Evolutionary Programming Based Optimal Placement of UPFC Device in Deregulated Electricity Market

Mr. K. Balamurugan[1], Dr. R. Muralisachithanandam[2], Dr. V. Dharmalingam[3], Mr. K. V. Sethuraman[4]
[1]Asst Prof., Dept. of Electrical and Electronics Engineering, SASTRA University, Thanjavur, INDIA
[2]Prof., Dept. of Electrical and Electronics Engineering, SASTRA University, Thanjavur, INDIA
[3]Principal, M.A.M School of Engineering, Tiruchirappalli, INDIA
[4]PG Scholar. Dept. of Electrical and Electronics Engineering, SASTRA University, Thanjavur, INDIA
[1]kbm@eee.sastra.edu, [2]zenmurali@gmail.com, [3]dharmalingamv@yahoo.co.in, [4]sethu333@gmail.com

***Abstract*—In deregulated power industry, the real time pricing of real power has an important issue to create fair open access and great impact of efficient and economics operation of deregulated electricity market. FACTS devices can be used to control the power flows. Therefore the optimal allocation of FACTS device can be used to achieve the optimal power flow without any constraints violation and thus to increase the utilization of the lowest cost generation in power system network. This paper proposes a new method of optimal placement of Unified power flow controller (FACTS) devices in Deregulated Electricity Market using Evolutionary Programming. Using proposed method, the allocation of UPFC devices and ratings are optimized. The main objective function is to minimizing the overall system cost, which includes the investment cost of UPFC device and bid offers of the market participants. The effectiveness of the proposed method is demonstrated on IEEE 14-bus system.**

Keywords: Evolutionary Programming, FACTS, UPFC, Deregulated Electricity Market, IEEE 14 Bus system

I. INTRODUCTION

In recent years, the processes of deregulation of the electricity market have changed the traditional concepts and practices of power systems. Better utilization of the existing power system to increase power transfer capability by installing FACTS (Flexible AC Transmission Systems) devices becomes Imperative [6]. FACTS devices can control the parameter and variables of the transmission line, i.e. line impedance, terminal voltages, and voltage angles in a fast and effective way. The benefit brought about by FACTS includes improvement of system dynamic behavior and thus enhancement of system reliability. However, their main function is to control power flows, Provided that they are placed at optimal allocations, FACTS devices are capable of increasing the system load ability too [7]. These aspects are playing an increasingly significant role in the operation and control of the deregulated electricity market. Many researches were made on the optimal allocation of FACTS devices. However, the investment cost of FACTS and their impact on bid curves of the market participants (suppliers and consumers) in liberalized electricity market are not wholly considered [1], [2].

The objective of this paper is to develop an algorithm by evolutionary programming method to find the best allocations for the UPFC devices. By means of FACTS optimal placement, the overall cost function, which includes the investment costs of UPFC and the bid offers of the market participants, is minimized. UPFC is a promising FACTS device for load flow control since it can either simultaneously or selectively control the active and reactive power flow along the line as well as its terminal voltages. This salient property has made the study of dynamic system performance of UPFC-controlled power systems a popular research topic for applications with a typical assumption of preconfigured UPFC layout. Either simultaneously or selectively controls the active and reactive power flow along the line as well as its terminal voltages. This salient property has made the study of dynamic system performance of UPFC-controlled power systems a popular research topic for applications with a typical assumption of preconfigured UPFC layout.

II. DEREGULATION

Historically, the electricity industry was a monopoly industry with a vertical structure. In a vertically integrated environment, enterprises were responsible for the generation, transmission and distribution of electrical power in a given geographical area. Such companies could be state owned as well as private. But the last two decades, and especially during the 1990s, the electricity supply service has been undergoing a drastic reform all over the world. The old monopolist power markets are replaced with deregulated electricity markets open to the competition. Different forces have driven the power market towards the deregulation. Not all of them are behind the reform in all these countries. Furthermore, in each different country the same reason has to be studied taking into consideration the local circumstances. However, it is possible to categorize all these various causes in technical, economical and political. The technical factor, which has given a stronger impulse towards deregulation, is the improved power generation technologies [3].

Even though the idea of deregulation is good, but not all of the electric system is suitable for such a change. Distribution and transmission are natural monopolies that invalidate them as participants in an open competitive market. This leaves generation as the only sector suitable for a competitive market. But this does not mean that distribution and transmission would be untouched. Competition can be established in generation, but only if the necessary changes are introduced in distribution and transmission to allow and encourage a competitive generation market [4]. Beyond the technical improvements, a set of economical reasons may be considered as the main force behind the electricity market reform. The key economical idea, which led to the deregulation, was that a well operated competitive market can guarantee both cost minimization and average energy prices hold at a minimum level. An open market provides stronger incentives to the supplier in order to apply cost-minimizing procedures than a regulated market. It also has the ability to drive the prices towards the marginal costs. The improvement of transmission technologies result in an efficient grid operated by the transmission companies. Devices such as FACTS enable a better control over the electrical features of the grid. Thus, the separation of generation and transmission decisions can be easier [5].

III. FACTS

With ever increasing demand of electric power, the existing transmission even in the developed countries are found to be weak which results in poor quality of unreliable supply. Also it is seen that in order to expand or enhance the power transfer capability of the existing transmission network huge sum of fitness are required and sometimes even difficulties are encountered in finding right-of-way for new lines. Lot of research has gone into developing new technologies over the past few years to gain increased efficiency from the existing power system. This program is known as flexible A.C. transmission system abbreviated as FACTS. The main objective of FACTS devices is to replace the existing slow acting mechanical controls required to react to the changing system conditions by rather fast acting electronics controls. Alternating current transmission system incorporating power-electronics based and other static controllers to enchance controllability and increase power transfer capability. These opportunities arise through the ability of FACTS controllers to control the interrelated parameters that govern the operation of transmission systems including series impedance, shunt impedance, current, voltage, phase angle, and the damping of oscillations at various frequences below the rated frequency [16].

The FACTS technology is not a single high-power controller, but rather a collection of controllers, which can be applied individually or in coordination with others to control one or more of the interrelated system parameters mentioned above. A well-chosen FACTS controller can overcome the specific limitations of a designated transmission line or a corridor. Because all FACTS controllers represent applications of the same basic technology, their production can eventually take advantage of technologies of scale. Just as the transistor is the basic element for a whole variety of microelectronic chip and circuits, the thyristor or high-power transistor is the basic element for a variety of high-power electronic controllers [17].

IV. MODELLING AND FORMULATION OF UPFC

Fig.1 provides the schematic layout of the UPFC configuration consisting of two voltage sourced inverters linked by a D.C. storage capacitor. Assuming negligible active and reactive power losses, it can be seen that I_e represents an ideal current source used to simulate the current extracted from bus P while U_T denotes a voltage injected into the transmission line through the series transformer. The mathematical relationship of the model is given in equations (1), (2) and (3). In which I_e consists of two components I_q and I_t.

$$\arg(I_q) = \arg(U_p) + \frac{\pi}{2} \tag{1}$$

$$\arg(I_t) = \arg(U_p) \tag{2}$$

$$I_t = U_T I_S^* / U_p \tag{3}$$

It can also be seen from the above equations that U_T, φ_T and I_q are the only independent control variables falling within the region defined as in equation (4).

$$\tau = \{U_T, \varphi_T, I_q \,|\, U_T \in [0, U_{Tmax}], \varphi_T \in [0, 2\pi], I_q \in [-I_{qmax}, I_{qmax}]\} \tag{4}$$

Where U_{Tmax} and I_{qmax} are given by the rating of the UPFC. Essentially a UPFC should be designed with its shunt inverter rating capacity larger enough to supply the reactive current I_q for upholding the bus voltage and active current I_t for satisfying requirement of the series voltage source U_T. For the series inverter its rating is defind by the thermal limit of the transmission line. Hence the cost of the UPFC device can be regarded as proportional to its rating which is related to the rated voltage and maximum current of the associated transmission line. The apparent power of the UPFC device can be obtained by equation (5).

$$|S| = \left|I_{qmax}^{*}\, U_{Tmax}\right| \tag{5}$$

The values denoted by the parameters U_{Tmax} and I_{qmax} can be used to describe not only the capacity but also the function of the UPFC [11], [12], [13]. A typical overall control decision vector including not just the parameters of the UPFC but also those of the conventional control devices. The transformers are differentiated as load tap changing and unload tap changing types because they have different tap setting constraints when facing with a multi-operating condition. Here U_{TB} is set as a benchmark to judge whether a UPFC is necessary or not, That is $U_{tlmax} < U_{TB}$ then the l^{th} UPFC does not need to be installed.

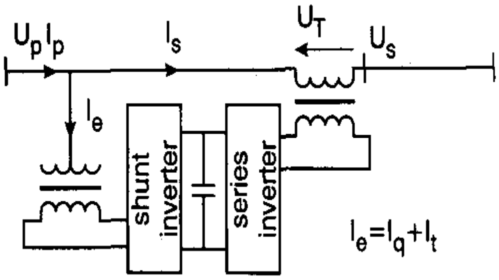

Fig.1. Schematic Lay Out Of UPFC

V. Optimal Placement of UPFC in Deregulated Market

This paper is proposed to determine the suitable allocation of FACTS devices or location of FACTS and also find the rating of the FACTS devices in deregulated electricity market that will give the minimum system cost. The overall system cost function which includes the bid offers of market participants (suppliers and consumers) and the investment cost of FACTS devices is employed to evaluate the power system performance and also to minimize the overall system cost [8], [9], [10]. The FACTS device used for our case study is the Unified Power Flow Controller (UPFC). The formulation for optimal choice and allocation of FACTS (UPFC) device can be expressed as following equations (6), (7), (8) and (9).

$$C_{Total} = C_1(f) + C_2(P_G) \tag{6}$$
$$C_1(f) = C(f)/\,(8760 * 5) \tag{7}$$
$$C(f) = 0.0003s^2 - 0.2691s + 188.22 \tag{8}$$
$$C_2(P_G) = \sum 0.5(a\,P_G^2 + b\,P_G + c) \tag{9}$$

Where,

C_1 (f) is the average investment costs of FACTS (UPFC) devices.

C (f) is the cost function of UPFC device.

C_2 (P_G) is the bid offers of the market participants.

C_{Total} is the overall cost of objective function C_1 (f) + C_2 (P_G).

A. Equality Constraints

Power flow equations corresponding to both real and reactive power balance equations are the equality constraints that can be written, for all the buses except buses i and j in which UPFC is connected, as the equations (10) and (11).

$$P_l = P_{gl} - P_{dl} = \sum_{m=1}^{N_b} V_l V_m[\,G_{lm}\cos(\delta_l - \delta_m) + B_{lm}\sin(\delta_l - \delta_m)] \tag{10}$$
$$Q_l = Q_{gl} - Q_{dl} = \sum_{m=1}^{N_b} V_l V_m[G_{lm}\sin(\delta_l - \delta_m) - B_{lm}\cos(\delta_l - \delta_m)] \tag{11}$$

$l = 1, 2 \ldots. N_b \quad$ but $l \neq i, j$.

For buses i and j were FACTS (UPFC) device are placed, the equality constrains can be written as the equations (12), (13), (14) and (15).

$$P_i = P_{gi} - P_{di} = \sum_{m=1}^{N_b} V_i V_m[G_{im}\cos(\delta_i - \delta_m) + B_{im}\sin(\delta_i - \delta_m)] - P_{is} \tag{12}$$
$$Q_i = Q_{gi} - Q_{di} = \sum_{m=1}^{N_b} V_i V_m[G_{im}\sin(\delta_i - \delta_m) - B_{im}\cos(\delta_i - \delta_m)] - Q_{is} \tag{13}$$
$$P_j = P_{gj} - P_{dj} = \sum_{m=1}^{N_b} V_j V_m\left[G_{jm}\cos\left(\delta_j - \delta_m\right) + B_{im}\sin\left(\delta_j - \delta_m\right)\right] - P_{js} \tag{14}$$

$$Q_j = Q_{gj} - Q_{dj} = \sum_{m=1}^{N_b} V_j V_m \left[G_{jm} \sin(\delta_j - \delta_m) - B_{jm} \cos(\delta_j - \delta_m) \right] - Q_{js} \qquad (15)$$

Where,

P_i real power injection at bus-i

Q_i reactive power injection at bus-i

P_{gi} real power generation at bus-i

Q_{gi} reactive power generation at bus-i

P_{di} real power load at bus-i

Q_{di} reactive power load at bus-i

V_i voltage magnitude at bus-i

δ_i load angle at bus-i

$Y_{ij} = G_{ij}+B_{ij}$ j^{th} element of Y-bus matrix

N_q number off reactive power sources in the system.

B. Inequality Constraints

1) Power generation limit:

This includes the upper and lower real power limit of generators is given in equation (16).

$$P_{gi}^{min} \le P_{gi} \le P_{gi}^{max} \qquad i = 1, 2, 3 \ldots Ng \qquad (16)$$

Where P_{gi}^{min} and P_{gi}^{max} are the minimum and maximum limits of real power generation at bus-i respectively.

2) Reactive power generator limit:

Let $\boldsymbol{Q_{gi}^{min}}$ and $\boldsymbol{Q_{gi}^{max}}$ be the maximum and minimum reactive power generation limits of reactive source generator - i respectively. Mathematically, it can be written as by equation (17).

$$Q_{gi}^{min} \le Q_{gi} \le Q_{gi}^{max} \qquad i = 1, 2, 3 \ldots Nq \qquad (17)$$

3) Voltage limit:

This includes the upper $\boldsymbol{V_i^{max}}$ and lower $\boldsymbol{V_i^{min}}$ limits on the bus voltage magnitude are given by equation (18).

$$V_i^{min} \le V_i \le V_i^{max} \qquad i = 1, 2, 3 \ldots Nb \qquad (18)$$

4) Phase angle limit:

The phase angle at each bus should be between lower $\boldsymbol{\delta_i^{min}}$ and upper $\boldsymbol{\delta_i^{max}}$ limits as given in equation (19).

$$\delta_i^{min} \le \delta_i \le \delta_i^{max} \qquad i = 1, 2, 3 \ldots Nb \qquad (19)$$

These limits may vary, depending upon the problem under consideration. Imposing phase angle limits at load buses is another way of limiting the power flow in the transmission lines, and as for generator buses, this is done for stability reasons.

5) UPFC control parameter limits

The voltage magnitude V_t and phase angle $\emptyset_t$ of series voltage of UPFC must lie within the limit. Mathematically, it can be written as by equations (20) and (21).

$$0 \le V_t \le V_t \qquad (20)$$

$$0 \le \emptyset_t \le 2\pi \qquad (21)$$

Reactive power component of shunt current $\boldsymbol{I_q}$ should also be less than its rating as given in equation (22).

$$I_q^{min} \le I_q \le I_q^{max} \qquad (22)$$

VI. EVOLUTIONARY PROGRAMMING

Evolutionary programming is different from conventional optimization methods. It does not need to differentiate cost function and constraints. It works by evolving a population of candidate toward the global solutions through the use of the mutation operator and selection scheme. This algorithm can move over hills and across valleys to discover a global optimal point. Because of this, EP is more robust than the existing direct search methods. Therefore in this paper, the EP algorithm is proposed to determine the optimal allocation of FACTS devices [14], [15]. The EP algorithm starts with random generation of initial individuals in a population and then the mutation and selection are preceded until the best individual, which has the highest fitness, is found. The main components of the algorithm are briefly explained as follows.

1) Initialization

The initial population is initialized randomly using sets of uniform random number distribution ranging over the feasible limits of each control variable as given by equation (23).

$$x_i = x_i^{min} + u(x_i^{max} - x_i^{min}) \tag{23}$$

Where *xi* is the *i*th element of the individual in a population .min *xi* and max *xi* are the lower and upper limits of the *i*th element of the individual. *u* is a uniform random number in the interval (0, 1).

2) Fitness Function

The fitness of the k^{th} individual can be calculated by using the equation (24).

$$f_k = K_f * F' \tag{24}$$

Where $\boldsymbol{f_k}$ is the fitness of the k^{th} individual. K_f is an arbitrary constant, and $\boldsymbol{F'}$ is the objective function.

3) Mutation

A new population is generated by using the Gaussian mutation operator. Each element of the k^{th} new trial solution vector, V_k', is computed by using the equation (25) and (26).

$$x'_{k,i} = x_{k,i} + N(0, \sigma_{k,i}^2) \tag{25}$$

$$\sigma_{k,i} = (x_i^{max} - x_i^{min}) \left[\frac{f_{max} - f_k}{f_{max}} + a^g\right] \tag{26}$$

Where $\boldsymbol{x'_{k,i}}$ is the value of the i^{th} element of the k^{th} offspring individual. $\boldsymbol{x_{k,i}}$ is the value of the i^{th} element of the k^{th} parent individual. $\boldsymbol{N(0, \sigma_{k,i}^2)}$ is a Gaussian random number with a mean of zero and standard deviation of *k*, *i*. $\boldsymbol{x_i^{min}}$and $\boldsymbol{x_i^{max}}$ are the lower and upper limits of the i^{th} element of the k^{th} parent individual. $\boldsymbol{f_k}$ is the fitness value of the k^{th} individual. f_{max} is the maximum fitness of the parent population. The '$\boldsymbol{a}$' is a positive number constant slightly less than one and '$\boldsymbol{g}$' is the iteration counter.

4) Selection

The selection technique utilized is a tournament scheme, which can be expressed in equation (27) and (28).

$$w_t = \begin{cases} 1 \text{ if } f_k > f_r \\ 0 \text{ otherwise} \end{cases} \tag{27}$$

$$S_k = \sum_{t=1}^{N_t} w_t \tag{28}$$

Where $\boldsymbol{f_k}$ is the fitness of the *k*th individual in the combined population. f_r is the fitness of the r^{th} opponent randomly selected from the combined population based on $\boldsymbol{r = [2 * P * u + 1]}$ is the greatest integer less than or equal to *x*. the **'*u*'** is a uniform random number in the interval [0, 1] and *P* is the population size.

5) Termination Criterion

If the maximum generation number is reached, the iteration process is terminated. Otherwise, the mutation and selection process will be reiterated until the criterion is satisfied.

VII. CASE STUDY

In order to verify the effectiveness of the proposed method, the 14-bus test system is simulated. The 14-bus test system consists of four generators at buses 1,2,3,6 respectively these are called as generator buses are owned by generating companies and buses 13,14,9 are load buses with respect to the load. Out of the five PV type buses including the generators, bus 1 is assumed to make up the transmission losses in the system for the sake of simplicity. The generators have their cost functions and loads have their benefit functions. Generator costs coefficients are given in Appendix A. Loads are assumed to maintain constant power factor demand. The 14 bus system bus data, line data are given in Appendix B and Appendix C.

A. CASE 1

In this case all the IEEE 14 bus system as illustrated in fig. 2 data's are fed and the program is simulated. Optimal power flow of the system without any UPFC device is found out and overall system cost which includes the total generation costs and FACTS device investment costs is found. With bus 1 as reference the lines 1-2, 1-5, 2-3, 3-4 & 4-5 are selected for our case study. The overall system cost function is found out as **5030.2 US$/hour** for a general 14 bus system without any FACTS device. The power outputs of the generators are shown in Table I. The power flow in line 1-2, 1-5, 2-3, 3-4 & 4-5 are shown in Table II. From the Table II it is clear that power flow in line 3-4 is less, hence it is necessary to increase the power flow and also decrease the cost of the overall power system.

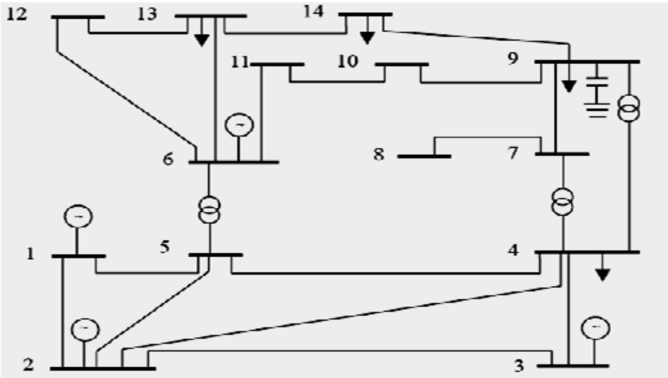

Fig.2. IEEE 14 Bus System Model

TABLE I
Real and Reactive Power output for 14-bus system without UPFC

Generator	Real power (P_g) MW	Reactive power (Q_g) MVAr	Overall system cost US$/hour
1	149.9906	65.3865	**5030.2**
2	149.6812	75.4458	
3	50.2016	17.0161	
4	50.2940	18.2954	

TABLE III
Power Flow results for 14-bus system without UPFC

Line	Power flow MW
1-2	58.8416
1-5	20.7883
2-3	23.8181
3-4	**16.0910**
4-5	80.1084

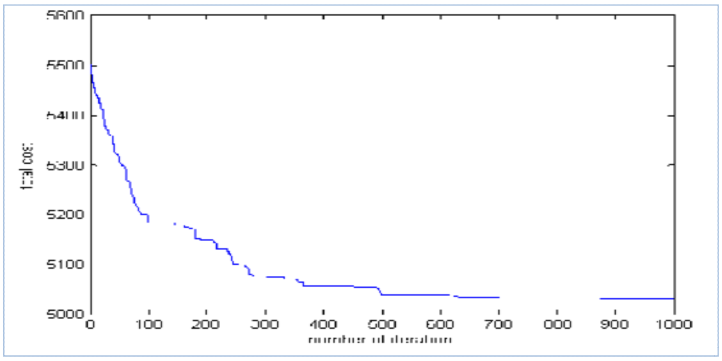

Fig.3. Total Cost Vs Number of iterations curve for system without UPFC device

B. CASE 2

Now the UPFC device is placed in line 3-4 in reference to case 1 and all the IEEE 14 bus system as illustrated in fig. 4 data's are fed and program is simulated. Optimal power flow of the system with UPFC device is found out and overall system cost is found. The power outputs of the generators are shown in Table III. The result gives the power flow of the lines 1-2, 1-5, 2-3, 3-4 & 4-5 shown in Table IV. From the Table IV it is clear that power flow of the line 3-4 is increased and overall system cost is reduced to 5026.9 US$/hour. The parameters of the UPFC device are given in Table V.

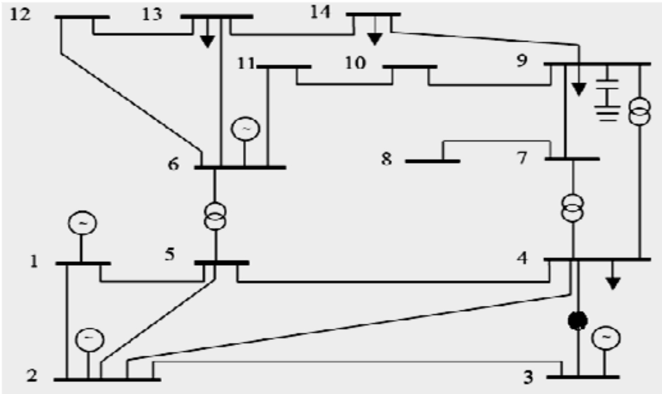

Fig.4. IEEE 14 bus system With UPFC device in line 3-4

TABLE III
Real and Reactive Power output with UPFC device in line 3-4

Generator	Real power (P_g) MW	Reactive power (Q_g) MVar	Overall system cost US$/hour
1	149.9596	78.3716	**5026.9**
2	149.8652	40.3493	
3	50.0432	16.2167	
4	50.1907	22.7433	

TABLE IV
Power Flow of the system with UPFC device in line 3-4

Line	Power flow MW
1-2	58.8416
1-5	20.7883
2-3	23.8181
3-4	**16.4552**
4-5	80.1084

TABLE V
UPFC device parameters

Device	Current (I)	Voltage (V_t)	Phase angle (P_t)	Turns ratio (T)
1	-1.0658	0.1260	5.6005	0.9264

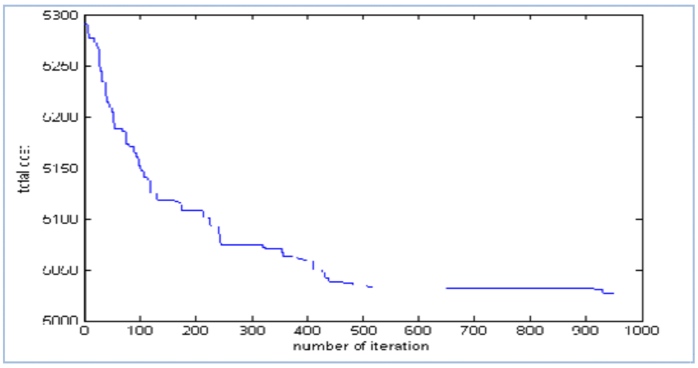

Fig.5.Total cost Vs Number of iteration curve for system with UPFC device in line 3-4

C. CASE 3

In this case 5 UPFC devices are placed in the selected lines 1-2, 1-5, 2-3, 3-4, and 4-5. All the IEEE 14 bus system as illustrated in fig. 6 data's are fed and the program is simulated. The power outputs of the generators are shown in Table VI. In this case a constant value of 0.1 called benchmark value is assumed for the voltage parameter of the UPFC device. When voltage falls below this value the respective UPFC can be removed from the system. From Table VII it is seen that the voltage parameters for UPFC placed in lines 2-3 and 3-4 are less than 0.1 and hence they can be removed. Now with 3 devices placed in the system as shown in figure 9, the cost of the system is also reduced to **5029.0 US$/hour**, hence the objective function is also achieved.

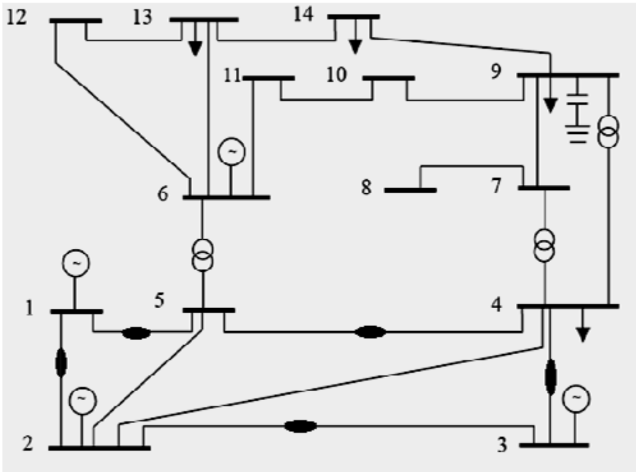

Fig.6. IEEE 14 bus system with 5 UPFC devices

TABLE VI
Real and Reactive power output for system with % UPFC devices

Generator	Real power (P_g) MW	Reactive power (Q_g) MVar	Overall system cost US$/hour
1	149.7130	75.2977	**5029.0**
2	149.9089	28.2165	
3	50.1367	15.5666	
4	50.3439	24.1350	

TABLE VII
UPFC device parameters

Device		Current (I)	Voltage (V_t)	Phase angle (P_t)	Turns ratio (T)
No	Line				
1	1-2	-1.3612	0.1441	5.1538	0.4952
2	1-5	-3.1783	0.1242	2.1932	0.0738
3	2-3	2.9921	**0.0886**	5.7490	0.6278
4	3-4	-1.3073	**0.0776**	2.7095	0.3566
5	4-5	2.0977	0.1029	5.1779	0.5223

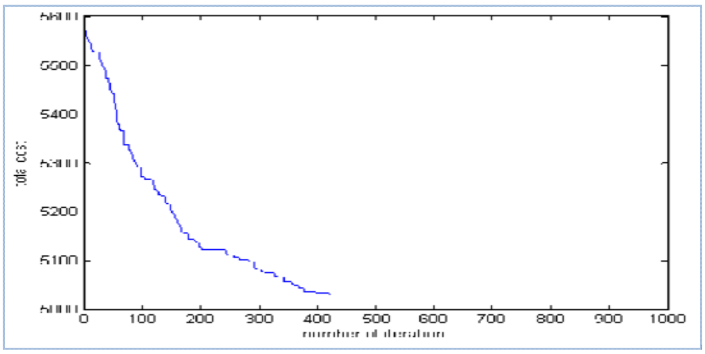

Fig.7. Total cost Vs Number of Iterations for a system with 3 UPFC devices

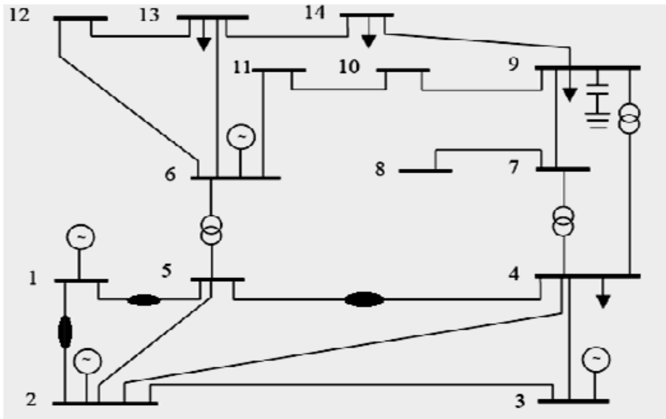

Fig.8. IEEE 14 bus system with 3 UPFC devices

VIII. CONCLUSION

In this paper, an Evolutionary Programming based approach is proposed to determine the optimal placement of UPFC devices in deregulated electricity market. The overall system cost function, which includes the bid offers of the market participants (suppliers and consumers) and the investment costs of FACTS devices, is employed to evaluate the power system performance. Simulation results validate the efficiency of this new approach in minimizing the overall system cost function. Furthermore, the locations of the FACTS devices, their numbers and ratings are optimized simultaneously. The proposed algorithm is an effective and practical method for the allocation of FACTS devices in deregulated electricity market.

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Appendix A
Voltage data for IEEE 14 Bus System

Bus no	Magnitude (PU)	Angle (radian)
1	1.067	.00
2	1.062	-.020
3	1.043	-.069

4	1.033	-.071
5	1.040	-.057
6	1.040	-.082
7	1.040	-.042
8	1.033	-.056
9	1.037	-.087
10	1.030	-.092
11	1.032	-.089
12	1.028	-.092
13	1.023	-.097
14	1.012	-.110

Appendix B
Generation data for IEEE 14 Bus System

Bus	Cost data		
	A	B	C
1	0.01	10	100
2	0.01	10	100
3	0.02	20	100
6	0.02	15	100

Appendix C
Line data for IEEE 14 bus system

From Bus	To Bus	r [p.u.]	X [p.u.]	B [p.u.]	Transfer Capacity [MVA]
1	2	0.01938	0.05917	0.0528	200
1	5	0.05403	0.22304	0.0492	100
2	3	0.04699	0.19797	0.0438	100
2	4	0.05811	0.17632	0	100
2	5	0.05695	0.17388	0.0340	100
3	4	0.06701	0.17103	0.0346	100
4	5	0.01335	0.04211	0.0128	100
4	7	0	0.20450	0	100
4	9	0	0.53890	0	100
5	6	0	0.23490	0	100
6	11	0.09498	0.19890	0	100
6	12	0.12291	0.25581	0	100
6	13	0.06615	0.13027	0	100
7	8	0	0.17615	0	100
7	9	0	0.11001	0	100
9	10	0.03181	0.08450	0	100
9	14	0.12711	0.27038	0	100
10	11	0.08205	0.19207	0	100
12	13	0.22092	0.19988	0	100
13	14	0.17093	0.34802	0	100