Optimal Location of UPFC and Comparative Analysis of Maximum Loadability with FACTS in Competitive Electricity Markets

ASHWANI KUMAR
Department of Electrical Engineering
National Institute of Technology, Kurukshetra, India PIN 136119

Abstract: Flexible ac transmission systems (FACTS) controllers, which can effectively enhance the loadability of the network by controlling the power flows, must be placed optimally due to their high cost. This paper proposes a mixed integer based non-linear programming approach for optimal location of UPFC for system loadability enhancement in competitive electricity markets. The method accounts for ac load flow equations with constraints on generation, line flows and FACTS controller parameters. New secure bilateral transaction matrix based on AC distribution factors has also been proposed. The system loadability has been determined in a hybrid electricity market model incorporating bilateral transaction matrix in the optimal power flow model. The results obtained with UPFC have been compared with the other optimally placed FACTS controllers like TCPAR and TCSC. The proposed technique has been demonstrated on IEEE 24 bus reliability test system.

Index Terms: Optimal power flow, secure transaction matrix, mixed integer non-linear programming, FACTS controllers, competitive electricity market.

I. INTRODUCTION

In the present pace of power system restructuring, transmission systems are being required to provide increased power transfer capability and to accommodate a much wider range of possible generation patterns. In this connection, the basic challenge of the evolving deregulated power system is to provide a network capable of delivering contracted power from any supplier to any consumer over a large geographic area under continuously varying patterns of contractual agreement. The demand of better utilization of existing power system and to increase power transfer capability by installing FACTS (Flexible AC Transmission Systems) devices have become imperative [1]. Thus, it has become important to determine the system loadability so that the total transfer capability (TTC) can be posted on the website called as Open Access Same Time Information System (OASIS) for its optimum commercial use. These studies can suggest the better distribution of generation resources, future requirement of installation of new transmission lines, and the option for installation of power flow control equipments to enhance the existing transmission transfer capability.

Flexible AC transmission system (FACTS) controllers have large potential to operate power systems in a flexible, secure, and economical way [2]. The studies on FACTS are concerned with FACTS controller deployment, deciding their number and optimal placement in the power system. The improvement in the system loadability, using genetic algorithm (GAs) and the cost of production was discussed in [3] and [4].

The method in [3] was applied to allocate a maximum of 50 FACTS controllers in IEEE 118-bus network. In [4], location of phase shifters were determined and restricted to a subset of 124 possible corridors. The allocation of thyristor controlled phase angle regulators (TCPARs) and thyristor controlled series capacitors (TCSCs) was carried out by Verma et al [5] through sensitivity analysis. The method, however, did not maximize the system loadability. In [6], assuming the position of TCSCs to be known, their settings have been calculated so as to minimize the total generating cost and wheeling charges.

A two-step procedure was proposed by Kobayashi et al [7] to locate and adjust phase shifters' angles. In the first step, the theoretical system maximum loadability is found without restrictions on number and location of the control devices. In the second step, this ideal loadability is maintained while minimizing the system-wide installed phase shifter capacity. In [8, 9], the number and location of FACTS devices were assumed to be known without considering installation costs. Only their settings were optimally adjusted to investigate their influence on generation cost and loadability. Tabu search methods were applied to locate unified power flow controllers (UPFCs) in [10] with the mixed goal of maximizing loadability while reducing losses. A FACTS placement approach using Mixed Integer Linear Programming (MILP) based on most recent advances exploiting branch and bound algorithms with Gomory cuts was proposed in [11]. The goal of MILP used was to the maximize system loadability, while limiting the total number of control devices and their installation costs while respecting all the constraints. The method was based on DC load flow to achieve remarkable gains in computation speed. However, the proposed methodology cannot be applied for deregulated electricity markets, where a hybrid market structure comprises of both bilateral and multilateral contracts. Huang [12] examined the impact of FACTS devices for congestion management by reducing transaction curtailment and TTC improvement issues. Cai et al. proposed an optimal choice and allocation of FACTS controllers based on genetic algorithm [13]. Leung et al. proposed optimal placement of FACTS controllers based on genetic algorithm [14]. Optimal placement of multi-type FACTS devices using hybrid TS/TA approach has been proposed in [15]. Evolutionary programming based approach for optimal location of UPFC has been proposed in [16]. However, in these papers the approach has not been applied for hybrid markets and for maximization of loadability of power systems. A hybrid particle swarm optimization technique for finding the maximum loadability of power systems has been presented in [17]. Location of UPFC for congestion management based on performance index was proposed in [18].

Bilateral transactions between sellers and buyers are deemed to be feasible, if these can be accommodated without the violations of system security limits [19]. References [20,21] discussed the secure bilateral transaction matrix determination in deregulated environment utilizing the approach of [22]. However, the secured transaction matrix was determined for the markets with only bilateral contracts. In [23], a methodology for determination of secure transaction matrix for hybrid market model has been proposed and the system loadability has been determined without and with optimal placement of TCPAR using MILP. Kumar et al. presented combined optimal placement of TCPAR and TCSC for loadability enhancement using DC load flow method based on mixed integer linear programming approach [24]. Since the method is based on DC load flow method, which is based on assumptions and results obtained may be quite optimistic. Optimal number and location of TCSC for loadability enhancement was proposed in [25]. However, DC distribution factors were utilized for secure transaction determination, which are constant depending on only system parameter and do not reflect any change in the system operating conditions.

In the present paper, a mixed integer non-linear programming approach has been proposed for optimal location of UPFC for the determination of maximum loadability for pool as well as hybrid electricity market. Only one UPFC is considered here for the placement because of the cost involved. The results have also been obtained for comparison with optimally placed TCPAR and TCSC for pool as well as hybrid electricity markets. The effectiveness of the proposed approach has been tested on IEEE 24-bus Reliability Test System (RTS) [26].

II. A LOSSLESS BILATERAL TRANSACTION MATRIX

The transaction matrix [22], T, is a collection of all possible transactions between generation (G), demand (D), and any other trading entities (E) such as the marketers and the brokers. Mathematically, transaction matrix (T) can be written as

$$T = \begin{bmatrix} GG & GD & GE \\ DG & DD & DE \\ EG & ED & EE \end{bmatrix} \tag{1}$$

In this work, it is assumed that there are no activities incurred by the trading entities (E). All transactions are, therefore, restricted to the suppliers (G) and the consumer (D). It is also assumed that there are no contracts made between two suppliers or two consumers. Thus, the diagonal block matrices (GG and DD) are zero. Neglecting the transmission losses, transaction matrix (T) can be simplified as:

$$T \equiv [GD] = [DG^T] \tag{2}$$

Each element of T represents a bilateral contract between a supplier (P_{gi}) in row i with a consumer (P_{dj}) in column j [21]. In general, the conventional load flow variables, generation ($\boldsymbol{P_g}$) and load ($\boldsymbol{P_d}$) vectors can be expanded into two-dimensional transaction matrix T as

$$\begin{bmatrix} \mathbf{P_d} \\ \mathbf{P_g} \end{bmatrix} = \begin{bmatrix} T^T & 0 \\ 0 & T \end{bmatrix} \begin{bmatrix} \mathbf{u_g} \\ \mathbf{u_d} \end{bmatrix} \tag{3}$$

where, $\boldsymbol{u_g}$ and $\boldsymbol{u_d}$, are the column vectors of ones with the dimensions of number of generators (n_g) and number of loads (n_d), respectively.

There are some intrinsic properties associated with this transaction matrix T [21] which are given below:

1. Column Rule: For a fixed total system load (PD) and a known load distribution (P_{di}), the sum of each column j of T is equal to the load

(P_{dj}) at node j. In another words, a load will purchase the exact amount of its consumption.

2. Row Rule: The sum of each row i of T cannot exceed the maximum capacity (P_{gi}^{max}) of the generation at node i. It means that no supplier can sell more than what it can produce.
3. Range Rule: Each contract (t_{ij}) has a range from zero to a maximum allowable value, t_{ij}^{max}. This maximum value is bounded by the value of corresponding P_{gi}^{max} or P_{dj}, whichever, is smaller.
$$0 \le t_{ij} \le t_{ij}^{\max} \le \min\left(P_{gi}^{\max}, P_{dj}\right) \qquad (4)$$
It is also possible for some contracts to be firm so that t_{ij}^{0} is equal to t_{ij}^{max}.
4. Flow Rule: Assuming $\boldsymbol{u_g} = \boldsymbol{u_d} = \boldsymbol{u}$ in (3), the line flows of the network in a ac model can be expressed as follows:
$$P_{line} = DF\left\lfloor \mathbf{P_g} - \mathbf{P_d} \right\rfloor \qquad (5)$$

DF is the distribution factor matrix [28]. If the $\boldsymbol{P_g}$ and $\boldsymbol{P_d}$ are substituted using the definition of T as given in (3), the line flows can be expressed as follows:

$$P_{line} = DF\left[T - T^{T}\right]\left[1\ldots1\ldots1\right]^{T} \qquad (6)$$

Since the matrix DF only depends on the configuration of the network parameters (i.e. branch reactance) and they remain constant. Therefore, the line flows will depend only on the differences between sending and receiving end contracts. In this paper, the AC distribution factors based on AC load flow approach has been used proposed for accurate determination of bilateral transaction which are also sensitive to any change in the system operating conditions, thus giving accurate impact of operating conditions to the change in the line flows [25]. The secure bilateral transaction has been determined using the approach proposed in [25].

3. STATIC REPRESENTATION OF UPFC

Figure3 shows static representation of UPFC [29]. The unified power flow controller consists of two switching converters which in the implementations considered as voltage sourced inverters labeled “inverter 1” and “inverter 2” in the figure is operated from a common dc link provided by a dc storage capacitor. This arrangement functions as an ideal ac to ac power converter in which the real power can freely flow in either direction between the ac terminals of the two inverters and each inverter can independently generate or absorb reactive power at its own ac output terminal. Inverter 2 provides the main function of the UPFC by injecting an ac voltage V_T with controllable magnitude V_T ($0<V_T<V_T^{max}$) and phase angle ($0<\phi_T<360$) at the power frequency in series with line via an insertion transformer. This injected voltage can be considered essentially as a synchronous ac voltage source. The transmission line current flows through this voltage source resulting in real and reactive power exchange between it and the ac system. The real power exchanged at the ac terminal (i.e at the terminal of the insertion transformer) is converted by the inverter into dc power, which appears at the dc link as positive or negative real power demand. The reactive power exchanged at the ac terminal is generated internally by the inverter.

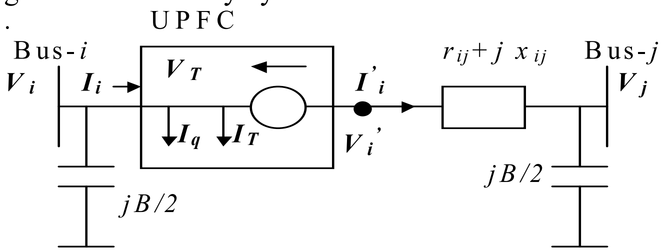

Fig. 3: Equivalent circuit of UPFC

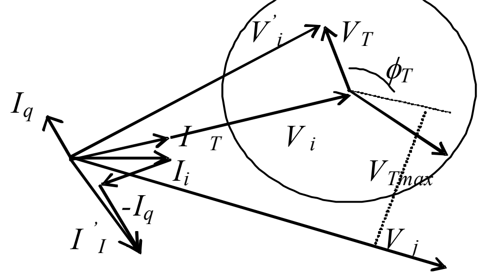

Fig.4: Vector Diagram of UPFC

Based on the principle of UPFC and the vector diagram shown in Fig. 4, the basic mathematical relations can be given as:

$$V_i^{'} = V_i + V_{T,}\ Arg(I_q) = Arg(V_i) \pm \pi/2, \quad (7)$$

$$Arg(I_T) = Arg(V_i), I_T = \frac{\mathrm{Re}[V_T I_i^{'*}]}{V_i} \qquad (8)$$

The Power flow equations from bus-i to bus-j and from bus-j to bus-i can be written as

$$S_{ij} = P_{ij} + jQ_{ij} = V_i I_{ij}^{*} = V_i(jV_i{'}B/2 + I_T + I_q + I_i^{'})^{*} \qquad (9)$$

$$S_{ji} = P_{ji} + jQ_{ji} = V_j I_{ji}^{*} = V_j (jV_j B/2 - I_i^{'})^{*} \quad (10)$$

Active and reactive power flows in the line having UPFC can be written, with above equations as,

$$\begin{aligned} P_{ij} &= \left(V_i^2 + V_T^2\right) g_{ij} + 2V_i V_T g_{ij} \cos\left(\phi_T - \delta_i\right) \\ &- V_j V_T \left[g_{ij} \cos\left(\phi_T - \delta_j\right) + b_{ij} \sin\left(\phi_T - \delta_j\right)\right] \\ &- V_i V_j \left(g_{ij} \cos\delta_{ij} + b_{ij} \sin\delta_{ij}\right) \end{aligned} \quad (11)$$

$$\begin{aligned} P_{ji} &= V_j^2 g_{ij} - V_j V_T \begin{bmatrix} g_{ij}\cos\left(\phi_T - \delta_j\right) \\ -b_{ij}\sin\left(\phi_T - \delta_j\right) \end{bmatrix} \\ &- V_i V_j \left[g_{ij}\cos\delta_{ij} - b_{ij}\sin\delta_{ij} \right] \end{aligned} \quad (12)$$

$$\begin{aligned} Q_{ij} &= -V_i I_q - V_i^2 \left(b_{ij} + \frac{b_{sh}}{2} \right) \\ &- V_i V_j \left[g_{ij}\sin\delta_{ij} - b_{ij}\cos\delta_{ij} \right] \\ &+ V_i V_T \begin{bmatrix} g_{ij}\sin\left(\phi_T - \delta_i\right) \\ + \left(b_{ij} + \frac{b_{sh}}{2} \right)\cos\left(\phi_T - \delta_i\right) \end{bmatrix} \end{aligned} \quad (13)$$

$$\begin{aligned} Q_{ji} &= -V_j^2 \left(b_{ij} + \frac{b_{sh}}{2} \right) \\ &+ V_i V_j \left[g_{ij}\sin\delta_{ij} + b_{ij}\cos\delta_{ij} \right] \\ &+ V_j V_T \begin{bmatrix} g_{ij}\sin\left(\phi_T - \delta_i\right) \\ + \left(b_{ij} + \frac{b_{sh}}{2} \right)\cos\left(\phi_T - \delta_i\right) \end{bmatrix} \end{aligned} \quad (14)$$

4. GENERAL OPF FORMULATION FOR LOADABILITY ENHANCEMENT FOR POOL MODEL WITH BILATERAL CONTRACTS

The problem formulation for the loadability enhancement with UPFC, and other FACTS controllers, TCPAR, and TCSC is formulated as a generalized mixed integer non-linear (MINLP) optimization problem for hybrid electricity market as:

$$\text{Max } f(\mathbf{x}, \mathbf{u}) \quad (15)$$

Subject to

$$\mathbf{g(x,u) = 0} \quad (16)$$

$$\mathbf{h(x,u) \le 0} \quad (17)$$

A. Objective function

The objective function in the problem is to maximize the system loadability for a pool model and mix of pool and bilateral market model.

$$Max \quad \begin{Bmatrix} w_p \rho_p + w_b \rho_b \\ \end{Bmatrix}_{u,\phi,xc,I_q,V_T,v,\delta,P_g,Q_g,P_f,Q_f,P_{gb},P_{gp}}$$

(18)

w_p, w_b and ρ_p , ρ_b are the suitable weight factors and loadability factors for pool and bilateral demands, respectively.

B. Operating constraints

i) Equality constraints: Equality constraints are power balance equations with incorporation of FACTS controllers [25].

$$\mathbf{P}_{g_i} - \rho_b \mathbf{P}_{\mathbf{db}i} - \rho_p \mathbf{P}_{dpi} = P_i \quad (19)$$

$$\mathbf{P_{gb}} = \rho_b \sum_b T_{sb} \text{ , } \mathbf{P_{db}} = \rho_b \sum_s T_{sb} \quad (20)$$

ii) Inequality constraints: Inequality constraints are constraints on voltage limits, angle limits, power flow limit and transaction limits [25]. In addition, there is control parameter limit as:

TCPAR:

$$-\mathbf{u.}*\phi^{\min} \le \phi \le \mathbf{u.}*\phi^{\max} \quad (21)$$

TCSC:

$$\mathbf{u1.*xc}^{\min} \le \mathbf{xc} \le \mathbf{u1.*xc}^{\max} \quad (22)$$

UPFC:

$$-\mathbf{u.}*\phi_T^{\max} \le \phi_T \le \mathbf{u.}*\phi_T^{\max} \quad (23)$$

$$-\mathbf{u.}*I_q^{\max} \le I_q \le \mathbf{u.}*I_q^{\max} \quad (24)$$

$$0 \le V_T \le u.*V_T^{\max} \quad (25)$$

The total number of installed phase shifters (N_ϕ) and thyristor controlled phase shifters (N_{xc}) must satisfy following relation.

$$N_\phi = \sum_{j=1}^{nbr} u_j \le N_\phi^{\max} \quad (26)$$

$$N_{xc} = \sum_{j=1}^{nbr} u1_j \le N_{xc}^{\max} \quad (27)$$

where, *nbr* is the number of branches.

u is the vector of binary variable ('0's and '1's) representing the location of FACTS devices, '1's represent presence and '0's represent absence of FACTS devices. $N_\phi^{\max}$ and $N_{xc}^{\max}$ are the maximum number of available FACTS controllers. $\boldsymbol{u}$ is n_l vector of binary variables for different FACTS controllers. Control parameter $\boldsymbol{\phi}$ is the vector of TCPAR settings and control parameter x_c is the vector of TCSC settings, δ is the vector of bus angles. N_ϕ^{max} and N_{xc}^{max} is the maximum number of TCPAR and TCSC.

$\phi_T^{\max}$, $I_q^{\max}$, $V_T^{\max}$ are the limits on parameters of UPFC (angle, injected current, injected voltage).

5. CASE STUDIES

The proposed algorithm has been tested on the IEEE RTS 24 bus system [17]. This network contains 32 generators installed at 10 buses, and 38 branches (line and transformers). The proposed bilateral transaction matrix and the secure bilateral transaction matrix obtained from the optimization problem are given in the Table I and Table II. In the Tables I and II, the value of transactions $T\ (i,j)$, represents the bilateral contracts between the i^{th} generator bus and j^{th} load bus. The given elements in the tables have positive real values and the rest of the contract values between generator and load buses are zero, which are not shown in these tables.

The values of the system loadability in a pool model and pool model with bilateral secure transaction matrix with and without the presence of UPFC, TCPAR and TCSC have been determined solving the optimization problem. The values of system loadability for a pool model without and with FACTS are given in Table III. From the table, it can be observed that with one number of each FACTS controller, loadability increases more in case of UPFC than that of TCPAR and TCSC with optimal placement and settings. To get the value of loadability as obtained with one UPFC, there will four TCPAR and 3 TCSC required. The values of the optimal control parameter and the location of FACTS controllers in the lines are also presented in Table III. The loadability enhancement with TCPAR and TCSC for pool model has been shown in Figs.5 and 6. The maximum number of TCPAR and TCSC required to get maximum loadability are five and three respectively. The angle of the phase shifter, in the present work, has been considered between –10 to +10 degrees, with 40 % compensation for TCSC, and for UPFC, the series injected angle, voltage and injected shunt current settings are between 0^0 to 360^0, 0.0 to 0.5 pu and 0.0 to1.0 pu, respectively. It is observed that UPFC is more flexible and versatile than TCPAR and TCSC to maximize lodability. The system loadability has also been determined for the hybrid model comprising the pool as well as bilateral transactions. The total bilateral contracts demand has been considered as 50 percent of the total pool demand. The system loadability has been determined for pool demand and bilateral demand in the hybrid model, separately. The system loadability without and with FACTS devices for pool demand and bilateral demand in the hybrid electricity market are given in the Table IV. The value of the device parameter settings and optimal location are given in this table. From the Table IV, it is observed that the there is slight increase in the loadability for the bilateral demand without and with the presence of TCPAR and TCSC, but incase of UPFC the loadability factors for pool and hybrid demand increases simultaneously with optimal placement and settings. The increase in loadability for hybrid model with TCPAR and TCSC has been shown in the Figs. 7 and 8. In the Figs.9 and 10, comparison of UPFC, TCPAR and TCSC for loadability enhancement has been presented for pool as well as hybrid market model. It is observed that one optimally placed UPFC is more flexible and efficient to control power flow due to its wide range of angle control and reactive power management capability compared to the other FACTS controllers. With TCPAR and TCSC, the pool demand increases considerably than bilateral demand, however, with UPFC, the bilateral demand increases considerably and overall increase in the pool and bilateral demand is found to be more than the overall increase in pool and bilateral demand with TCPAR and TCSC. Thus, UPFC can manage more effectively the increase in bilateral demand in hybrid type of electricity markets, where more and more transactions are negotiated between seller and buyers.

Table 1: arbitrary proposed bilateral transaction matrix

Value of transaction between gen. and load bus (p.u)				
T(1,1)=0.5	T(1,2)=0.3	T(1,3)=0.2	T(1,15)=0.1	T(1,18)=0.4
T(2,10)=0.2	T(2,13)=0.3	T(2,15)=0.4	T(2,18)=0.5	T(2,19)=0.2
T(7,9)=0.2	T(7,10)=0.2	T(7,13)=0.4	T(7,15)=0.5	T(13,18)=1.5

Table 2: Secure Bilateral Transaction Matrix (AC Method)

Value of transaction between generation and load bus (p.u.)					
T(1,1)=.50	T(1,2)=.30	T(1,3)=.198	T(2,10)=0.273	T(2,13)=.41	T(2,15)=0.42
T(2,18)=.26	T(2,19)=.22	T(7,9)=.55	T(7,10)=.25	T(7,13)=.43	T(7,14)=.25
T(7,15)=1.06	T(7,18)=.14	T(13,8)=.44	T(13,18)=1.41	T(13,20)=.265	T(15,14)=.28
T(16,5)=.18	T(16,13)=.30	T(16,16)=.19	T(16,19)=.10	T(18,3)=.69	T(18,14)=.13
T(18,16)=.132	T(18,20)=.146	T(21,2)=.125	T(21,4)=.313	T(21,5)=.144	T(21,7)=.57
T(21,8)=.105	T(21,13)=.105	T(21,19)=.117	T(23,6)=.58	T(23,10)=.313	

Table 3: system loadability with and without facts controllers for pool model

No. of FACTS controllers	Loadability (ρ_p)	Controller settings	Optimal Location (line)
0	1.0368	----	----
1 TCPAR	1.1025	ϕ=-9.99^0	1- 2
2 TCPAR	1.1300	-9.99, -9.99	1-2, 11-14
3 TCPAR	1.1653	-9.99, -9.99, -9.99	1-2,11-14, 15-24
4 TCPAR	1.1758	-4.86, -9.74, 9.99, -8.83	1-2,11-14, 15-24,17-22
5 TCPAR	1.1765	-4.64, -8.76, 9.99, -6.23, -5.48	1-2, 11-14, 15-24, 17-22, 21-22
1 TCSC	1.1096	0.0420	10-11
2 TCSC	1.1278	0.042, 0.042	3-24, 10-11
3 TCSC	1.1765	0.040, 0.0347,0.042	3-24, 10-12, 10-11
1 UPFC	1.1570	ϕ=-174^0 | V_T=0.0452 pu | I_q=-1.00 pu	3-24

Table 4: system loadability with and without facts controllers for hybrid model

No. of FACTS devices	Loadability		Controller settings	Optimal Location (Line)
	Pool (ρ_p)	Bilateral (ρ_b)		
0	1.1445	1.0565	----	----
1 TCPAR	1.1460	1.0569	ϕ=-5.09^0	10 – 12
2 TCPAR	1.1465	1.0570	-5.822, 2.305	10-12, 15-24
3 TCPAR	1.1510	1.0581	-9.01, 9.99, -4.714	2-6, 6-10, 10-12
1 TCSC	1.1494	1.0578	0.0302	6-10
2 TCSC	1.1510	1.0582	0.0302, 0.0324	6-10,10-12
1 UPFC	1.1051	1.1132	ϕ=4.551^0 | V_T=0.0225 pu | I_q=1.0 pu	15 – 24

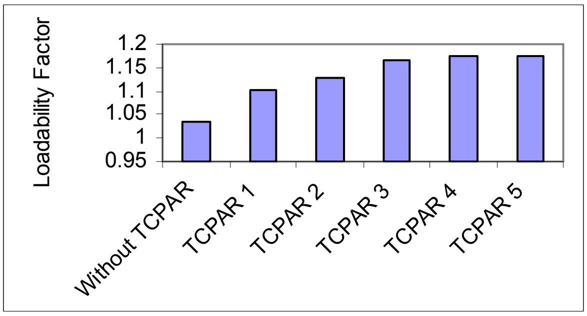

Fig. 5: System Loadability without and with TCPAR for Pool Model

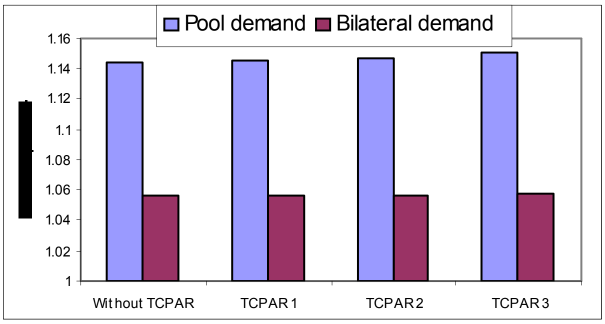

Fig. 7: System Loadability without and with TCPAR for Hybrid Model

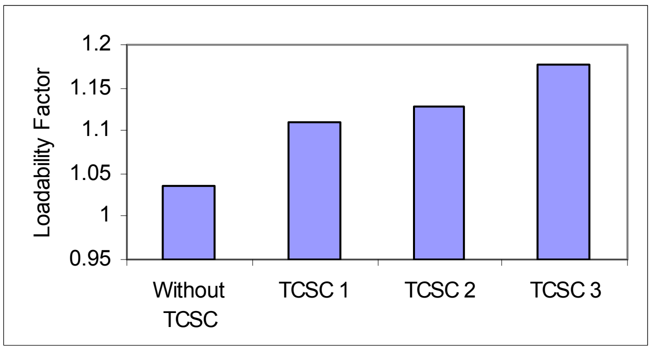

Fig. 6: System Loadability without and with TCSC for Pool Model

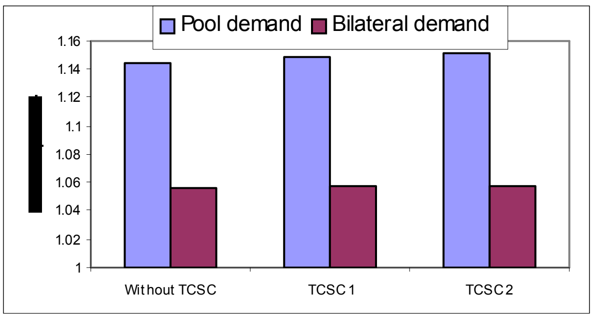

Fig. 8: System Loadability without and with TCSC for Hybrid Model

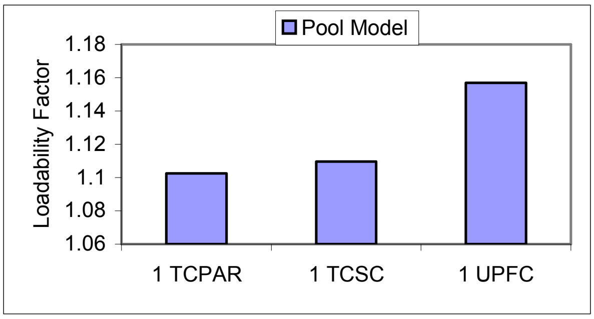

Fig.9: System Loadability with FACTS Controllers (Pool Model)

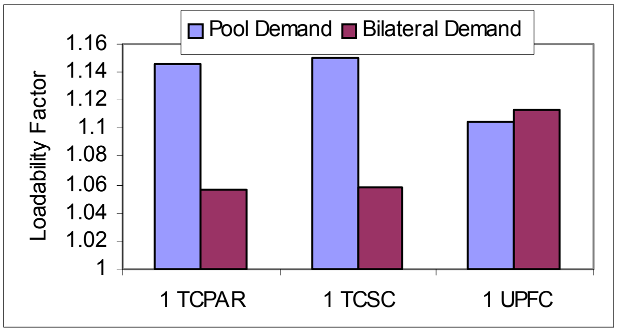

Fig.10: System Loadability with FACTS Controllers (Hybrid Model)

6. CONCLUSIONS

In this paper, a new secure bilateral transaction matrix has been determined with ACDF utilizing non-linear programming approach for hybrid electricity markets. Mixed integer non-linear programming approach has been proposed for optimal location of UPFC to enhance loadability of power systems in deregulated electricity environment. A comparative study of UPFC with other FACTS controllers like TCPAR and TCSC has been presented for enhancement of system loadability for pool as well as hybrid model. It is found that the one UPFC is much more effective than many TCPAR and TCSC due to its wide control of angle and reactive power management capability.

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