage, active and reactive power control

B. Objective Function

The main objective of this study is to determine the optimal parameters setting of the UPFC installed in the practical power network to minimize the overloaded lines and the bus voltage violations at different load incrementation. The strategy consists on decomposing the objective function in two linked stages:

Stage1: Active power planning at a specified reactive power control. The objective function can be expressed as follows:

$$Min\ OPI = \sum_{i=1}^{Nline} \left| \frac{P_{ij}}{P_{ij}^{\max}} \right| \quad (16)$$

St. $P_{ij} \leq P_{ij}^{\max}$ (17)

$$V_{cR}^{\min} \leq V_{cR} \leq V_{cR}^{\max} \qquad (18)$$

$$V_{vR}^{\min} \leq V_{vR} \leq V_{vR}^{\max} \qquad (19)$$

$$V_i^{\min} \leq V_i \leq V_i^{\max} \qquad (20)$$

Where:

OPI represents the overload index in lines

P_{ij} and $P_{ij}^{\max}$ represent the current active power in line (i-j) and the active power rate of line (i-j), respectively.

V_i represents the voltage magnitude at bus i;

Stage 2: Reactive power planning at the active optimal power desired. The objective function consists to minimize the voltage magnitudes deviation at load buses. The formulation of the objective function is expressed as follows:

$$Min = \left\{ \sum_{i=1}^{NL} \left| V_k - V_k^{ref} \right| \right\} \qquad (21)$$

St. $OPI \leq OPI^{desired}$ (22)

$$V_{cR}^{\min} \leq V_{cR} \leq V_{cR}^{\max} \qquad (23)$$

$$V_{vR}^{\min} \leq V_{vR} \leq V_{vR}^{\max} \qquad (24)$$

Where:

$OPI^{desired}$ represents the desired optimal overload index obtained during the first stage.

NL is the number of load buses; V_k^{ref} is the prespecified reference value of the voltage.

II. OVERVIEW OF PSO TECHNIQUE

The PSO can best be understood thought an analogy similar to the one that led to the development of the PSO. Imagine a swarm of bees in a field [3]. Their goal is to find in the field the location with the highest density of flowers without any knowledge of the field a priori, the bees begin in random locations with random velocities looking for flowers each bee can remember the locations that it found the most flowers, and somehow knows the locations where the others bees found an abundance of flowers. The main target is that the bees explore the field: overflying locations of greatest concentration hoping to find the absolute highest concentration of flowers. Soon, all the bees swarm around this point. Unable to find any points of higher flower concentration, they are continually drawn back to the highest flower concentration as indicated in Fig. 6 (a, b).
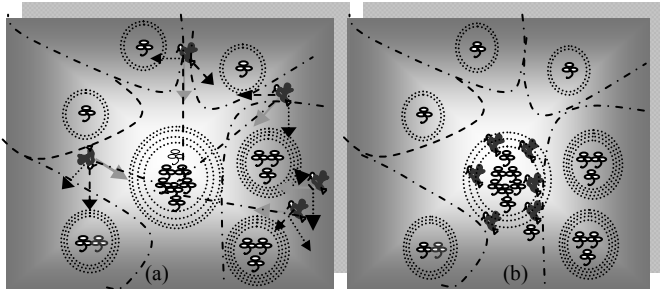

Fig . 6 (a) swarm mechanism search: The particles in PSO are attracted both to the area of highest concentration found by the entire swarm, and the best location personally encountered by the particle.
(b) All the bees swarm around the best location.

A. Problem Formulation

Let $X_i = (x_{i1}......x_{in})$, and $V_i = (v_{i1}.......v_{in})$ denote the coordinates and the corresponding flight speed of the particle i in a search space, respectively. The velocity of the particle is changed according to the relative locations of $Pbest$ and $Gbest$. It is accelerated in the directions of these locations of greatest fitness according to the following equation [6].

$$V_i^{k+1} = \omega V_i^k + c_1 rand \times \left(Pbest_i^k - X_i^k \right) \qquad (25)$$
$$+ c_2 Rand \times \left(Gbest_i^k - X_i^k \right)$$

where

V_i^k velocity of particle i at iteration k;

ω inertia weight factor;

c_1, c_2 acceleration constant;

X_i^k position of particle i at iteration k;

$Pbest_i^k$ best position of particle i until iteration k;

$Gbest_i^k$ best position of group until iteration k;

Once the velocity has been determined it is simple to move the particle to its next location, and a new coordinate X_i^{k+1} is computed for each of the N dimensions according the following equation:

$$X_i^{k+1} = X_i^k + V_i^{k+1} \qquad (26)$$
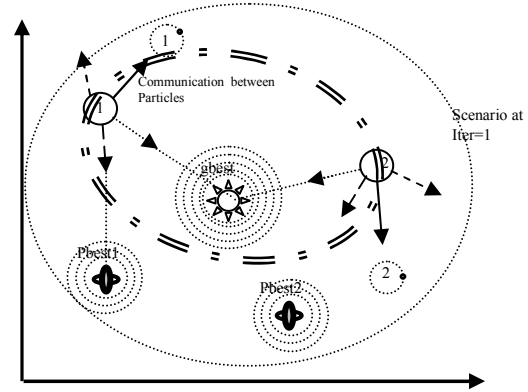
Fig. 7 The search mechanism of the particle swarm optimization

B. Algorithm Steps for UPFC Parameters Control:

In this paper the following variables are considered as the optimization variables:

- The series voltage source (V_{cR}) of the UPFC is considered as the first variable to be adjusted. The working range for this variable is [0.02 0.2].
- The second variable to be optimized is the shunt voltage source (V_{vR}), the working range for this variable is [0.9 1.1].

The main idea is that these variables are optimized indirectly by adjusting the active power desired and the reactive power desired at a specified line to enhance the power system security.

The series voltage source and the shunt voltage source of the UPFC Controller are taken as the particles of the PSO. Then the PSO algorithm is as follows.

Step1: the particles are randomly generated between the maximum and minimum operating limits of UPFC parameters: in this paper, the structure of a particle for UPFC parameters adjustment problem is composed of a set of element (Active power desired, reactive power desired and voltage desired).

Step2: The particle velocities are generated randomly.

Step3: Objective function values of the particles are evaluated. These values are set the best value of the particles.

Step4: the best value among all the pbest values (gbest) is identified.

Step5: new velocities for the particles are calculated using (25). The new velocity is simply the old velocity scaled by ω and increased in the direction of gbest and pbest for that particle dimension. c_1 and c_2 are scaling factors that determine the relative 'pull' of pbest and gbest. c_1 is a factor determining how much the particle is influenced by the memory of his best location, and c_2 is a factor determining how much the particle is influenced by the rest of the Swarm.

In this paper, the weighting factor is defined as follows [6], [10]:

$$\omega = \omega_{\max} - \frac{\omega_{\max} - \omega_{\min}}{Iter_{\max}} \times Iter \qquad (27)$$

where

$\omega_{\max}, \omega_{\min}$ initial, final weights;

$Iter_{\max}$ maximum iteration number;

$Iter$ current iteration number.

Step6: the positions for each particle are updated using (26). The resulting position of a particle is not always guaranteed to satisfy the inequality constraints.

If $v_{i,j} > V_j^{\max}$, then $v_{i,j} = V_j^{\max}$. If $v_{i,j} < V_j^{\min}$, then $v_{i,j} = V_j^{\min}$

Stap7: New objective function values are calculated for the new positions of the particles. If the new value is better than the previous pbest, the new value is set to pbest. If the stopping criterion is met, the positions of particles represent the optimal solution; otherwise the procedure is repeated from step4.

III. APPLICATION STUDY

The algorithm proposed is developed in the Matlab programming language using 6.5 version. The proposed strategy is tested using modified IEEE 30-bus system. The test examples have been run on a 2.6-Ghz Pentium-IV PC.

IEEE 30-Bus power system test consists on six generators, thirty buses, forty one transmission lines, and twenty one loads. For the voltage constraint the lower and upper limits are 0.9 p.u and 1.07 p.u., respectively, (expect for PV buses where $V_{\max} = 1.1$ p.u.).

In this study the increase in the load is regarded as a parameter which affects the power system to voltage collapse.

$$\begin{cases} P_L = \lambda P_{oL} \\ Q_L = \lambda Q_{oL} \end{cases} \qquad (28)$$

Where, P_{oL} and Q_{oL} are the active and reactive base loads, P_L and Q_L are the active and reactive loads at bus L for the current operating point.

Table. I shows the transmission line loading without UPFC installation and without load incrementation, the line (1-2) is loaded at the rating 116.56 MW which is near to the maximum rating level (130 MW). The main goal of the algorithm proposed is to keep the critical buses under their rating level with load incrementation to enhance the power system security. Table. II depicts the results for one UPFC installed at line 3-4 at loading factor equal 1.18 (PD= 334.142 MW), with the optimized parameters setting of the UPFC, the transmission lines loading for critical buses are reduced and maintained on their security limits. For this loading factor (1.18) the line 1-2 is loaded to the rating 100.4706 MW which is lesser than the base case at loading factor equal 1 (PD=283.4 MW).

TABLE I
TRANSMISSION LINE LOADING WITHOUT UPFC INSTALLATION FOR IEEE 30-BUS WITH LOADING FACTOR = 0%

Line	Rating (MVA)	From Bus P(MW)	To Bus P(MW)
	Loading Factor λ=1.00		
	Without UPFC		
	PD=283.4 MW		
1-2	130	116.6500	-114.40
1-3	130	61.6900	-60.20
2-4	65	32.1800	-31.64
3-4	130	57.8000	-57.39
2-5	130	63.6700	-61.96
2-6	65	43.4200	-42.45
4-6	90	49.2300	-48.95
5-7	70	-13.0400	13.140
6-7	130	36.2700	-35.940
6-8	32	8.3700	-8.360
6-9	65	18.6400	-18.640
6-10	32	13.1300	-13.130
9-11	65	-11.8200	11.820
9-10	65	30.4600	-30.460
4-12	65	32.2100	-32.210
12-13	65	-12.1600	12.160
12-14	32	7.6500	-7.590
12-15	32	18.1300	-17.940
12-16	32	7.3900	-7.340
14-15	16	1.3900	-1.380
16-17	16	3.8400	-3.830
15-18	16	5.9700	-5.930
18-19	16	2.7300	-2.730
19-20	32	-6.7700	6.790
10-20	32	9.0600	-8.990
10-17	32	5.1700	-5.170
10-21	32	15.9000	-15.820
10-22	32	7.6500	-7.610
21-22	32	-1.6800	1.680
15-23	16	5.1600	-5.13
22-24	16	5.9300	-5.90
23-24	16	1.9300	-1.9200
24-25	16	-0.8800	0.8800
25-26	16	3.5400	-3.5000
25-27	16	-4.4200	4.4500
27-28	65	17.7000	-17.7000
27-29	16	6.1900	-6.1200
27-30	16	7.0600	-6.9200
29-30	16	3.7200	-3.6800
8-28	32	2.7600	-2.7500
6-28	32	14.9800	-14.9500
Ploss (MW)	**9.080**		

Table. IV shows the optimal parameters setting of the UPFC obtained by applying simple PSO technique.

Fig. 8 shows the voltage magnitude at different buses for different loading factor which are all on their security limits.

Fig. 9 shows the active power rating for all transmission lines with load incrementation equal 18%.

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Line	Rating (MVA)	From Bus P(MW)	To Bus P(MW)
12-15	32	19.8689	-19.5499
12-16	32	8.9419	-8.8258
14-15	16	1.9355	-1.9223
16-17	16	4.9758	-4.9363
15-18	16	7.4715	-7.3976
18-19	16	3.8776	-3.8634
19-20	32	-6.5866	6.6022
10-20	32	9.1039	-9.0222
10-17	32	4.9725	-4.9637
10-21	32	15.4119	-15.2899
10-22	32	7.0978	-7.0442
21-22	32	-3.9601	3.9624
15-23	16	4.9801	-4.9278
22-24	16	3.0818	-3.0611
23-24	16	1.4078	-1.3887
24-25	16	-5.1202	5.1740
25-26	16	3.9069	-3.8500
25-27	16	-9.0810	9.1882
27-28	65	9.9017	-9.9017
27-29	16	0.7135	-0.7039
27-30	16	14.2014	-13.6073
29-30	16	-1.9361	1.9473
8-28	32	2.1337	-2.1288
6-28	32	7.7824	-7.7729
Ploss(MW)		**10.83**	

TABLE II
TRANSMISSION LINE LOADING AFTER UPFC INSTALLATION FOR IEEE 30-BUS WITH LOADING FACTOR = 18%

Line	Rating (MVA)	From Bus P(MW)	To Bus P(MW)
		Loading Factor λ=1.18 *One UPFC at Line 3-4* **PD=334.412 MW**		
1-2	130	100.4706	-98.7456
1-3	130	95.3835	-91.5885
2-4	65	24.4277	-24.0990
3-4	130	73.6479	-72.9896
2-5	130	67.6187	-65.5868
2-6	65	36.6332	-35.8943
4-6	90	54.0395	-53.7160
5-7	70	-18.4892	18.7906
6-7	130	46.2327	-45.6946
6-8	32	6.4701	-6.4393
6-9	65	14.9808	-14.9808
6-10	32	12.5666	-12.5666
9-11	65	-20.8400	20.8400
9-10	65	35.8208	-35.8208
4-12	65	34.0811	-34.0811
12-13	65	-17.2400	17.2400
12-14	32	9.2818	-9.1643
12-15	32	20.3730	-20.0243
12-16	32	8.4503	-8.3311
14-15	16	1.8483	-1.8342
16-17	16	4.2011	-4.1620
15-18	16	7.3896	-7.3126
18-19	16	3.5366	-3.5226
19-20	32	-7.6874	7.7088
10-20	32	10.4115	-10.3048
10-17	32	6.4724	-6.4580
10-21	32	16.8443	-16.6991
10-22	32	7.8153	-7.7510
21-22	32	-3.9509	3.9533
15-23	16	4.7928	-4.7350
22-24	16	3.7977	-3.7704
23-24	16	0.9590	-0.9370
24-25	16	-5.5587	5.6229
25-26	16	4.1965	-4.1300
25-27	16	-9.8194	9.9461
27-28	65	10.8789	-10.8789
27-29	16	0.9327	-0.9201
27-30	16	15.1085	-14.4319
29-30	16	-1.9119	1.9239
8-28	32	1.5393	-1.5326
6-28	32	9.3601	-9.3463
Ploss (MW)		**12.64**	

TABLE III
TRANSMISSION LINE LOADING AFTER UPFC INSTALLATION FOR IEEE 30-BUS WITH LOADING FACTOR=10%

Line	Rating (MVA)	From Bus P(MW)	To Bus P(MW)
		Loading Factor λ=1.10 *One UPFC at Line 3-4* **PD= 311.74 MW**		
1-2	130	74.1832	-73.2322
1-3	130	95.2485	-91.4636
2-4	65	17.2465	-17.0768
3-4	130	74.6223	-73.9478
2-5	130	61.7590	-60.0617
2-6	65	29.2967	-28.8222
4-6	90	53.0735	-52.7649
5-7	70	-20.3383	20.6573
6-7	130	46.2747	-45.7373
6-8	32	1.1639	-1.1537
6-9	65	14.7628	-14.7628
6-10	32	11.6033	-11.6033
9-11	65	-16.6000	16.6000
9-10	65	31.3628	-31.3628
4-12	65	29.5911	-29.5911
12-13	65	-20.4000	20.4000
12-14	32	8.8603	-8.7555

TABLE IV
PARAMETERS SETTING OF THE UPFC AT DIFFERENT LOADING FACTOR

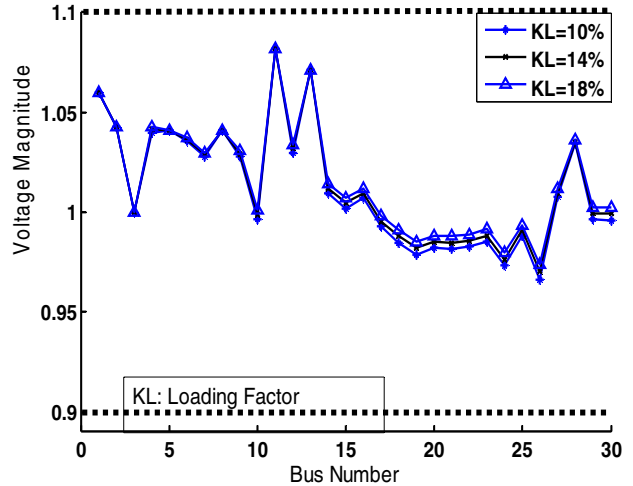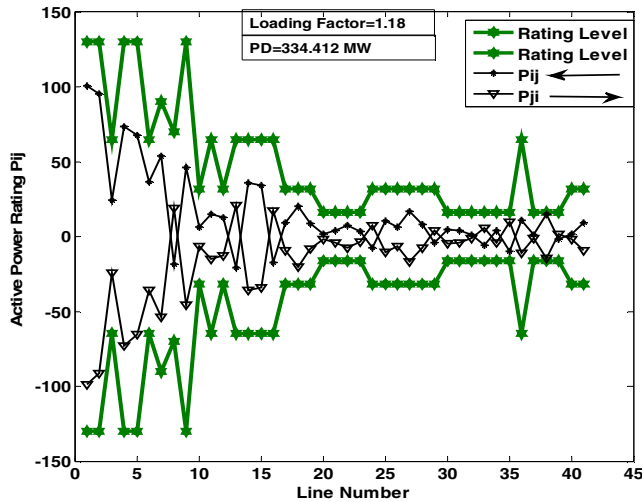| p.u	λ=1.1 (p.u)	λ=1.14(p.u)	λ=1.18(p.u)
	Loading Factor *One UPFC at Line 3-4*		
V_{cR}	0.1397	0.1297	0.1135
V_{vR}	1.0001	1.0002	1.0002
OPI	15.8269	16.5855	17.3221
$Ploss$	0.1083	0.1181	0.1264
V min	0.9738	0.9701	0.9664
PD (MW)	311.74	323.076	334.4120

Fig. 8 Voltage magnitude at different loading factor.

Fig. 9 Active power rating level at loading factor =1.18 (PD=334.412 MW).

IV. CONCLUSION

In this paper a simple strategy for planning and control of versatile FACTS devices known as UPFC to enhance the system security is presented and demonstrated on the practical IEEE 30-Bus power system network at different load incrementation. The main idea of the approach proposed based PSO technique is to decompose the control strategy into two stages, the active power planning designed to minimize the overload index for all lines, and in the second stage a complementary reactive power control to adjust the voltage magnitude deviation.

The results show that the approach proposed confirm that flexible multi-control of this device coordinated with efficient location enhance the system security of power system by eliminating the overloaded lines and the bus voltage violation without affecting the physical constraints.

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