Proceedings of the World Congress on Engineering and Computer Science 2008
WCECS 2008, October 22 - 24, 2008, San Francisco, USA

DC Model of UPFC and its Use in Competitive Electricity Market for Loadability Enhancement

Ashwani Kumar and Saurabh Chanana

Abstract— **This paper presents a mixed integer programming based approach for optimal placement of DC model of Unified Power Flow Controller in the deregulated electricity environment. The method accounts for DC load flow equations taking constraints on generation, line flow, and UPFC parameters. The security of transactions has become important issue to reserve the available transfer capability. Therefore, it has become essential to determine secure transactions occurring in the new environment. The secure transactions have been determined in a hybrid market model and system loadability has been determined for a pool model and hybrid model. The proposed technique has been demonstrated on IEEE 24 bus reliability test system.**

Index Terms— **Secure transaction matrix, system loadability, mixed integer linear programming, UPFC location, distribution factors.**

I. Introduction

The determination of transfer capability has emerged as an important index to reserve the further remaining capability of the network to utilize the network potential fully as well as avoiding the congestion in the system [1]. 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.

Ashwani Kumar (email: ashwa_ks@yahoo.co.in) is AP and S. Chanana(email: s_chanana@rediffmail.com) is lecturer in the Department of Electrical Engineering, National Institute of Technology, Kurukshetra, India FAX: +91-1744-238050

A two-step procedure was proposed by Kobayashi et al [7] to locate and adjust phase shifters' angles. 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 using DC method. However, the proposed methodology cannot be applied for deregulated electricity markets, where a hybrid market structure comprises of both bilateral and multilateral contracts.

In a deregulated environment, the number of bilateral transactions has grown rapidly. Bilateral transactions between sellers and buyers are deemed to be feasible, if these can be accommodated without the violations of system security limits [12]. References [13,14] discussed the secure bilateral transaction matrix determination in deregulated environment utilizing the approach of [15]. However, the secure transaction matrix was determined for the markets with only bilateral contracts and the impact of slack bus has not been considered. Garver and Horne [16] proposed a method to compute loadability of generation and transmission networks based on linear programming. Interior point nonlinear optimization technique to determoine system loadability and relationship od loadability with voltage stability was presented in [17]. Direct interior point algorithm and its simplified model were presented to determine the power system maximum loadability and the issues of load curtailment and ATC were also discussed [18]. Gan et al. estimated the loadability of generation and transmission system proposing new algorithm for generation rescheduling [19]. Alomoush presents an approximate model of UPFC based on DC load flow assumptions and discussed its role in restructured power systems [20].

In the present paper, a secure bilateral transaction matrix has been determined using a linear programming based approach to minimize the deviation from the proposed transactions and considering the impact of slack bus on the distribution factors determination. Mixed Integer Linear Programming (MILP) approach has been utilized to maximize the system loadability, in the presence of optimally placed UPFC. The results have also been obtained with conventional controller like Thyristor Controlled Phase Angle Regulator (TCPAR). The optimization problem has been solved utilizing GAMS solver 21.3 [21]. An approach has been applied in a deregulated electricity environment comprising pool and hybrid model. The effectiveness of the proposed approach has been tested on IEEE 24-bus Reliability Test System (RTS) [22].

II. A Lossless Bilateral Contract Model: Transaction Matrix, T

The bilateral contract model, used in this paper, is basically a subset of the full transaction matrix proposed in [15]. In its general form, the transaction matrix *T*, as shown in (1), 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.

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

Only transactions are restricted to the suppliers (G) and the consumer (D) in this work. Neglecting the transmission losses, transaction matrix (*T*) can be simplified as:

$$T \equiv \left[GD\right] = \left[DG^T\right] \quad (2)$$

Each element of *T*, namely t_{ij}, represents a bilateral contract between a supplier (P_{gi}) in row *i* with a consumer (P_{dj}) in column *j*. Furthermore, the sum of row *i* represents the total power produced by generator *i* and the sum of the column *j* represents the total power consumed at load *j*.

$$T \equiv \begin{bmatrix} t_{1,1} \ \cdots \ t_{1,nd} \\ t_{2,1} \ \cdots \ t_{2,nd} \\ t_{ng,1} \cdots \ t_{ng,nd} \end{bmatrix} \quad (3)$$

where, n_g is the number of generators, and n_d is the number of loads.

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

$$\begin{bmatrix} \boldsymbol{P_d} \\ \boldsymbol{P_g} \end{bmatrix} = \begin{bmatrix} T^T & 0 \\ 0 & T \end{bmatrix} \begin{bmatrix} \boldsymbol{u_g} \\ \boldsymbol{u_d} \end{bmatrix} \quad (4)$$

where, $\boldsymbol{u_g}$ and $\boldsymbol{u_d}$, are the column vectors of ones with the dimensions of n_g and n_d, respectively and bilateral transaction matrix possess some intrinsic properties of column rule, row rule, range rule and flow rule [15]. The range rule and flow rules are used to determine:

Range Rule: Each contract 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.

$$0 \le t_{ij} \le t_{ij}^{\max} \le \min\left(P_{gi}^{\max}, P_{dj}\right) \quad (5)$$

It is also possible for some contracts to be firm so that t_{ij}^{0} is equal to t_{ij}^{max} .

Flow Rule: Assuming $\boldsymbol{u_g} = \boldsymbol{u_d} = \boldsymbol{u}$ in (4), the line flows of the network in a DC model can be expressed as follows:

$$P_{ij} = DF\left[\mathbf{P_g} - \mathbf{P_d}\right] \quad (6)$$

DF is the distribution factor matrix [22]. If the P_g and P_d are substituted using the definition of *T* as given in (4), the line flows can be expressed as follows:

$$P_{ij} = DF\left[T - T^T\right]\begin{bmatrix} 1 \\ \vdots \\ 1 \end{bmatrix} \quad (7)$$

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. DF_n^k denotes how much active power flow over a transmission line connecting bus-*i* and bus-*j* would change due to active power injection at bus-*n*. DC load flow based approach, discussed in [23] is considered for determination of distribution factors. To determine these distribution factors (DFs), real power flows in a line connected between bus *i* and bus *j* using DC power flow formulation is given as:

$$P_{ij} = \frac{\delta_i - \delta_j}{x_{ij}} = b_{ij}\left(\delta_i - \delta_j\right) \quad (8)$$

where, x_{ij} and b_{ij} are the series reactance and susceptance of the transmission line.

δ_i is the phase angle of voltage at bus-*i*.

Equation (8) can be rewritten in the vector form as:

$$\left[\mathbf{P_{ij}}\right] = \left[\mathbf{L_{ij}}\right]^T \left[\boldsymbol{\delta}\right] \quad (9)$$

where, $[\boldsymbol{L_{ij}}]$ is a sensitivity vector of the line power flow with respect to bus voltage phase angle. All the elements of $[\boldsymbol{L_{ij}}]$ are zero except the i^{th} and j^{th} elements, which are b_{ij} and - b_{ij}, respectively. $[\delta]$ is a vector of the voltage phase angles at all the buses. The DC load flow equation, describing the relationship between the bus voltage angle vector $[\delta]$ and real power injection vector $[\boldsymbol{P}]$ for a N_B-bus system, is given as follows:

$$\left[\mathbf{P}\right] = \left[\mathbf{B}\right]\left[\boldsymbol{\delta}\right] \quad (10)$$

where, $[B]$ is the N_B x N_B susceptance matrix, whose entries are:

$$B_{ij} = -b_{ij} \qquad \forall ij \quad i \neq j$$
$$B_{ii} = \sum_{j=1}^{N_B} b_{ij} \qquad i = 1,2,\ldots\ldots, N_B \quad (11)$$

Selecting bus *n* to be the reference bus, the row and column of the $[\boldsymbol{B}]$ matrix corresponding to the reference bus can be eliminated. The voltage at other buses relative to this bus can be solved in terms of $[\boldsymbol{P}]$ as:

$$\left[\boldsymbol{\delta}_{-\mathbf{n}}\right] = \left[\mathbf{B}_{-\mathbf{n}}\right]^{-1}\left[\mathbf{P}_{-\mathbf{n}}\right] \quad (12)$$

Where, $(.)_{-n}$ represents a vector without n^{th} element or a matrix with corresponding n^{th} row and column eliminated. The actual phase angles can be rewritten by simply adding the relative phase angles and the phase angles of the reference bus.

$$\left[\boldsymbol{\delta}\right] = \begin{bmatrix} \delta_{-n} \\ 0 \end{bmatrix} + \delta_n \{1\} \quad (13)$$

$$[\boldsymbol{\delta}]=\begin{bmatrix}[\mathbf{B}_{-n}]^{-1} & 0\\ 0 & 0\end{bmatrix}[\mathbf{P}]+\delta_n\{1\} \quad (14)$$

where, δ_n is the phase angle of bus n. {1} is a nx1 unity vector. Combining (9) and (14), the power flow in the line connected between buses i and j, can be expressed in terms of real power injections as:

$$[\mathbf{P_{ij}}]=[\mathbf{L_{ij}}]^T\begin{bmatrix}[\mathbf{B_{-n}}]^{-1} & 0\\ 0 & 0\end{bmatrix}[\mathbf{P}]+\delta_n[\mathbf{L_{ij}}]^T\{1\} \quad (15)$$

$$[\mathbf{P_{ij}}]=\left[DF_n^{ij}\right][\mathbf{P}] \quad (16)$$

The second term of (15) is equal to zero because $[\boldsymbol{L}_{ij}]^{T}\{1\}=0$. Thus, the distribution factor $[D_n^{ij}]$, with bus-n as a reference bus is obtained as:

$$DF_n^{ij}=\begin{bmatrix}[\mathbf{B_{-n}}]^{-1} & 0\\ 0 & 0\end{bmatrix}[\mathbf{L_{ij}}] \quad (17)$$

The n^{th} element corresponding to slack bus in the equation (11) is zero. To obtain the fairness in the competitive environment, the line flow sensitivity at the slack bus should not be zero corresponding to the injections at the slack bus. To attain this, a shift factor has been defined in ref. [19]. This shift factor is given as:

$$\beta_{ij}=-\left(\frac{DF_n^{ij}(i)+DF_n^{ij}(j)}{2}\right) \quad (18)$$

The corrected distribution factors (DFs) for the transmission line, connected between buses i and j, can be obtained as:

$$DF_{ncorr}^{ij}=D_n^{ij}+\beta_{ij} \quad (19)$$

III. General Problem Formulation for Pool Model with Bilateral Contracts

The problem for the secure bilateral transaction matrix has been formulated as a linear programming problem using the contracts as controllable variables and the security/operating limits of the system as the constraints. The bilateral transaction in pool model can be 58.8 percent of the total power fed in a pool [14]. However, in the present work, we have considered that 50 percent of the total power fed into the pool can be contracted between the sellers and the buyers. The objective is to find the secure transaction which is defined as the absolute error between a proposed transaction matrix and the actual secured transaction denoted by T. The optimization problem utilizing DC power flow equations is given as:

$$\text{Min}\ \sum_i\sum_j b_{ij}\left|t_{ij}-t_{ij}^0\right| \quad (20)$$

subject to

$$P_{gbi}=\sum_j t_{ij}\ ,\ P_{dbj}=\sum_i t_{ij} \quad (21)$$

$$P_{gi}=P_{gpi}+P_{gbi}\ ,\ P_{dj}=P_{dpj}+P_{dbj} \quad (22)$$

$$\boldsymbol{P_g}-\boldsymbol{P_d}=\boldsymbol{A^t}P_{ij} \quad (23)$$

$$P_{ij}=B_l A\boldsymbol{\delta} \quad (24)$$

$$\boldsymbol{P_{ij,b}}=DF\left(\boldsymbol{P_{gb}}-\boldsymbol{P}_{db}\right) \quad (25)$$

$$\boldsymbol{P_{ij,p}}=DF\left(\boldsymbol{P_{gp}}-\boldsymbol{P}_{dp}\right) \quad (26)$$

$$\boldsymbol{P}_{ij}=\boldsymbol{P}_{ij,b}+\boldsymbol{P}_{ij,p} \quad (27)$$

$$0\le t_{ij}\le t_{ij}^{\max} \quad (28)$$

$$P_{gi}^{\min}\le P_{gi}\le P_{gi}^{\max} \quad (29)$$

$$-P_{ij}^{\max}\le P_{ij}\le P_{ij}^{\max} \quad (30)$$

where, t_{ij}^0 is the ij^{th} element of the proposed transaction matrix T^0 and P_{ij} is the line power flow between buses i and j. P_{gi} and P_{di} are the generation and demand at bus i, respectively, for a hybrid model comprising pool and bilateral contracts. A is a branch-node incidence matrix and B_l is the diagonal matrix of line succeptances. In this paper, b_{ij} is assumed to be 1 for all (i,j) terms, however, it can be any value for planning and operational studies. P_{gpi} and P_{gbi} are pool and bilateral generation at bus i. P_{dpi} and P_{dbi} are pool and bilateral demand at buses i.

Equation (20) represents the generation and demand for bilateral transactions, whereas (21) represents the power balance equation for the hybrid model. In (23), power injection at any node i is determined. Equations (25), (26), and (27) represent power flow equations for bilateral, pool, and pool plus bilateral models. Equations (28), (29) and (30) represent the inequality constraints for transaction matrix, power generation, and line power flows.

Equations (20) to (30) have been solved using GAMS solver 21.3 [21]. With the help of linear programming optimization problem, the secure bilateral transaction matrix is determined and the obtained secured bilateral transaction matrix has been used in the hybrid electricity markets to determine the power system loadability.

IV. Static Model Representation of TCPAR

The phase shift in TCPAR [24] shown in Fig. 1, is achieved by adding or subtracting a variable voltage, which is perpendicular to the phase voltage of the line. This perpendicular voltage component is obtained from a transformer connected between the other two phases.

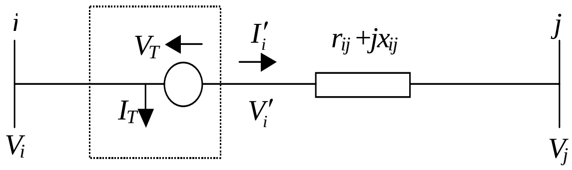

Fig. 1: Equivalent circuit of TCPAR

Based on the basic relationships [19], the active power flow equations in a line connected with TCPAR can be written as:

$$P_{ij}=-t^2V_i^2Y_{ij}\cos\theta_{ij}+tV_iV_jY_{ij}\cos(\theta_{ij}+\delta_j-\delta_i-\phi) \quad (33)$$

$$P_{ji}=-V_j^2Y_{ij}\cos\theta_{ij}+tV_iV_jY_{ij}\cos(\theta_{ij}+\delta_j-\delta_i-\phi) \quad (34)$$

where, Y_{ij} and θ_{ij} are the magnitude and angle of ij^{th} element of $[Y_{Bus}]$ matrix and $t=\dfrac{1}{\cos\phi}$

The power flow equation, which can be derived with DC load, flow assumptions, can be written as:

$$P_{ij}=B_l\ A^t\delta+B_l\phi \quad (35)$$

The equivalent circuit model represents the phase shifter as a continuous variable. In addition, an integer variable u_l = {0,1} is introduced that define the presence (u_l =1) or absence (u_l =0) of the phase shifter in branch l.

V. Static Model Representation of UPFC

Figure 2 shows static representation of UPFC [24]. The unified power flow controller consists of two switching converters and 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 on the line side 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.

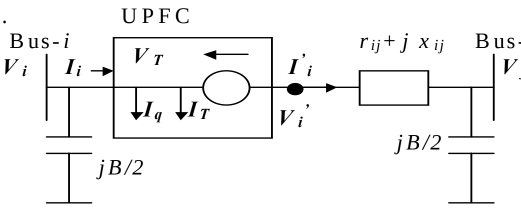

Fig.2: Equivalent circuit of UPFC

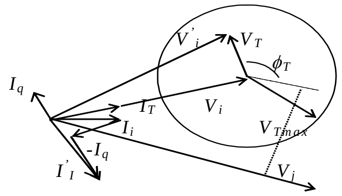

Fig.3. Vector Diagram of UPFC

Based on the principle of UPFC and the vector diagram, the basic mathematical relations can be given as

$$V_i^{'} = V_i + V_{T,} \; Arg(I_q) = Arg(V_i) \pm \pi/2, \quad (36)$$

$$Arg(I_T) = Arg(V_i)\,, I_T = \frac{\mathrm{Re}[V_T I_i^{'*}]}{V_i} \quad (37)$$

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

$$S_{ij} = P_{ij} + jQ_{ij} = V_i I_{ij}^{*} = V_i (jV_i' B/2 + I_T + I_q + I_i^{'})^{*} \quad (38)$$

$$S_{ji} = P_{ji} + jQ_{ji} = V_j I_{ji}^{*} = V_j (jV_j B/2 - I_i^{'})^{*} \quad (39)$$

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

$$\begin{aligned} P_{ij} = & \left(V_i^2 + V_T^2\right) g_{ij} + 2V_i V_T\, g_{ij} \cos\left(\phi_T - \delta_i\right) - \\ & V_j V_T \left[g_{ij} \cos\left(\phi_T - \delta_j\right) + b_{ij} \sin\left(\phi_T - \delta_j\right)\right] \\ & - V_i V_j \left(g_{ij} \cos \delta_{ij} + b_{ij} \sin \delta_{ij}\right) \end{aligned} \quad (40)$$

$$\begin{aligned} P_{ji} = & V_j^2 g_{ij} - V_j V_T \left[g_{ij} \cos(\phi_T - \delta_j) - b_{ij} \sin(\phi_T - \delta_j)\right] - \\ & V_i V_j \left[g_{ij} \cos\delta_{ij} - b_{ij} \sin\delta_{ij}\right] \end{aligned} \quad (41)$$

$$\begin{aligned} Q_{ij} = & -V_i I_q - V_i^2 (b_{ij} + b_{sh}/2) - -V_i V_j \left[g_{ij} \sin\delta_{ij} - b_{ij} \cos\delta_{ij}\right] \\ & V_i V_T \left[g_{ij} \sin(\phi_T - \delta_i) + (b_{ij} + b_{sh}/2)\cos(\phi_T - \delta_i)\right] \end{aligned} \quad (42)$$

$$\begin{aligned} Q_{ji} = & -V_j^2 (b_{ij} + b_{sh}/2) + V_i V_j \left[g_{ij} \sin\delta_{ij} + b_{ij} \cos\delta_{ij}\right] + \\ & V_j V_T \left[g_{ij} \sin(\phi_T - \delta_i) + (b_{ij} + b_{sh}/2)\cos(\phi_T - \delta_i)\right] \end{aligned} \quad (43)$$

Based on the assumptions of DC power flow, the active power flow equations of the line can be derived and are as follows [24]:

$$P_{ij} = -b_{ij}\left(\delta_{ij} + V_T \sin\phi_T\right) \quad (44)$$

$$P_{ji} = b_{ij}\left(\delta_{ij} + V_T \sin\phi_T\right) \quad (45)$$

VI. OPF Formulation for System Loadability and Optimal Location of UPFC

Optimal power flow control with UPFC and TCPAR are considered here. The problem formulation for the both controllers is same except the power flow equations in constraints of the optimization problem. A generalized mixed integer non-linear (MINLP) optimization problem is used incorporating secure bilateral transaction matrix as discussed in section III.

$$\text{Max} \quad f(\boldsymbol{x}, \boldsymbol{u}) \quad (46)$$

Subject to

$$\boldsymbol{g(x, u) = 0} \quad (47)$$

$$\boldsymbol{h(x, u) \le 0} \quad (48)$$

A. Objective function

The comparative study is based on how much the UPFC is more effective than the TCPAR on the basis of loss minimization and enhancing the loadability with same number of controllers. Hence the objective here is to maximize system loadability.

$$Max \quad \begin{Bmatrix} \rho_p \\ \rho_b \end{Bmatrix}_{u,\phi,v,\delta,P_g,P_f,Q_f,P_{gb},P_{gp}} \quad (49)$$

where *PLT* is the total real power transmission loss and PL_j is the real power loss in line-*j*. ρ_p , ρ_b are the loadability factors for pool and bilateral demands, respectively.

B. Operating constraints

i) Equality constraints: Equality constraints are same as that defined in section III with incorporation of TCPAR and UPFC in power flow equations. In case of maximization of loadability (20) and (30) are modified as

$$P_{g_i} - \rho_b P_{dbi} - \rho_p P_{dpi} = P_i \quad (50)$$

$$\boldsymbol{P_{gb}} = \rho_b \sum_b T_{sb} \;, \boldsymbol{P_{db}} = \rho_b \sum_s T_{sb} \quad (51)$$

ii) Inequality constraints: All inequality constraints are the same as described in section III with addition of following more constraints

$$N_\phi = \sum_{j=1}^{nbr} u_j \le N_\phi^{\max} \quad (52)$$

and for TCPAR and UPFC:

$$-u.*\phi_T^{\max} \le \phi \le u.*\phi_T^{\max} \quad (53)$$

and for UPFC the equation (40) is one more inequality constraint along with other above constraints

$$0 \le V_T \le u.*V_T^{\max} \quad (54)$$

where $\phi_T^{\max}$, $V_T^{\max}$ are the limits on parameters of FACTS controllers (angle, injected voltage). *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

ISBN: 978-988-98671-0-2

FACTS devices. $N_{\phi}^{\max}$ is the maximum number of available FACTS controllers.

Equation (50) represents the power flow injection at any bus *i*, whereas (51) gives the power generation to meet bilateral contracts. Equation (52) represents the total number of FACTS controllers used should be less than or equal to total available devices. Equations (53) and (54) represent the limits on parameters of FACTS controllers.

VII. Case Studies

The proposed algorithm has been tested on the IEEE RTS 24 bus system [22]. This network contains 32 generators distributed among 10 buses, and 38 branches (line plus transformers). The system loadability has been determined for the base case considering only the pool model. The loadability is found to be 1.030 p.u., which is also reported in [11]. 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 tables shown in Appendix, 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 for a pool model and pool model with secure bilateral transaction matrix without and with the presence of TCPAR and UPFC have been determined by solving an optimization problem. The values of system loadability for a pool model without and with UPFC and TCPAR are given in Table III. Only one UPFC has been considered due to its cost. The values of the optimal control parameter ϕ and V_T and the location of TCPAR and UPFC on the lines are also given in the Table III. The angle of the phase shifter in the present work has been considered between –10 to +10 degrees. The loadability of the system increases with the presence of TCPAR as well as UPFC in a pool model. It is observed from the table that minimum three TCPARs are required to obtain the loadability as obtained with one UPFC. The value of the loadability for the system with and without TCPAR for a pool model is shown in bar chart in Fig. 4 and for UPFC is shown in the Fig. 6.

The system loadability determined for the hybrid model comprising the pool as well as bilateral transactions has been shown in the Figs. 5 and 7. The system loadability has been determined for pool demand and bilateral demand in the hybrid model, separately. The system loadability without and with TCPAR as well as with UPFC for pool demand and bilateral demand in the hybrid electricity market are given in the Table IV. The value of the TCPAR parameter setting and optimal location along with the UPFC parameter setting and optimal location are also given in this table.

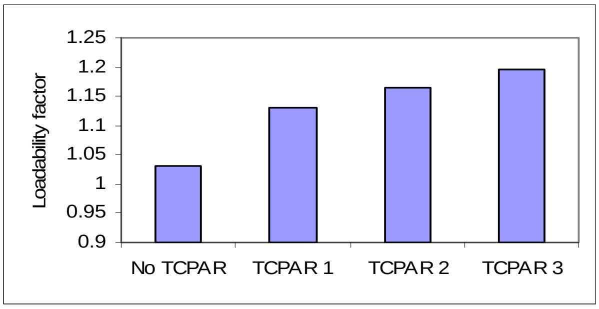

Fig. 4: System Loadability without and with TCPAR

From the Table IV, it is observed that the loadability for the pool demand increases substantially for hybrid model without and with the presence of TCPAR and UPFC. Minimum three numbers of TCPARs are required to obtain the loadability as obtained from one UPFC. The loadability for the bilateral demand remains same due to the fact that the optimal transaction matrix has been used in the hybrid model. The loadability for the pool demand and the bilateral demand in the hybrid model is also shown in Fig. 5 in the presence of TCPAR and in Fig. 7 in the presence of UPFC.

The line flows for few lines in the presence of TCPAR and UPFC are shown in the figures 8 and 9. It is interesting to observe that the line 21-22 was having negligible flow. However, in the presence of optimally placed TCPARs, and UPFC the lines are utilized more effectively.

For hybrid model, two TCPARs are required to obtain the value of loadability as with one UPFC. The highlighted elements in the table show the line flows for the optimally placed TCPARs and UPFC in the corresponding lines. It is observed from the table that lines 16-17 reaches near to its full capacity when two TCPARs are optimally placed in the lines.

All the Tables from I to IV have been shown in the Appendix.

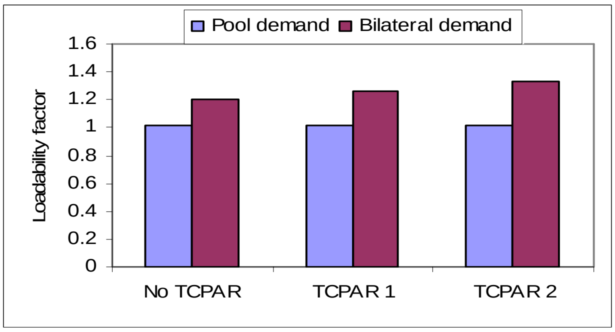

Fig. 5: System Loadability without and with TCPAR for Hybrid model

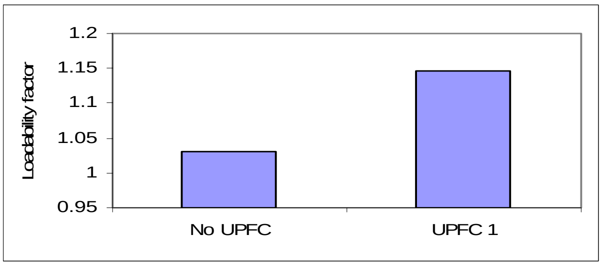

Fig. 6: System Loadability without and with UPFC

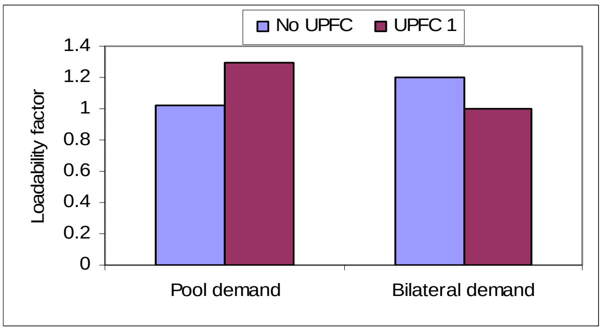

Fig. 7: System Loadability without and with UPFC for Hybrid model

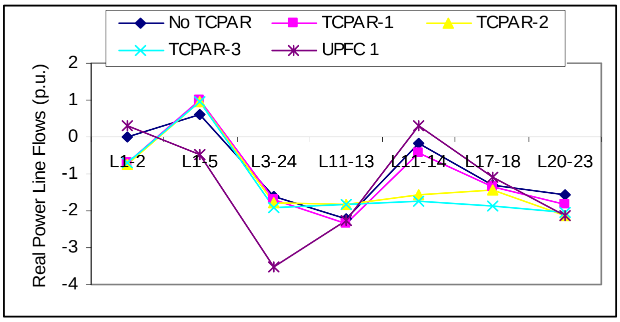

Fig. 8: Real Power Line flows with TCSC for Pool Model

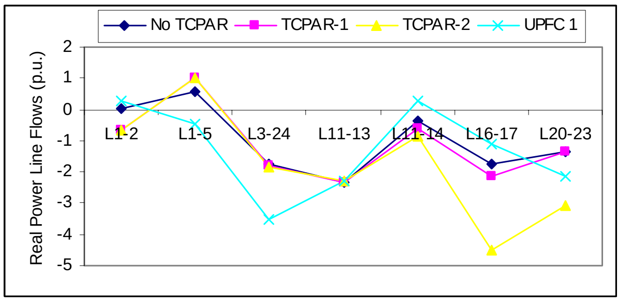

Fig. 9: Real Power Flows with TCSC for Hybrid Model

VIII. Conclusions

In this paper, a new model to obtain the secure bilateral transaction matrix has been proposed for the hybrid type of electricity markets taking into account the effect of slack bus. The secure bilateral transaction matrix obtained has been utilized in the hybrid market model. The system loadability has been determined for pool as well as hybrid market model in the presence of optimally placed UPFC TCPAR. It has been observed that the system loadability increases for pool as well as hybrid market model in the presence of UPFC and TCPAR. In the hybrid market model, the system loadability has been determined for pool demand and bilateral demand separately. The pool demand increases substantially with UPFC and TCPAR in the hybrid model. However, the bilateral demand remains almost same. The lines in the presence of UPFC andTCPAR are found to be utilized optimally and effectively.

Appendix

TABLE I
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)=0.3	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(7,18)=0.0
T(13,18)=1.5	T(13,15)=0.0			

TABLE II
Secure Bilateral Transaction Matrix

Value of transaction between gen. and load bus (p.u.)						
T(1,1)=.50	T(1,2)=.37	T(1,3)=.20	T(1,8)=.08	T(1,15)=.42	T(1,18)=.19	
T(2,10)=.43	T(2,13)=.34	T(2,15)=.43	T(2,18)=.20	T(2,19)=.23		
T(7,6)=.68	T(7,9)=.22	T(7,10)=.24	T(7,13)=.98	T(7,15)=.52	T(7,16).26	T(7,19)=.05
T(13,7)=.57	T(13,8)=.77	T(13,9)=.66	T(13,18)=1.27	T(13,20)=.15	T(15,16)=.24	
T(16,7)=.05	T(16,10)=.30					
T(23,1)=.04	T(23,2)=.19	T(23,3)=.70	T(23,4)=.37	T(23,5)=.36	T(23,14)=.97	T(23,15)=.21
T(23,19)=.63	T(23,20)=.49					

TABLE III
System Loadability with and without UPFC and TCPAR for Pool Model

No. of TCPAR	Loadability in p.u.	ϕ(in degree)	Optimal Location (Line No.)	No. of UPFC	Loadability in p.u.	V, ϕ(in degree)	Optimal Location (Line No.)
0	1.0300	0.0		0	1.0300	0.0	
1	1.1109	-10.0	1, 1-2	1	1.1460	0.5, -90.0	7, 3-24
2	1.1375	-10.0, -10.0	1-2, 11-14				
3	1.1654	-10.0, -10.0, -6.58	1-2, 11-14, 21-22				

TABLE IV
System Loadability with and without TCPAR for Hybrid Model

No. of TCPAR	Loadability in p.u.		ϕ(*in degree*)	Optimal Location (Line No.)	No. of UPFC	Loadability in p.u.		V_T, ϕ(in degree)	Optimal Location (Line No.)
	Pool	Bilateral				Pool	Bilateral		
0	1.1992	1.0166	0.0		0	1.1992	1.0166	0.0	
1	1.2628	1.0166	-10.0	1-2	1	1.2920	1.000	0.5, -90.0	3-24
2	1.3343	1.0166	-10.0, -10.0	1-2, 16-17					

REFERENCES

[1] North American Electric Reliability Council (NERC), "Available transfer capability definition and determination", Rep., June 1996.

[2] Y. H. Song and A. Jones, Flexible AC transmission systems (FACTS), London, UK, :IEE, 1999..

[3] S. Gerbex, R. Cherkaoui, and J. Germond, "Optimal location of multi-type FACTS devices in power system by means of genetic algoithm," *IEEE Trans. on Power Systems*, vol. 16, pp. 537-544, Aug. 2001.

[4] P. Paterni, S. Vitel, M. Bena, and A. Yokoyama, "Optimal allocation of phase shifters in the French network by genetic algorithm," *IEEE Trans. on Power Systems*, vol. 14, pp. 37-43, Feb. 1999.

[5] K.S. Verma, S.N. Singh, and H.O. Gupta, "Location of Unified Power Flow Controller for Congestion Management", *Electric Power System Research*, vol. 58, pp. 89-96, June 2001.

[6] E.J. Oliveira and J.W.M. Lima, "Allocation of FACTS devices in competitive environment," *in Proc. 13th Power System Comput. Conf., Norway*, pp.1184-1190, June 1999.

[7] N. Kobayashi, T. Yamoda, Y. Sekine, H. Okamoto, and Y. Tada, "Some fundamental observations on the optimality of load flow control," *in Proc. 13th Power System Comput. Conf., Norway*, pp. 1263-1269, June 1999.

[8] J. Griffin, D. Atanackovic, and F.D. Galiana, "A study of the impact on FACTS on the secure-economic operation of power systems," *in Proc. 12th Power System Comput. Conf., Norway*, pp. 1077-1082, 1999.

[9] F.D. Galiana, K.C. Almeida, M. Toussaint, J. Griffin, D. Atanackovic, B.T. Ooi, and D.T. McGills, "Assessment and control of the impact of FACTS devices on power system performance," *IEEE Trans. on Power Systems*, vol. 11, pp. 1931-1936, Nov. 1996.

[10] H. Mori and Y. Goto, "A parallel tabu search based method for determining optimal location of FACTS in power system," *in Proc. Int. Conf. Power System-Techno*., vol. 2, pp. 1077-1082, 2000.

[11] F.G.M. Lima, F.D. Galiana, I. Kockar, and J. Munoj, "Phase shifter placement in large scale system via Mixed Integer Linear Programming," *IEEE Trans. on Power systems*, vol. 18, pp. 1029-1034, Aug. 2003.

[12] G. Hamoud, "Feasibility assessment of simultaneous bilateral transactions in a deregulated environment," *IEEE Trans. on Power systems*, vol. 15, No. 1, pp. 22-26, Feb. 2000.

[13] J.W.M. Cheng, D.T. McGills, and F.D. Galiana, "Probabilistic security analysis of bilateral transactions in a deregulated environment," *IEEE Trans. on Power systems*, vol. 14, No. 3, pp. 1153-1159, Aug. 1999.

[14] J.W.M. Cheng, F.D. Galiana, and D.T. McGills, "Studies of bilateral contracts with respect to steady state security in a deregulated environment," *IEEE Trans. on Power systems*, vol. 13, No. 3, pp. 1020-1025, Aug. 1998.

[15] F.D. Galiana and M. Ilic, "A mathematical framework for the analysis and management of power transactions under open access," *IEEE Trans. on Power systems*, vol. 13, No. 2, pp. 681-687, May. 1998.

[16] L. L. Garver and G. E. Horne, "Load supplying capability of generation transmission network", IEEE Trans. on Power Apparatus and Systems, vol. 12, No. 1, pp. 957-962, 1979.

[17] G. D. Irrisari, X. wang, X. Tong, and J. Mokhatri, "maximum loadability of power systems using interior point nonlinear optimization method ", IEEE Trans. on Power Systems, vol. 12, No. 1, pp. 162-172, Feb. 1997.

[18] Y. Dai, J. D. McCalley, and V. Vittal, "Simplification, expension and enhancement of direct interior point method for power system maximum loadability", IEEE Trans. on Power Systems, vol. 15, No. 3, pp. 1014-1021, Aug. 2000.

[19] D. Gan, Z. Qu, and X. Wu, "Loadability of power systems with steay state and dynamic security constraints", Electric Power and Energy systems, vol. 25, pp. 91-96, 2003.

[20] M. I. Alomoush, "Derivation of UPFC DC load flow model with examples of its use in restructured power systems", IEEE Trans. on power systems, vol. 18, No. 3, pp. 1173-1180, Aug. 2003.

[21] A User's Guide, GAMS Software, 1998.

[22] IEEE Reliability Test System, A report prepared by the Reliability Test System Task Force of the Applications of Probability Methods Subcommittee, *IEEE Trans. on Power Apparatus and Systems*, vol. PAS-98, pp. 2047-2054, Nov.- Dec. 1979.

[23] A.J. Wood and B.F. Wollenberg, Power Generation, Operation and Control, New York: Wiley, 1996.

[24] Ge Shaoyun, "Optimal Power System Operation and Control Incorporating FACTS Devices", PhD. Thesis, The Hong Kong University, Aug. 1998.