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COST EFFECTIVE SOLUTION FOR OPTIMAL PLACEMENT AND PARAMETER SETTING OF MULTIPLE UPFC USING PARTICLE SWARM OPTIMIZATION

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ABSTRACT

The Unified Power Flow Controller (UPFC) is one of the most important Flexible AC Transmission System (FACTS) device which is used to improve the stability of the power system. The performance of the UPFC mainly depends upon the location and parameters setting of this device in the system. In this paper the location and parameter setting of the UPFC devices are found using Particle Swarm Optimization (PSO), such as to obtain improved voltage profile, minimal total system loss, minimal reactive power transfer and maximization of the stability limit. Further it proposes a cost effective objective function in which the coefficients of the system parameters in the objective function are so chosen that they reflect real time cost or penalty value. The effectiveness of the proposed objective function is tested in IEEE-30 bus test system with multiple UPFC devices. The results of optimal placement and size of UPFC using PSO with cost effective objective function and conventional objective function are compared. The cost effective objective function provides better results as compared to conventional solution.

Keywords: *FACTS, UPFC, Particle Swarm Optimization (PSO), Stability, Loadability.*

1. INTRODUCTION

Modern power systems are becoming increasingly stressed because of increasing demand and are difficult to control. Issues such as limited investment in generation, economic and environmental limitation, competitive business environment etc. have forced the modern power systems to optimally utilize their existing generation and transmission facility. This has resulted in stressed operating condition of power systems close to their stability limits. These stressed power systems are experiencing a new threat of voltage instability. Several incidents of system collapse for the past one decade are mainly caused by the voltage instability. Voltage collapse is characterized by a slow variation in the system operating point, due to increase in the loads, in such a way that the voltage magnitude gradually decreases until a sharp accelerated change occurs.

One of the most important FACTS device UPFC can play an important role in the power system security enhancement. However, considering the high capital investment involved in adopting UPFC devices it becomes essential to optimize the overall cost involved by optimally choosing the size and the location of the UPFC devices in the power system. UPFC can regulate the active and reactive power control as well as adaptive to voltage-magnitude control simultaneously because of its flexibility and fast control characteristics. Placement of this device in suitable location can lead to control in line flow and maintain bus voltages at desired level thereby improving the voltage stability margins.

Rajive Tiwari et.al [1] proposed a decoupled model of UPFC for improving the voltage stability margin which is evaluated using the L-index. A single UPFC is alone used to improve the voltage stability.

C. R. Foerte-Esquivel et.al [2] presented comprehensive load flow model of UPFC which is a straightforward extension of the power flow equations and it is incorporated into an existing Newton-Raphson load flow algorithm.

The modeling of lossless UPFC-embedded transmission lines including the effect of line charging susceptance is presented by Muwaffaq I. Alomoush [3]. A. Nabavi-Niaki et.al [4] proposed comprehensive development procedures and

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mathematical models of UPFC for steadystate, transient stability and eigenvalue studies.

The above references are not considered the initial conditions of UPFC. The improper selection of initial conditions of UPFC degrades Newton's quadratic convergence, or more seriously, cause the solution to oscillate or even diverge. C.R. Fuerte-Esquivel et.al [5] investigated the influence of the UPFC initial conditions on convergence and derived the analytical equations to give good UPFC initial conditions.

Genetic Algorithms (GA) and PSO have been applied by H. I. Shaheen etal [6] to find out the optimal location and the optimal parameters setting of UPFC device under single contingencies to eliminate or minimize the overloaded lines and bus voltage violations.

Ch.Rambabu et.al [7] introduce optimal placement of the multiple type FACTS such as TCSC, SVC and UPFC to reduce the line losses and improve the voltage profile. K.R.Padiyar et.al [8] proposes a control strategy for UPFC in which to control real power flow through the line, while regulating magnitudes of the voltages at its two ports. The steady state and transient characteristics of UPFC is analyzed by Yao Shu-jun, et.al [9].

Ashwin Kumar Sahoo et.al [10] presents an application of Single- Input Fuzzy Logic Controller (SFLC) to determine the control signal of UPFC for improvement of power system stability. A dual-bridge matrix converter model with its control scheme for UPFC is presented by R. Norouzizadeh et.al [11]. In this model, the two converters and the capacitor in the UPFC's structure are replaced with a dual-bridge matrix converter which results in considerable decrease in UPFC's cost and volume.

P. S. Venkataramu et.al [12] proposed a placement strategy for UPFC, which enhances the Voltage Stability Margin of the system. The location for the installation of UPFC is identified using voltage stability index (VSI) and the voltage change index (VCI). J.guo et.al [13] proposed a control strategy for UPFC to damp the active power oscillations and maintain the UPFC shunt bus voltage. K. Visakha et.al [14] presented an approach for selection of UPFC suitable locations considering normal and network contingencies using L-index.

Mehmet Tumay et.al [15] proposed the steady-state modeling of UPFC for the implementation of the device in the conventional Newton-Raphson (NR) power flow algorithm. The operating principles and the unique control features of a variable structure unified power flow controller (VSUPFC) on the basis of its feasible hardware implementations, working modes, advanced control functions and flexibilities under different system operating conditions are investigated by Tsao-Tsung Ma [16] using recurrent fuzzy neural controllers.

The mathematical model of UPFC and transient stability improvement using UPFC is presented by Prechanon Kumkratug [17]. The cost/worth of UPFC impacts on Available transfer capability is evaluated by Mahmud Fotuhi-Firuzabad et.al [18]. Shahrokh Shojaeian et.al [19] propose adaptive input-output feedback linearization control (AIFLC) technique in order to damp the low frequency oscillations of practical multi-machine multi-UPFC power systems.

This paper is mainly concerned with the improvement of voltage stability by optimal sizing and allocation of a multiple UPFC using PSO. The main feature of the proposed algorithm is, the fitness function or objective function of algorithm has included the cost of real power and UPFC device. UPFC device model is incorporated into a Newton- Raphson algorithm to perform load flow analysis. Decoupled model is used for modeling UPFC in power flow study without modifying of Jacobian matrix elements. PV curve of weak buses are drawn for analyzing the voltage maintenance under different load conditions (for different values of λ).

2. PARTICLE SWARM OPTIMIZATION

Particle Swarm Optimization (PSO) is a one of the powerful tool for power system optimization problems. The PSO mimics the behaviors of individuals in a swarm to maximize the survival of the species. In PSO, each individual decides based on its own experience Pbest as well as other individual's experiences Gbest. Deception of velocity and position updates in PSO are shown in figure 1. The modified velocity and position of each particle can be calculated using the current velocity and distance from $pbest_{id}$ to $gbest_{id}$ as shown in the various following equations:

$$v_{id}^{(t+1)} = \left[W_{id} * v_{id}^{t} + C_1 * rand_1() * (pbest_{id} - x_{id}^{(t)}) + C_2 * rand_2() * (gbest_{id} - x_{id}^{(t)}) \right], \quad (1)$$

$$x_{id}^{(t+1)} = x_{id}^{(t)} + v_{id}^{(t+1)}$$
$$i = 1, 2, \ldots, n, \quad d = 1, 2, \ldots, m \quad (2)$$

where,

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$V_{id}^{(t)}$: Velocity of particle i at iteration t; in d - dimensional space,

$V_{d,min} \leq V_{id}^{(t)} \leq V_{d,max}$

$X_{id}^{(t)}$: Current position of particle i at iteration t,
Wid : Inertia weight factor,
t : Number of iterations,
n : Number of particles in a group,
m : Number of members in a particle,
C1, C2 : Acceleration constants,
rand1 ( ) , ran2( ): Random number between 0 and 1.

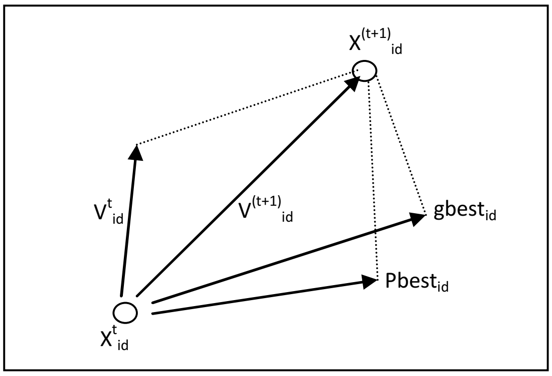

Figure.1. Deception of velocity and position updates in PSO.

3. OBJECTIVE OF THE OPTIMIZATION

In electric power systems, the load demand is seldom constant. The load demand is increases day by day. It is difficult to change transmission utility with the increasing demand. The main aim of the objective function is to obtain the best utilization of the existing transmission utility and voltage profile under various load conditions. In this respect, the FACTS devices are located so as to

(i) minimize the voltage deviations in the system
(ii) minimize power system total loss
(iii) have the minimum possible UPFC sizes and
(iv) maximize loadability limit

The above multi objective optimization problem is transformed into a single objective optimization problem. The fitness function is made by four objectives as follows.

The first objective is to maintain the voltage level under different loading conditions. In order to account for the voltage deviation the parameter Fv in the objective function is evaluated using the fitness function given by equation (3)

$$F_v = \sqrt{\sum_{i=1}^{30} (V_i - 1)^2} \qquad (3)$$

where i=1…30 is the number of buses and V_i is the voltage of bus i.

The second objective is to minimize the line losses. For ensuring the minimization of the power system losses system loss parameter F_L is evaluated using equation (4) and (5).

$$P_{Lk} = P_{sending} - P_{recieving} \qquad (4)$$

$$F_L = P_{L\_total} = F_{loss} = \sum_{1}^{41} P_{lk} \qquad (5)$$

where P_{lk} indicates the loss in line ending to buses l and k, and $F_L = F_{loss}$ represents the total loss of power network and 1….41 is the no. of lines in the IEEE 30 bus system.

The third objective is to minimize the UPFC sizes. For optimal choice of the UPFC size parameter F_s in the objective function is evaluated using the fitness function as given in equation (6).

$$F_s = \sum_{j=1}^{2} S_j \qquad (6)$$

where the number of UPFC is 2 and S_j is the value of UPFC in MVA.

For the best utilization of the existing transmission facility steady state stability plays important role for ensuring best utilization fourth parameter of the objective function F_{ML} is concerned with steady state stability limit. This is evaluated as inverse of maximum loadability as per equation (7).

$$F_{ML} = \frac{1}{\lambda_{crit}} \qquad (7)$$

Thus, the objective function is given by equation (8):

$$F = \omega_1 F_V + \omega_2 F_L + \omega_3 F_S + \omega_4 F_{ML} \qquad (8)$$

where, functions F_V , F_L , F_S and F_{ML} are given by equations (3), (5), (6) and (7) respectively. The weightage factor that multiplies each term of objective is adjusted to reflect the relative importance that each goal has with respect to the other. For conventional solution, it is decided to give equal importance to all objective terms, giving values of ω_1= 1, ω_2 =1/ (base case loss), ω_3 = 1/(No. of UPFC*250) and ω_4 = 1, so that the four terms in

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the fitness function are comparable in magnitude. UPFC size is limited to be between 0 MVA and 250 MVA. So denominator term for ω_3 is taken as number of UPFC devices multiplied by 250. Thus equal weight-age is given to all parameters in the objective function.

The equal weight-age for all parameters need not provide the best solution always in practice. Mostly, it will lead to more investment in reactive power compensation. To avoid such problem, in the proposed algorithm, the value of weight multiplier for each parameter is decided based on the real time cost of each parameter. ω_2 is the weight multiplier for the real power loss and it is taken as the cost of generating the power. (ω_2 is taken as Rupees 5crore per MW. It is the cost of thermal power generation). ω_3 is the weight multiplier for UPFC size and it is taken as the cost of UPFC device. (ω_3 = Rs50 lakhs per MVA) ω_1 and ω_4 are weight multipliers for voltage deviation and loadability limit. Since the cost cannot be specified, a penalty is levied for voltage deviation and loadability. (Rs10 crore and 5 crore respectively). Objective function with respective cost weight-age multipliers for the parameters is termed as cost effective objective function. The flow chart of proposed algorithm is as shown in Fig.2.

4. DISCUSSION OF RESULTS

The proposed algorithm is tested in IEEE 30 bus test system. Under specified loading conditions the system is able to maintain a good voltage profile without any compensation in order to apply the algorithm for testing under various conditions two different cases have been studied in details.

Case 1: In this case the load of the system is increased to 1.6 times of the base load by multiplying both real and reactive power of the load by a factor 1.6. The system under stressed conditions is analyzed for optimal placement and size of UPFC device using conventional as well as cost effective functions. UPFCs are incorporated in IEEE 30 bus system for real and reactive power control resulting in improvement of the system performance.

Case:2 In this case instead of loading the slack generator to take case of increasing load, all generating units are increased in their capacity by 1.6 times of the base case.

In both cases the UPFC device is modeled as the decoupled model in the power flow algorithm such a decoupled model can be implemented in Newton Raphson formula algorithm without any need to modify the Jocobian matrix elements [7]. The number of UPFCs used are two in both cases.

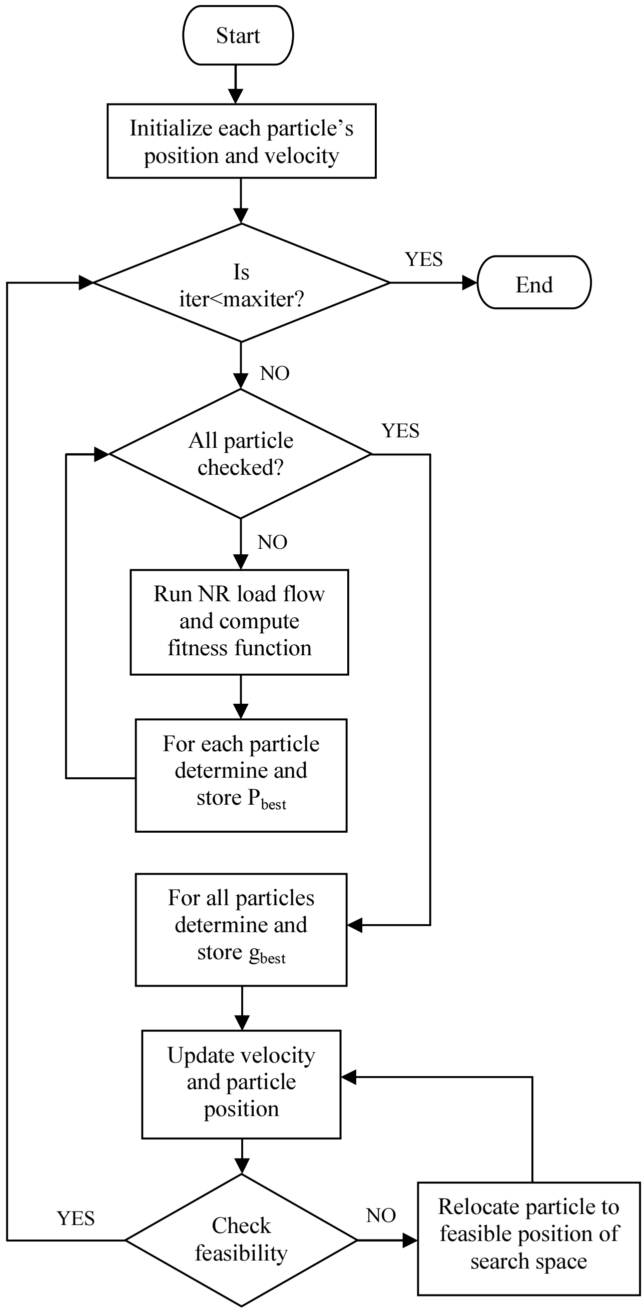

Figure.2. Flow chart of the proposed algorithm

4.1. Case 1: When real and reactive power of load increased by 1.6 times of base case.

The optimal choice of location and size of the UPFC devices are so chosen as to minimize the voltage deviation, line losses, and maximize the

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stability limit. Solutions are obtained using PSO with conventional as well as cost effective objective functions. Optimal parameters such as size and location of UPFC obtained by using conventional as well as cost effective objective functions are tabulated in table-I and table-II. It can be observed from the tables- I and II that the total reactive power compensation required is less (1.954 Mvar) in case of solution obtained by using cost effective objective function.

TABLE - I. UPFC PLACEMENT WHEN EQUAL IMPORTANCE GIVEN FOR ALL OBJECTIVES.

Details	UPFC-1	UPFC-2
Location (line number)	9	12
Real power exchange (MW)	7.093	3.544
Reactive power supplied by UPFC at shunt terminal (Mvar)	32.84	30.89
Reactive power supplied by UPFC at series terminal (Mvar)	37.32	41.25
Voltage magnitude at shunt terminal (V)	1.031	0.99
Voltage magnitude at series terminal (V)	0.1871	0.1332
Voltage angle at shunt terminal (degree)	45.6	328
Voltage angle at series terminal (degree)	202	23.9
Total reactive power supplied by both UPFCs (Mvar)	142.304	

TABLE - II. UPFC PLACEMENT WHEN IMPORTANCE GIVEN TO ALL OBJECTIVES BASED ON THEIR REAL TIME COST.

Details	UPFC-1	UPFC-2
Location (line number)	9	27
Real power exchange (MW)	3.846	3.332
Reactive power supplied by UPFC at shunt terminal (Mvar)	44.97	25.98
Reactive power supplied by UPFC at series terminal (Mvar)	33.9	35.5
Voltage magnitude at shunt terminal (V)	1.051	0.953
Voltage magnitude at series terminal (V)	0.1098	0.1106
Voltage angle at shunt terminal (degree)	182	323
Voltage angle at series terminal (degree)	262	142
Total reactive power supplied by both UPFCs (Mvar)	140.35	

Total power system losses, as obtained using conventional and cost effective objective functions are tabulated in table-III It can be observed from table-III that losses are less in case of solution obtained using cost effective objective function.

TABLE - III. POWER SYSTEM TOTAL LOSSES

Real power loss (MW)			
Conventional solution	Cost effective solution	Decrement of losses	Decrement of losses(%)
20.3735	20.3469	0.0266	0.13

Voltage profile of the system is tabulated in table-IV. It is observed that good voltage profile is maintained in both the solutions.

TABLE – IV. BUS VOLTAGES FROM NR POWER FLOW RESULTS

Bus NO	Voltage in p.u (conventional solution)	Voltage in p.u (cost effective solution)	Bus NO.	Voltage in p.u (conventional solution)	Voltage in p.u (cost effective solution)
1	1.030	1.030	16	0.997	1.015
2	1.020	1.010	17	1.004	1.022
3	0.999	0.995	18	0.971	0.990
4	0.993	0.987	19	0.974	0.992
5	0.999	0.980	20	0.984	1.002
6	1.001	0.991	21	0.996	1.033
7	1.013	0.994	22	0.994	1.030
8	0.990	0.980	23	0.965	0.989
9	1.020	1.025	24	0.967	0.993
10	1.021	1.037	25	0.965	0.980
11	1.020	1.020	26	0.955	0.950
12	1.002	1.019	27	0.979	0.986
13	0.992	1.020	28	0.992	0.984
14	0.980	1.000	29	0.954	0.951
15	0.977	0.996	30	0.952	0.952

To analyze the voltage stability of the system the PV curve is drawn for [20] weak buses 26, 29 and 30.

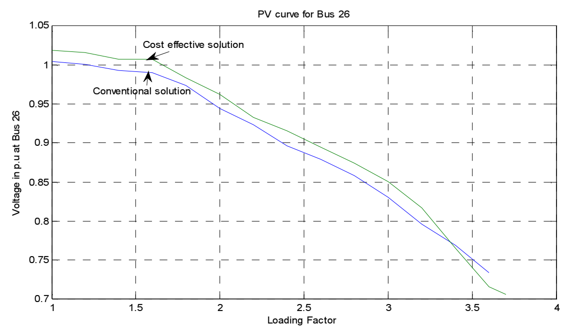

Figure.3. PV curve for bus 26 conventional and cost effective solution

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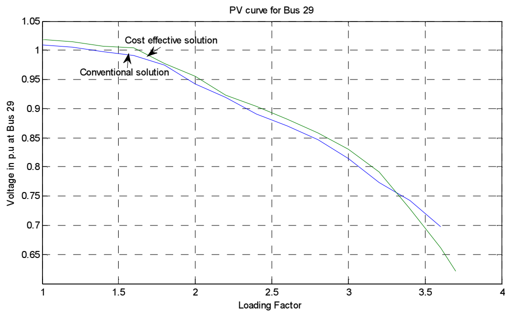

Figure.4. PV curve for bus 29 conventional and cost effective solution

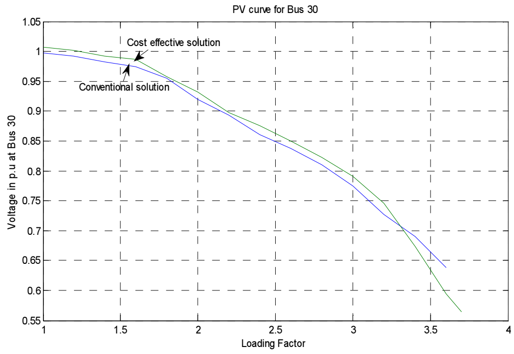

Figure.5. PV curve for bus 30 conventional and cost effective solution

In order to assess the maximum stability limit of the system the load is increased steadily from the base load in order of 0.1 p.u. PV curves evaluated are exhibited in figs.3, 4 and 5. Buses 26,29 and 30 are observed to be critical in terms of the voltage level. So these three buses are chosen for analyzing the maximum stability limit. It can be observed from PV curves that the system maintains stability up to the loading factor of 3.6 and 3.7 for conventional and cost effective objective functions respectively. However the voltages at busses 26, 29 and 30 are maintained with in permissible limits up to the loading factors of 1.8 and 1.9 only in case of conventional and cost effective objective functions respectively.

4.2 Case 2: When real and reactive power of generation and load increased by 1.6 times of base case.

As carried out in case: 1 the optimal choice of location and size of the UPFC devices are so chosen as to improve the system performance. Solutions are obtained using PSO with conventional as well as cost effective objective function. Optimal parameters such as size and location of UPFC obtained by using conventional as well as cost effective objective function are tabulated in tables V and VI. It can be observed from the tables V and VI that the total reactive power compensation required is less (17.82 Mvar) in case of solution obtained by using cost effective objective function.

TABLE - V. UPFC PLACEMENT WHEN EQUAL IMPORTANCE GIVEN FOR ALL OBJECTIVES.

	UPFC-1	UPFC-2
Location (line number)	31	9
Real power exchange (MW)	3.547	1.525
Reactive power supplied by UPFC at shunt terminal (Mvar)	19.51	39.15
Reactive power supplied by UPFC at series terminal (Mvar)	28.84	28.29
Voltage magnitude at shunt terminal (V)	1.021	0.9841
Voltage magnitude at series terminal (V)	0.1386	0.1046
Voltage angle at shunt terminal (degree)	9.77	160
Voltage angle at series terminal (degree)	172	182
Total reactive power supplied by both UPFCs (Mvar)	115.787	

TABLE - VI. UPFC PLACEMENT WHEN IMPORTANCE GIVEN TO ALL OBJECTIVES BASED ON THEIR REAL TIME COST.

	UPFC-1	UPFC-2
Location (line number)	31	7
Real power exchange (MW)	2.994	0.1206
Reactive power supplied by UPFC at shunt terminal (Mvar)	15.4	34.02
Reactive power supplied by UPFC at series terminal (Mvar)	24.42	24.14
Voltage magnitude at shunt terminal (V)	0.9786	0.9579
Voltage magnitude at series terminal (V)	0.1217	0.1294
Voltage angle at shunt terminal (degree)	342	167
Voltage angle at series terminal (degree)	244	232
Total reactive power supplied by both UPFCs (Mvar)	97.967	

Total power system losses has obtained using conventional and cost effective objective function are tabulated in table-VII It can be observed from table-VII that losses are less in case of solution obtained by using cost effective objective function.

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TABLE - VII. POWER SYSTEM TOTAL LOSSES

Real power loss (MW)			
Conventional solution	Cost effective solution	Decrement of losses	Decrement of losses(%)
9.07049	9.05363	0.01686	0.186

Voltage profile of the system is tabulated in table-VIII it is observed that good voltage profile is maintained in both the solutions.

TABLE – VIII. BUS VOLTAGES FROM NR POWER FLOW RESULTS

Bus NO	Voltage in p.u (conventional solution)	Voltage in p.u (cost effective solution)	Bus NO.	Voltage in p.u (conventional solution)	Voltage in p.u (cost effective solution)
1	1.030	1.030	16	1.011	1.005
2	1.030	1.030	17	1.012	1.003
3	1.030	1.019	18	0.990	0.980
4	1.009	1.016	19	0.988	0.979
5	1.010	1.010	20	0.996	0.986
6	1.014	1.013	21	1.018	1.001
7	1.017	0.995	22	1.023	1.017
8	1.010	1.010	23	1.009	1.011
9	1.022	1.015	24	1.032	1.027
10	1.025	1.015	25	1.014	1.012
11	1.010	1.010	26	0.986	0.979
12	1.023	1.020	27	1.018	1.016
13	1.010	1.010	28	1.010	1.009
14	1.005	0.995	29	0.985	0.983
15	1.003	0.994	30	0.966	0.964

The PV curve for bus 26, 29 and 30 is given below.

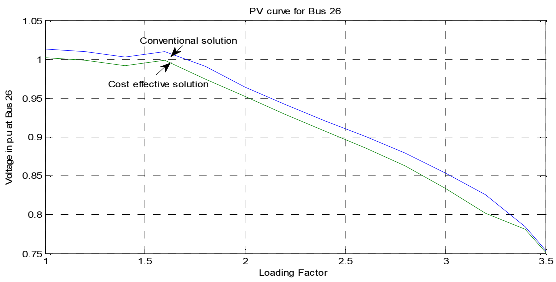

Figure.6. PV curve for bus 26 conventional and cost effective solution

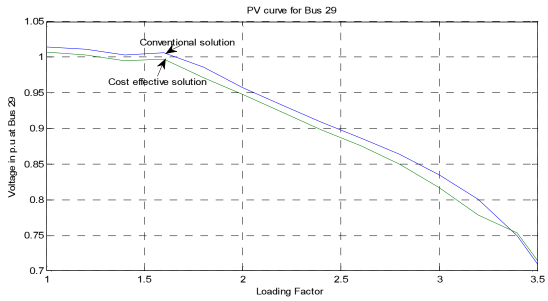

Figure.7. PV curve for bus 29 conventional and cost effective solution

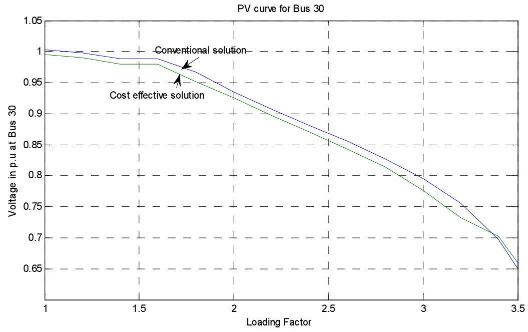

Figure.8. PV curve for bus 30 conventional and cost effective solution

In order to assess the maximum stability limit of the system the load is increased steadily from the base load in order of 0.1 p.u. P.V curves evaluated are exhibited in figs. 6, 7 and 8. Buses 26, 29 and 30 are observed to the critical in terms of the voltage level. So these three buses are chosen for analyzing the maximum stability limit. It can be observed from PV curves that the system maintains stability up to the loading factor of 3.5 for both conventional and cost effective objective function. However the voltages at busses 26, 29 and 30 are maintained with in permissible limits up to the loading factors of 1.9 only for both conventional and cost effective objective function.

COMPARISON OF OBJECTIVE VALUES

TABLE – IX. OBJECTIVE VALUES

Objective functions	Case 1		Case 2	
	For conventional	For cost effective	For conventional	For cost effective
Voltage deviation (p.u)	0.14	0.14	0.096	0.093
Real power loss (MW)	20.3735	20.3469	9.07049	9.05363
UPFC size(MVA)	142.701	140.533	115.898	98.016
Maximum loadability limit	3.6	3.7	3.5	3.5

Table-IX shows the actual value of the objective functions. From the table it is noted that the real power loss, and UPFC size obtained by cost effective objective function is better than the conventional objective function. The voltage deviation and stability limit are more or less equal for both cases.

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TABLE – X. COST OF REAL POWER LOSS AND UPFC SIZE

Objective functions	Case 1		Case 2	
	For conventional	For cost effective	For conventional	For cost effective
Cost of Real power loss (Rs)	1018675000	1017345000	453524500	452681500
Cost of UPFC (Rs)	713505000	702665000	579490000	490080000
Total cost (Rs)	1732180000	1720010000	1033014500	942761500
Cost of saving (Rs)	12170000		90253000	

Real time cost evaluated, using the values specified for the cost of generation and the cost of UPFC, are tabulated in table-X. It can be observed from table–X that there is a considerable saving in the cost while using the cost effective objective function for fixing up the location and size of the UPFC devices.

5. CONCLUSION

In earlier solutions obtained for optimal locations and size of UPFC device equal weightage has been given to all the parameters in the objective function. In order to make it more practical weightage factors proportional to real time cost or penalty value of the parameters in the objective function is suggested and implemented in this paper. Results obtained for various cases studied on IEEE-30 bus system show that the system performance in terms of voltage deviation, total losses and loadability limit are improved by optimal choice of location and size of UPFC devices in the system. The results obtained by using the cost effective objective function and conventional objective function reflect the supremacy of the cost effective objective function in terms of improved system losses and loadability limit.

In this paper the PSO technique is applied for obtaining the optimal solution for the location and size of the UPFC devices. Effectiveness of utilizing real time cost of various parameters in the objective function has been established through a detailed analysis through various simulations studies carried out in MATlab SIMUlink environment.

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