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Impact of UPFC on Congestion Relief and Allocation in Deregulated Power System with Pool and Bilateral Contracts

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Abstract: Congestion management comprising congestion relief and congestion cost allocation is one of the important operational tasks to be carried out in deregulated power system. Very few methods reported in literature address the combined problem of congestion relief and cost allocation. Congestion relief is obtained using optimal injection corrections from willing participants (both GENCO's and DISCO's) for a price and adjustments of the control settings of the UPFCs (cost free) located in the transmission lines. The solution approach proposed takes care of the enforcement of the operating limits of the control parameters of UPFC. Congestion usage charges for using the congested lines are allocated equitably to the transactions causing congestion. This study addresses the impact of UPFCs on congestion relief and allocation of congestion charges to dominant transactions in a combined pool and bilateral market using DC-load flow model. Linear Programming optimization technique is used to solve this congestion management problem. The results obtained for IEEE 24 bus Reliability Test System demonstrate the impact of cost free action of UPFCs on congestion relief and equitable allocation of charges.

Key words: Congestion management, relief, allocation, UPFC, dominant transactions

INTRODUCTION

The advent of the open access transmission and the spread of competitive markets in electric power industry all over the world have resulted in the growing prominence of transmission congestion. There is a realization that congestion is a major obstacle to vibrant competitive electricity markets. Various congestion management schemes suitable for different restructured paradigms have been reported in the literature. Congestion may be reduced to some extent by preventive action such as ownership rights. It can also be controlled by corrective control actions such as phase shifters (Baldich and Kalam, 1996), FACTS operations (Singh and David, 2001), re-dispatch of generation and curtailments of loads and/or transactions (Rodrigues and Silva, 2003).

Recently, FACTS devices have received more attention in transmission system operations as they can alter power system parameters in order to control power flows and stabilize system, thereby increasing transmission capabilities to the required levels (Ge and Chung, 1999; Li *et al*., 2000). The UPFC which has been recognized as one of the best-featured FACTS device offers a unique combination of fast shunt and series compensations and provides a flexible power system control, therefore, it can be utilized in the power system to control line active and reactive power, achieve maximum power transfer capability, stabilize system, reduce generation cost associated with out-of-merit order and help the system to operate with more security.

To control, operate and evaluate price usage of power system, it is usually necessary to know whether or not and to what extent each market participant contributes to a transmission usage. The demand on allocation process is of more importance in an open-accessed restructured power system in order to allocate the transmission charges to different power system users using reasonable and fair allocation and pricing rules that are based on the actual usage of the transmission system. Rau (2000) proposed an approach to allocate the congestion cost to the nodes of the transmission network based on the node's responsibility. Baran *et al*. (2000) proposed an equitable allocation of congestion relief cost to transactions that cause congestion. The allocation

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reflects the actual usage of the congested facilities by the transactions and recovers the cost. In Wu *et al.* (2004) the simple continuous integration method based on sensitivity is proposed for the congestion cost allocation. Tao and Gross (2002) presents a physical flow based congestion management allocation mechanism for multiple transaction networks with only bilateral transactions, using dc load flow model. Jayashree and Khan proposed congestion management by load curtailment and control settings of the UPFC parameters. This study addresses congestion relief by optimal injection corrections from willing participants (both GENCO's and DISCO's) for a price and adjustments of the control settings of the UPFCs (cost free) located in the transmission lines. It also addresses allocation of congestion charges to dominant transactions in a combined pool and bilateral market using DC-load flow model.

PROBLEM DESCRIPTION

There are two broad paradigms that may be employed for congestion relief. These are the cost-free means and the non-cost-free means (Glatvitsch and Alvardo, 1998). The former include actions like operation of transformer taps, phase shifters, or FACTS devices. These means are termed as cost-free only because the marginal costs involved in their usage are nominal. It is not always possible for cost free means and some non-cost free methods such as rescheduling generation and prioritization and curtailment of loads/transactions have to be exercised to relieve congestion (Singh and David, 2001). The congestion management scheme is designed for a day-ahead market with pool and bilateral transactions, with a time frame of 1 h. It is assumed that the bilateral trading and pool transactions have been finalized separately without considering transmission congestion that may arise. The ISO now takes up the congestion management problem to relieve any congestion that may arise due to transmission constraints to enforce security and the congestion relief means available to the ISO is the acquisition of incremental/decremental injections into the nodes from every willing participants, either a generating entity GENCO or a load entity DISCO and the adjustments of control settings of the UPFCs already present in the system.

A separate bidding process for participating in transmission congestion management market is considered by the ISO. The ISO, based on the bids received from every willing participants, determines the most economical re-dispatch of the bid resources, implements the re-dispatch schedule and allocates the re-dispatch charges in a transparent manner from among all the transactions, both pool and bilateral, contributing to the congestion.

Generalized framework for pool and bilateral transactions: The multi-transaction framework used for bilateral market (Tao and Gross, 2002) is adopted in this study. A bilateral transaction is a set of selling entities supplying a specified amount of real power 't' to a set of buying entities. A transaction $m \varepsilon M$ is denoted by a triplet, $T^{(m)}$,

$$T^{(m)} = \left\{t^{(m)}, S^{(m)}, B^{(m)}\right\} \quad (1)$$

$S^{(m)}$ is a set of selling entities(GENCOS) supplying a specified amount of real power $t^{(m)}$ to $B^{(m)}$, a set of buying entities(DISCOS).
The set is a collection of 2- tuples

$$S^{(m)} = \left\{(s_i^{(m)}, \sigma_i^{(m)})\ ;\ i=1,2.......N_s^{(m)}\right\} \quad (2)$$

Where,
$N^{(m)}_s$ is the number of selling entities in transaction m
$s^{(m)}_i$ is the Id number of the bus of the selling entity i
$\sigma^{(m)}_i$ is the MW supplied by the selling entity i
Similarly the set $B^{(m)}$ is a collection of 2- tuples

$$B^{(m)} = \left\{(b_j^{(m)}, \beta_j^{(m)})\ ;\ j = 1,2.......N_b^{(m)}\right\} \quad (3)$$

Where,
$N_b^{(m)}$ is the number of buying entities in transaction m
$b_j^{(m)}$ is the Id number of the bus of the buying entity j
$\beta_j^{(m)}$ is the MW consumed by the buying entity j

The above multi-transaction framework is used for a combined pool and bilateral market. For this purpose, all the pool transactions already settled by the ISO using market-clearing procedure are treated as a single bilateral transaction between the group of sellers and group of buyers with the transaction amount given by

$$t = \sum_{i=1}^{NPS} PG_i = \sum_{j=1}^{NPB} PD_j$$

Where, NPS is the number of pool sellers and NPB is the number of pool buyers.

POWER INJECTION MODEL OF UPFC

UPFC consists of two linked self-commutating converters sharing a common dc capacitor, which are

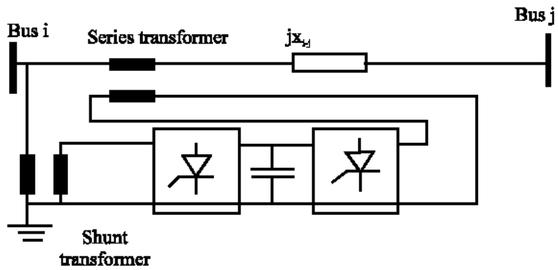

Fig. 1: Schematic diagram of UPFC

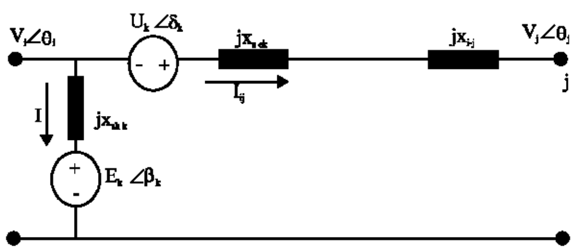

Fig. 2: Equivalent circuit of lossless UPFC embedded line

connected to the ac system through series and shunt coupling transformers. It is assumed that there are NU number of lossless UPFCs connected in the system. The k^{th} UPFC is inserted at the i^{th} end of line i-j is shown in Fig. 1. Since DC load flow model is used only line reactance $x_{i\text{-}j}$ is considered, neglecting line resistance and line charging susceptance. The equivalent circuit of this k^{th} UPFC-embedded transmission line is shown in Fig. 2 which comprises a voltage source in series with a reactance for each converter. The controllable voltages of the converters are $U_k = U_k \angle \delta_k$ and $E_k = E_k \angle \beta_k$. The bus voltages are $V_i = V_i \angle \theta_i$, $V_j = V_j \angle \theta_j$. The voltage source model shown in Fig.2 is converted into an equivalent current source model as shown in Fig. 3.

Setting all the bus voltage magnitudes to be 1.0 p.u and after simplification, the current source model leads to the Power Injection Model (PIM) (Mlomoush, 2003) of k^{th} UPFC embedded line i-j shown in Fig. 4.

Expressions for $P_{i,k}^{sh}$, $P_{i,k}^{se}$ and $P_{j,k}^{sh}$ are derived from Fig. 3 and 4 and using $V_i = V_j = 1.0$ p.u, $P^{sh}_{i,k}$ = Power injection at bus i due to current source $I_{i,k}^{sh}$

$$= \text{Real}\ \{(V_i\ \theta_i)\ I_{i,k}^{sh}*\} = \frac{E_k}{x_{shk}} \sin(\beta_k - \theta_i)\ ;\ k = 1,2...NU \quad (4)$$

$P_{se}^{i,k}$ = Power injection at bus i due to current source $I_{se}^{i,k}$

$$P_{j,k}^{se} = \text{Real}\ \{(V_i \angle\theta_i) I_{j,k}^{se^*}\} \frac{U_k}{x_k} \sin(\theta_i - \delta_k);\quad k=1,2.....NU \quad (5)$$

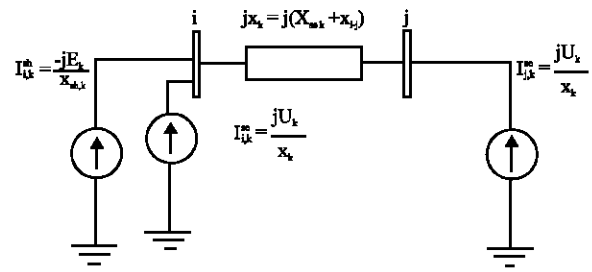

Fig. 3: Current source model of UPFC

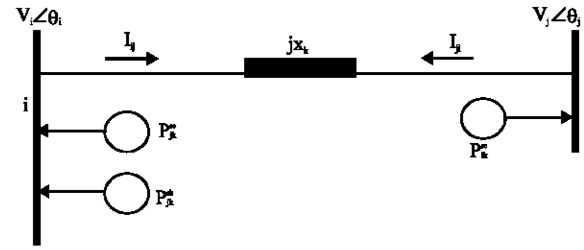

Fig. 4: PIM model of UPFC embedded line

$P_{j,k}^{si}$ = Power injection at bus j due to current source $I_{se}^{j,k}$
= Real $\{(V_j \angle \theta_j\ I_{se}^{j,k*}\}$

$$\frac{U_k}{x_k} \sin(\delta_k - \theta_j);\ k = 1,2...\ NU \quad (6)$$

Power exchange constraint: The active power drawn from the grid by the shunt converter ($P_k^{ex,sh}$) must be equal to the active power delivered into the network by series converter ($P_k^{ex,se}$).

$$\text{i.e } P_k^{ex,sh} = P_k^{ex,se} \quad (7)$$

From Fig. 2

$$P_k^{ex,sh} = \text{Real}\ \{E_k \angle\beta_k\ I^*\} = \frac{E_k}{x_{shk}} \sin(\theta_i - \beta_k);\ k= 1,2...NU \quad (8)$$

$$P_k^{ex,se} = \text{Real}\ \{Uk \angle \delta k\ I_{ij}^*\} = -\frac{U_k}{x_k} \sin(\delta_k - \theta_i) - \frac{U_k}{x_k} \sin(\theta_j - \delta_k);\ k = 1,2...NU \quad (9)$$

From Eq. 4 and 8 $P_k^{ex,sh} = -P_{i,k}^{sh}$ and from Eq. 5, 6 and 9

$$P_k^{ex,se} = (P_{i,k}^{se} + P_{j,k}^{se}) \quad (10)$$

Hence Eq. 7 becomes

$$-P_{i,k}^{sh} = (P_{i,k}^{se} + P_{j,k}^{se}) \quad (11)$$

From Eq. 11

$$P_{j,k}^{se} = (P_{i,k}^{se} + P_{i,k}^{sh}) \quad (12)$$

Hence PIM model of UPFC with the satisfaction of power exchange constraint is given by the Fig. 4 and Eq. 4, 5, 6 and 12 . Out of the three power injections $P_{i,k}^{se}$ $P_{j,k}^{sh}$ and $P_{j,k}^{se}$ the first two injections are chosen as independent decision variables. In order to satisfy the power exchange constraint Eq. 12, the third injection $P_{j,k}^{se}$ is expressed in terms of the two chosen decision variables as = $P_{j,k}^{se} = -(P_{i,k}^{se} + P_{i,k}^{sh})$.

PROBLEM FORMULATION

The congestion assignment and congestion relief (Tao and Gross, 2002) are two preliminary steps required for the formulation of optimal congestion management problem. In the first step (Congestion assignment) the overload caused, Δfl, in each congested line l is equitably distributed as $\Delta f_l^{(m)}$ to each one of the dominant transaction, m which has caused overloads (Tao and Gross, 2002). In the second step (Congestion relief) the injection corrections ΔP_k offered by k^{th} participant, the injection corrections $\Delta P_{i,k}^{se}$ and $\Delta P_{j,k}^{sh}$ of the kth UPFC are sectionalized into $\Delta P^{(m)}_k$, $P_{i,k}^{se(m)}$ and $\Delta P_{j,k}^{sh(m)}$, respectively covering each one of the dominant transaction, m which is required to relieve all the overloads $\Delta f^{(m)}_l$ caused by that transaction m.

Congestion assignment: A DC load flow is run for the proposed congested state with all the pool and preferred bilateral transactions and the active power flows fl in MW, l∈L are obtained. The subset $\tilde{L}$ of overloaded lines are identified:

$$\tilde{L} \triangleq \left\{ l \in L : f_l > f_l^{max} \right\}$$

Where, f_l^{max} is maximum MW rating of the line.

The overload Δfl in line $l \in \tilde{L}$ is defined as $\Delta f_l = f_l - f_l^{max}$. For each line $l \in \tilde{L}$, the transactions in the set M is partitioned into two subsets, D_l, the dominant transactions which cause congestion in that line and, the counter transactions, using sensitivity information,

$$\varphi_l^{(m)} \triangleq \left(\frac{\partial f_l}{\partial t^{(m)}} \right) \quad (13)$$

A transaction m is a dominant transaction if $\varphi_l^{(m)} \geq 0$ and a counter transaction if $\varphi_l^{(m)} > 0$.

The overload caused, Δf_l is equitably shared among all the dominant transactions, $m \in D_l$ as follows:

$$\Delta f_l^{(m)} = \frac{\varphi_l^{(m)} t^{(m)}}{\sum_{m \in D_l} \varphi_l^{(m)} t^{(m)}} \Delta f_l = U_l^{(m)} \Delta f_l \quad (14)$$

Where, $U_l^{(m)}$ is the fraction of share of overload Δf_l to transaction m.

Congestion relief

Relief by willing participants: ISO must run an auction of incremental/decremental adjustments to select the most economic means to provide overload relief. The participants in the adjustment auction need not be limited to be participants in the proposed transactions.

Let K be the set of willing participants (GENCOS or DISCOS) offering to correct their injections for a cost in the congestion relief bid. A participant is denoted by a quadruplet, $R^{(K)}$.

$$R^{(k)} = \left\{ (r_k, \Delta P_k, c_k^+, c_k^-), k = 1, 2 \ldots N_r \right\} \quad (15)$$

Where, N_r is the number of relief participants

- Δp_k : The injection correction (increase or decrease) offered by the k^{th} participant.
- r_k : The Id number of the bus at which the injection of the k^{th} participant is available.
- C^+_k : The incremental bid price in \$/Mw-hr.
- C^-_k : The decremental bid price in \$/Mw-hr.

The increment in revenue for congestion relief participant to increase its injection is given by $c^+_k \Delta P_k$ and to decrease its injection is $c^-_k \Delta P_k$. The injection correction, ΔP_K, k∈K, are sectionalized into $\epsilon P_k^{(m)}$, $m \in \tilde{M}$

Where,

$$\tilde{M} \triangleq \bigcup_{l \in \tilde{L}} D_l \text{ and } \Delta P_k^{(m)}$$

is the net incremental/decremental injection acquired from the participant k, which is required to relieve all the overloads caused by the m^{th} transaction,

$$\Delta f_l^{(m)}, l \in \tilde{L}^{(m)}, m \in \tilde{M}$$

$$\text{Where, } \tilde{L}^{(m)} \triangleq \left\{ 1 : 1 \in \tilde{L} \text{ and } \varphi_l^{(m)} \geq 0 \right\}$$

The sensitivity $\Psi_{l,k}$, the change in the active power flow with respect to change in net injection ΔP_K of the k^{th} participant, is defined as

$$\psi_{l,k} \triangleq \frac{\partial f_l}{\partial P_k}\ ,\ l \in L \qquad (16)$$

Relief by UPFCs: Let KU be the set of UPFCs already present in the system. An UPFC k∈KU is denoted by a triplet, $F^{(K)}$

$$F^{(k)} = \left\{ \left(L_k, \Delta P^{se}_{i,k}, \Delta P^{sh}_{i,k} \right),\ k = 1,2 \ldots NU \right\}$$

Where, NU is the number of UPFCs

L_K : The Id number of the line i-j in which the kth UPFC is connected.
$\Delta p^{se}_{i,k}$: The series incremental injection at the ith node.
$\Delta p^{sh}_{i,k}$: Shunt incremental injection at the ith node.

The UPFC injections $\Delta P^{se}_{i,k}$, $\Delta P^{sh}_{i,k}$, are sectionalized as stated earlier into $\Delta P^{se(m)}_{i,k}$, $\Delta P^{sh(m)}_{i,k}$, reply,

$$m \in \tilde{M},\ k \in KU$$

$$\tilde{M} \triangleq \bigcup_{l \in \tilde{L}} D_l$$

The sensitivities $\psi_{i,kse}$, $\psi_{i,ksh}$ the change in the active power flow with respect to change in the series injection $\Delta p^{se}_{i,k}$ and shunt injection $\Delta P^{sh}_{i,k}$ of the k^{th} UPFC resply, are defined as

$$\psi_{l,kse} \triangleq \frac{\partial f_l}{\partial P^{se}_{i,k}},\ l \in L \qquad (17)$$

$$\psi_{l,ksh} \triangleq \frac{\partial f_l}{\partial P^{sh}_{i,k}},\ l \in L \qquad (18)$$

LP model for congestion management: Congestion relief problem can be stated using the overload share fraction $U^{(m)}_l$ given in Eq. 14 and the sensitivities $\Psi_{i,k}$, $\Psi_{i,kse}$ and $\Psi_{i,ksh}$ defined in Eq. 16-18 resply.

The mathematical statement of the problem is as follows:
The ISO's objective is
To determine

$$\Delta P_k, k \in K$$
$$\Delta P^{se}_{i,k}, \Delta P^{sh}_{i,k}, k \in KU$$

To minimize the total congestion charges

$$Z = \sum_{k \in K} c_k \Delta P_k = \sum_{k \in K} c_k \left[\sum_{m \in \tilde{M}} \Delta P^{(m)}_k \right] \qquad (19)$$

Where,

$$c_k = \begin{cases} c^+_k \ \text{if}\ \Delta P_k = \sum_{m \in \tilde{M}} \Delta P^{(m)}_k > 0 \\ c^-_k \quad \text{otherwise} \end{cases}$$

Subject to
Power balance constraint

$$\sum_{k \in K} \sum_{m \in \tilde{M}} \Delta P^{(m)}_k = 0 \qquad (21)$$

Constraints for removal of existing overloads

$$-\sum_{k \in K} \psi_{l,k} \Delta P^{(m)}_k - \sum_{k \in KU} \psi_{l,kse} \Delta P^{se(m)}_{i,k} - \sum_{k \in KU} \psi_{l,ksh} \Delta P^{sh(m)}_{i,k} = \Delta f^{(m)}_l = U^{(m)}_l \Delta f_l \quad l \in \tilde{L}, m \in \tilde{M} \qquad (22)$$

The equality constraints (22) ensure that the congestion relief acquired by ISO for each dominant transaction is that required to relieve exactly the amount of overloads caused in various lines by that transaction.

Constraints to ensure that no new overloads are caused in all the lines due to enforcement of Eq 22:

$$f_l + \sum_{k \in K} \psi_{l,k} \Delta P_k + \sum_{k \in KU} \psi_{l,kse} \Delta P^{se}_{i,k} + \sum_{k \in KU} \psi_{l,ksh} \Delta P^{sh}_{i,k} \le f^{max}_l, l \in L \qquad (23)$$

Increment/Decrement limits

$$\Delta P^{min}_k \le \Delta P^{(m)}_k \le \Delta P^{max}_k, k \in K \qquad (24)$$

$$\Delta P^{semin}_{i,k} \le \Delta P^{se(m)}_{i,k} \le \Delta P^{semax}_{i,k}, k \in KU \qquad (25)$$

$$\Delta P^{shmin}_{i,k} \le \Delta P^{sh(m)}_{i,k} \le \Delta P^{shmax}_{i,k}, k \in KU \qquad (26)$$

Total increment/Decrement limits

$$\Delta P^{min}_k \le \Delta P_k \le \Delta P^{max}_k, k \in K \qquad (27)$$

$$\Delta P^{se\,min}_{i,k} \le \Delta P^{se}_{i,k} \le \Delta P^{se\,max}_{i,k}, k \in KU \qquad (28)$$

$$\Delta P^{sh\,min}_{i,k} \le \Delta P^{sh}_{i,k} \le \Delta P^{sh\,max}_{i,k}, k \in KU \qquad (29)$$

Where,

$$\Delta P_k^{max} = P_k^{max} - P_k^o, \Delta P_k^{min} = P_k^{min} - P_k^o, \Delta P_{i,k}^{se\,max}$$
$$= P_{i,k}^{se\,max} - P_{i,k}^{seo}, \Delta P_{i,k}^{se\,min} = P_{i,k}^{se\,min} - P_{i,k}^{seo} \Delta P_{i,k}^{sh\,max}$$
$$= P_{i,k}^{sh\,max} - P_{i,k}^{sho} \text{ and } \Delta P_{i,k}^{sh\,min} = P_{i,k}^{sh\,min} - P_{i,k}^{sho}$$

Superscript 'o' represents the condition in congested base case. The series injection $P^{sco}_{i,k}$ and the shunt $P^{sho}_{i,k}$ injection of the k^{th} UPFC in the congested base case are taken as zero.

Separation of markets

$$\sum_{k \in S^{(m)} \cup B^{(m)}} \Delta P_k = 0, \; m \in M' \quad (30)$$

Where, M′ is the subset of transactions willing to provide congestion relief.

This constraint is imposed to balance the generation and load of willing participants within each transaction coming forward for congestion relief.

SENSITIVITY RELATIONS

Sensitivity relations $\varphi_l^{(m)}$, $\Psi_{i,k}$, $\Psi_{i,kse}$, $\Psi_{i,ksh}$ used in the congestion management problem are stated in this study.

Let $\Delta\delta^{(a)}$ be the changes in state caused by an action 'a' which may be due to anyone of the following transaction, m congestion relief action of participant, k and congestion relief action by UPFCs. The corresponding change in active power flow f_{p-q} due to the above action will be $\Delta f^{(a)}_{p-q}$.

$$\Delta f_{(p-q)}^{(a)} = \left[\frac{\partial f_{p-q}}{\partial \boldsymbol{\delta}}\right]^t \Delta\boldsymbol{\delta}^{(a)} \quad (31)$$

$$\Delta f_{p-q}^{(a)} = \frac{\partial f_{p-q}}{\partial \delta_p}\Delta d_p^{(a)} + \frac{\partial f_{p-q}}{\partial \delta_q}\Delta d_q^{(a)} \quad (32)$$

Equation 32 can be written as

$$\Delta f_{p-q}^{(a)} = A\Delta d_p^{(a)} + B\Delta d_q^{(a)} \quad (33)$$

Where, $A=1/x_{pq}$ and $B= -1/x_{pq}$

Change in real power injection due to cause of action 'a' changes the state $\Delta\delta^{(a)}$ as given by dc load flow

$$\left[B'\right] \Delta\delta^{(a)} = (\Delta PI)^{(a)} \quad (34)$$

and hence $\Delta d^{(a)} = \left[X'\right](\Delta PI)^{(a)}$

Where, $\left[X'\right] = \left[B'\right]^{-1}$

Sensitivity with respect to transaction: Sensitivity $\varphi_l^{(m)}$ is defined (Eq. 13) as the change in active power flow in the line p-q, $\Delta f^{(m)}_{p-q}$ due to unit change in the m th transaction. The change in real power injection due to the transaction m can be written as

$$(\Delta PI)^{(m)} = \xi^{(m)} t^{(m)} \quad (35)$$

Where, n^{th} component of the vector $\xi^{(m)}$ can be written as

$$\xi_n^{(m)} = \begin{cases} s_i^{(m)} \text{ if } n = s_i^{(m)} & ; \; i = 1,2....N_s^{(m)} \\ -\beta_j^{(m)} \text{ if } n = b_j^{(m)} & ; \; j = 1.....N_b^{(m)} \\ 0 & ; \text{ otherwise} \end{cases} ; m\hat{I}M \quad (36)$$

The change in active power flow in the line p-q $\Delta f^{(m)}_{p-q}$, can be written by substituting Eq. 36 in 34 and in turn in 33

$$\Delta f_{p-q}^{(m)} = \varphi_l^{(m)} t^{(m)} \quad (37)$$

Sensitivity with respect to relief action by willing participants: Sensitivity $\Psi_{l,k}$ is defined (Eq. 16) as the change in active power flow in the line p-q, due to unit change in the injection. The change in real power injection due to the congestion relief action of k^{th} participant can be written as

$$(\Delta PI)^{(K)} = \xi^{(k)} \Delta P_k \quad (38)$$

Where n^{th} component of vector can be written as

$$\xi_n^{(k)} = \begin{cases} 1 \text{ if } n = r_k & ; \; k = 1,2....N_r \\ 0 & ; \text{ otherwise} \end{cases} \quad (39)$$

The change in active power flow in the line p-q, can be written by substituting Eq. 39 in 34 and in turn in 33

$$\Delta f_{p-q}^{(k)} = \psi_{l,k} \Delta P_k \quad (40)$$

Sensitivity with respect to relief action by UPFCs series injections: Sensitivity $\Psi_{l,kse}$ is defined (Eq. 17) as the change in active power flow in the line p-q, $\Delta f^{(kse)}_{p-q}$ due to unit change in the series injection of the k^{th} UPFC. The change in real power injection due to the congestion relief action of k[th] UPFC series injection can be written as

$$(\Delta PI)^{(kse)} = \xi^{(kse)} \Delta P^{se}_{i,k} \quad (41)$$

Where, n[th] component of vector $\xi^{(kse)}$ can be written as

$$?^{(kse)}_{n} = \begin{Bmatrix} 1 \text{ if } n = i \ ; \ i = \text{sending end of line } L_k \\ -1 \text{if } n = j \ ; \ j = \text{receiving end of line } L_k \\ 0 \qquad ; \text{ otherwise} \end{Bmatrix}$$

The change in active power flow in the line p-q, $\Delta f^{(kse)}_{p-q}$ can be written by substituting Eq. 41 in 34 and in turn in 33

$$\Delta f^{(kse)}_{p-q} = \psi_{l,kse} \Delta P^{se}_{i,k} \quad (42)$$

Sensitivity with respect to relief action by UPFCs shunt injection: Sensitivity is defined (Eq. 18) as the change in active power flow in the line p-q, $\Delta f^{(ksh)}_{p-q}$ due to unit change in the shunt injection of the k[th] UPFC connected in the line i-j. The change in real power injection due to the congestion relief action of k[th] UPFC shunt injection can be written as

$$(\Delta PI)^{(ksh)} = \xi^{(ksh)} \Delta P^{sh}_{i,k} \quad (43)$$

Where n[th] component of vector $\xi^{(ksh)}$ can be written as

The change in active power flow in the line p-q, can be written by substituting Eq. 43 in 34 and in turn in 33

$$\xi^{(ksh)}_{n} = \begin{Bmatrix} 1 \text{ if } n = i \ ; \ i = \text{sending end of line } L_k \\ -1 \text{if } n = j \ ; \ j = \text{receiving end of line } L_k \\ 0 \qquad ; \text{ otherwise} \end{Bmatrix} \quad (44)$$

SOLUTION APPROACH

The congestion management problem 19-30 is solved using Linear programming optimization tool LINPROG in MATLAB. Since only are the physical control parameters and are only fictitious equivalent injections of UPFC, their maximum values are estimated by satisfying Eq. 4-6, the power exchange constraint Eq. 12 and the range of control parameters

$$\left.\begin{matrix} U^{min}_k \le U_k \le U^{max}_k \\ E^{min}_k \le E_k \le E^{max}_k \\ 0 \le \theta_k \le 2\Pi \\ 0 \le \beta_k \le 2\Pi \quad k=1,2.....NU \end{matrix}\right\} \quad (45)$$

The estimated values are used in the LP problem and the optimal solution is obtained. Physical control parameters corresponding to optimal solution are obtained by satisfying Eq. 4-6 and 45. If the physical parameters obtained are within the range (45) optimal solution is reached otherwise and are reset suitably and the LP is resolved. The above process is repeated until the physical parameters are within the range.

POST OPTIMALITY ANALYSIS

To allocate the congestion charges incurred to the dominant transactions the congestion usage-pricing scheme is adapted. This scheme also provides incentive to transactions, which are helpful in relieving the congestion.

Usage charges: Let $\Delta p_k^{(m)}$, $\Delta p_{i,k}^{se(m)}$, $\Delta p_{i,k}^{sh(m)}$ and Z^* be the optimal corrections and the congestion relief cost respectively. The shadow prices corresponding to the constraints (23) and (24) obtained are $\rho_l^{*(m)}$ and μ_l^*, respectively. The expenditure μ_l^* is incurred to ensure that there is no overload in the ISO determined schedule. The usage rate x_l^* is obtained from the shadow prices as

$$x^*_l; l \in L' = \begin{cases} \mu^*_l + \sum_{m \in D_l} \left[\dfrac{\rho^{*(m)}_l \varphi^{(m)}_l t^{(m)}}{\sum_{m \in D_l} \varphi^{(m)}_l t^{(m)}} \right] & ; \text{ if } l \in \tilde{L} \\ \mu^*_l & ; \text{ otherwise} \end{cases} \quad (46)$$

Where L′ is the set of critical lines for which $x^*_l \neq 0$

In the ISO determined schedule the flow $f_l^{*(m)}$ associated with line l and transaction m is approximated by

$$f^{*(m)}_l \simeq \varphi^{(m)}_l t^{(m)} + \sum_{k \in K} \psi_{l,k} \Delta P^{*(m)}_k + \sum_{k \in KU} \psi_{l,kse} \Delta P^{se(m)*}_{i,k} + \sum_{k \in KU} \psi_{l,ksh} \Delta P^{sh(m)*}_{i,k},; m \in \tilde{M}\ ,\ l \in L' \quad (47)$$

Where $\varphi_l^{(m)} t^{(m)}$ is the flow in line l attributable to transaction m in the congested state and

$$\sum_{k \in K} \psi_{l,k} \Delta P^{*(m)}_k$$

is the change in the line flow that is due to the relief action by willing participants associated with transaction m.

$$\sum_{k\in KU} \psi_{l,kse}\Delta P_{i,k}^{se(m)*} \text{ and } \sum_{k\in KU} \psi_{l,ksh}\Delta P_{i,k}^{sh(m)*}$$

is the change in the line flow that is due to the relief action by the UPFCs series and shunt injections reply. The congestion usage charge for line l allocated to transaction m is given as

$$X_l^{*(m)} = x_l^* f_l^{*(m)};\ m \in \tilde{M},\ l \in L^{'} \tag{48}$$

Equation (38) gives the congestion usage charges for congestion management .

RESULTS AND DISCUSSION

Modified IEEE 24 bus Reliability Test System (RTS) is used in this paper to demonstrate the effectiveness of the proposed method for congestion relief and allocation. Changes made in the line data are given in Appendix A. GENCO and DISCO data and the transaction profile of the system are given in Appendix B. For congestion relief, nine GENCOS with ID numbers 1,2,9,20,21,22,23,30,31 and six DISCOS with ID numbers 2,7,10,13,16,17 are taken as willing participants. All these relief participants are transaction participants. G21,G22,G23,G30,G31,D2,D7and D10 belong to transaction T1, G9 and D13 belong to transaction T2, D16 and D17 belong to transaction T3 and G1 and G2 belong to transaction T4. With a view to highlight the effect of UPFC in enhancing congestion relief actions, simulations were made on the system without UPFC and then with UPFC.

Congestion management without UPFC-Case 1: The DC load flow is run on the congested base case with all transactions taken. The overloads MW caused by the transactions is shown in column 4 of Table 1. The overload share assigned to the dominant transactions T1, T2 and T3 computed using Eq. (5) are given in column 5.

Table 1: Overloads and share assigned to dominant transactions

State 1	Over loaded lines 2	Rating, MW 3	Overload Δf_l, MW 4	$\Delta f^{l(m)}$, MW 4MW5	T1	T2	T3	T4	Line flows after correction, MW6 T5
Base case	7-8	59.5	48.43	45.90	---	---	2.52	---	59.5
(Congested)	15-16	68	93.92	69.04	---	8.04	16.84	---	68
	17-18	136	91.92	87.09	---	1.72	3.11	---	136

Table 2: Congestion correction and charges payable to relief participants-without UPFC

	Gencos				Discos	
ID number	9	21	22	23	7	13
ΔP_k, MW	57.151	124.22	-136.97	-24.306	37.056	-57.151
Incremental/Decremental bid price, $/MW-hr	22	12	5	5	24	19
Relief charges ($/h) payable by ISO to participants	1257.3	1490.6	684.85	121.53	889.34	1085.9
Total charge ($/h) paid by ISO	5529.52($/h)					

Table 3: Computation of congestion usage charges and allocation to transactions-without UPFC

Congested line l	Usage rate x^*_l, $/hr/pu MW	$\frac{\text{Allocated Flow}}{\text{Usage Charge}}, \frac{f_l^{*(m)}, \text{pu MW}}{X_l^{*(m)}, \$/\text{hr}}$ T1	T2	T3	T4	T5
7-8	5201.9	1.2642	-----	-0.5537	0.0695	------
		6576.2		-2880.4	361.7	
15-16	2238.3	2.0952	------	0.2441	0.5111	------
		4689.7		546.3	1144.1	
17-18	1393.9	2.9179	------	0.0577	0.1042	------
		4067.4		80.5	145.3	
Net usage charges($/hr) paid by each transaction to ISO		15.333	----	-2253.6	1651.1	-----
Net usage charge($/hr) collected by ISO		14.731 ($/hr)				

Table 4: Congestion correction and charges payable to relief participants –with UPFC

	GENCOS				DISCOS	
ID number	9	21	22	23	7	13
ΔP_k, MW	48.141	83.133	-84.667	-35.522	37.056	-48.141
Incremental decremental bid price, $/MW-hr	22	12	5	5	24	19
Relief charges ($/hr) payable by ISO to participants	1059.1	997.59	423.33	177.61	889.34	914.68
Total charge ($/hr) paid by ISO	4461.65($/hr)					

Table 5: Computation of congestion usage charges and allocation to transactions-with UPFC

Congested line l	Usage rate x^*_l, \$/hr/pu MW	$\frac{\text{Allocated Flow } f_l^{*(m)}, \text{pu MW}}{\text{Usage Charge}, X_l^{*(m)}, \$/\text{hr}}$ T1	T2	T3	T4	T5
7-8	5201.9	1.2642 / 6576.2	-----	-0.5537 / -2880.4	0.0695 / 361.7	------
15-16	2280.6	2.0952 / 4778.3	------	0.2441 / 556.6	0.5111 / 1165.7	------
17-18	1347.4	2.9179 / 3931.7	------	0.0577 / 77.8	0.1042 / 140.4	------
Net usage charges(\$/hr) paid by each transaction to ISO		15,286	----	-2246	1668	-----
Net usage charge(\$/hr) collected by ISO		14,708 (\$/hr)				

Table 6: Shows the power injections, control parameters of UPFCs

Location of UPFC	$P^{se}_{i,k}$ (MW)	$P^{sh}_{i,k}$ (MW)	U_k p.u. voltage	θ_k rad	E_k p.u. voltage	β_k rad
9-11	-62.63	-4.0	0.2	4.4644	1.0	-0.6401
14-16	57.50	4.0	0.2	0.6753	1.0	0.8031
17-22	-73.06	-4.0	0.2	4.46	1.0	-0.4907

The solution obtained for LP optimization problem is given in Table 2. Only four GENCOS and two DISCOS out of 15 participants have non-zero injection correction Δp_k. The injection corrections show that the separation of market constraint Eq. 30 has been enforced properly, reducing the transaction T1 by 37.056MW from 1597 MW and increasing Transaction T2 by 57.151MW from 520 MW. Line flows after carrying out this injection corrections are given in column 6 of Table 1. The proposed method has corrected all the overloads effectively. The charges payable by ISO to GENCO and DISCO participants are given in Table 2. Table 2 also gives the total relief charge paid by ISO to participants providing relief.

Table 3 presents the usage rate x^*_l computed using Eq 46 from the shadow prices $\rho_l^{*(m)}$ and μ^*_l corresponding to constraints (22) and (23) obtained from LP optimization, the active power flow $f_l^{*(m)}$, the congestion usage charges $X_l^{*(m)}$ allocated to each transaction and the net congestion usage charge collected by ISO. The negative allocated flow of a congested line allocated to a transaction indicates that this transaction is a counter transaction for this line and hence the corresponding negative usage charges implies that the ISO should reimburse the amount to the transaction.

Congestion management with UPFC-Case 2: The same case is run and the LP problem is solved by considering the UPFCs. It is assumed that there are three UPFCs already present in the lines 9-11,14-16,17-22 of the system. The data for the UPFCs are given in Appendix C. The solution obtained for LP optimization problem is given in Table 4. In this phase also only four GENCOS and two DISCOS out of 15 participants have non-zero injection correction ΔP_k.

Table 5 presents the usage rate x^*_l, the flow $_l^{*(m)}$, the congestion usage charges $X_l^{*(m)}$ allocated to each transaction and the net congestion usage charge collected by ISO by considering the impact of UPFCs.

Table 7 presents a comparison of the associated charges in the two cases studied.(with and without UPFCs.). It is seen that the relief charges payable by ISO to relief participants and usage charges payable by dominant transactions to ISO are reduced and the ISO surplus is increased due to introduction of UPFCs

Table 7 comparison of charges without and with UPFCs

CONCLUSION

Impact of UPFCs on congestion management for a power market with pool and bilateral transactions has been studied using LP based optimization method The linearised constraints are generated from the sensitivity relations derived from DC load flow model. The congestion management carried out includes congestion relief obtained through optimal injection correction using willing participants GENCOS and DISCOS for a charge as well as adjustments of control settings of UPFCs (cost free) and equitable allocation of the congestion usage charges to the transactions which have caused congestion. Congestion usage charge is arrived at using the shadow prices obtained from optimization results. The results obtained for IEEE 24 bus Reliability Test

System demonstrate the impact of cost free action of UPFCs on congestion management. Due the cost free actions of UPFCs, relief charges payable by ISO to relief participants and usage charges payable by dominant transactions to ISO are reduced and the ISO surplus is increased.

Appendix A: System data

Bus data and line data are taken from reference IEEE (1996). Certain changes made in line data are given below:

Data for MVA rating of the line connected between buses 1-5, 6-10, 7-8 ,17-18 , 3-9, 8-9 and 15-16 are changed to 100 MVA, 165MVA, 160 MVA ,160 MVA,90MVA,70MVA and 80MVA. MW rating of all the lines is taken as 0.85 times that of MVA rating

Appendix B: Data for GENCO ,DISCO and Transaction

Table B1: GENCO data

GENCO ID No.	Bus No.	$P_k=P_G$ (MW)	P^{min}_G (MW)	P^{max}_G (MW)	Incremental cost $/MW-hr	Decremental cost $/MW-hr
1	1	14.85	9.8	40	30	29
2	1	14.85	9.8	40	16	15
3	1	60.84	15.2	152	16	15
4	1	60.84	15.2	152	30	29
5	2	40.00	15.8	40	30	29
6	2	0.00	10.0	40	30	29
7	2	60.84	15.2	152	16	15
8	2	60.84	15.2	152	16	15
9	7	15.6	15.0	200	22	21
10	7	54	25.0	200	22	21
11	7	54	25.0	300	22	21
12	13	94.64	68.95	394	22	21
13	13	204.63	68.95	394	22	21
14	13	71.76	68.95	394	20	19
15	15	19.99	2.4	24	30	29
16	15	19.99	2.4	24	30	29
17	15	19.99	2.4	24	30	29
18	15	19.99	2.4	24	30	29
19	15	19.99	2.4	24	30	29
20	15	154.91	54.25	310	12	11
21	16	154.91	54.25	310	12	11
22	18	400.05	100	800	7	5
23	21	400.05	100	800	7	5
24	22	70.27	50	100	22	21
25	22	70.27	50	100	22	21
26	22	57.49	50	100	22	21
27	22	19	15	100	22	21
28	22	49.51	20	100	22	21
29	22	30.34	20	100	22	21
30	23	54.29	54.25	310	12	11
31	23	154.91	54.25	310	12	11
32	23	373	140	700	12.5	11.5

Table B2: DISCO data

GENCO ID No.	Bus No.	$P_D=P_K$ (MW)	P^{min}_D (MW)	P^{max}_D (MW)	Incremental cost $/MW-hr	Decremental cost$/MW-hr
1	1	127.32	75.6	285.12	20	22
2	2	97.42	67.84	256.08	20	22
3	3	219.98	126.0	475.2	20	22
4	4	88.58	51.81	195.36	21	23
5	5	78.51	49.71	187.44	21	23
6	6	135.75	95.22	359.04	21	23
7	7	124.57	87.51	330.0	21	24
8	8	192.48	119.7	451.4	22	24
9	9	196.47	122.52	462	20	23
10	10	194.83	136.5	514	21	23
11	13	338.78	185.52	698	20	22
12	14	161	135.81	512.16	20	22
13	15	253.76	221.91	923.28	19	21
14	16	83	70.02	264	19	21
15	18	266.24	233.01	879.12	19	21
16	19	198.48	126.72	477.84	19	22
17	20	139.84	89.61	337.92	19	21

Table B3: The transaction profiles of the system

Transactions	Transaction amount $t^{(m)}$, MW	GENCO ID number and fraction $\sigma_i^{(m)}$	DISCO ID number and fraction $\beta_j^{(m)}$
Pool transaction T1	1597	(20, 0.097),(21,0.097), (22,0.251), (23, 0.251),(24, 0.044),(25,0.044), (26, 0.036),(28,0.031), (29, 0.019), (30,0.034),(31, 0.096)	(1,0.068),(2, 0.061),(3, 0.113), (4,0.046), (5,0.045),(6, 0.085), (7, 0.078),(8, 0.107),(9,0.109), (10,0.122),(11,0.166)
Bilateral transaction T2	520	(3,0.117),(4, 0.117),(7, 0.117), (8,0.117),(9, 0.030),(12, 0.182), (13,0.182),(14, 0.138)	(13,0.488),(15,0.512)
Bilateral transaction T3	500	(10,0.108),(11, 0.108), (27,0.038),(32,0.746)	(12,0.322),(14,0.166), (16, 0.300),(17,0.212)
Bilateral transaction T4	240	(1,0.0625),(2,0.0625),(13,0.4583), (18,0.0833),(19,0.0833),(17,0.0833), (15,0.0833),(16, 0.0833)	(1,0.078),(4,0.061),(5,0.031), (8,0.090),(9,0.090),(11,0.307), (16,0.202),(17,0.141)
Bilateral transaction T5	40	(5,1.0)	(3,1.0)

Appendix C-UPFC Data

Series reactance	Shunt reactance	Voltage magnitude series		Voltage magnitude converter shunt		Rating of shunt	Rating of series converter	Base
X_{se}(p.u)	X_{se}(p.u)	U^{min}(p.u)	U^{max}(p.u)	E^{min}(p.u)	E^{max}(p.u)	(MW)	(MW)	MVA
0.1	10	0.0	0.2	0.0	1.0	4	6	100

REFERENCES

Baldick, R.and E. Kalm, 1996. Contract paths, phase shifters and efficient electricity trade. Presented at the IEEE/PES Summer Meeting, Denver, Colorado, USA, paper 96 SM 495-2 PWRS.

Singh, S.N. and A.K.David, 2001. Optimal location of FACTS devices for congestion management. Int. J. Elec. Power Sys. Res., 58: 71-79.

Rodrigues, A.B., 2003. M.G.Da Silva, Impact of multilateral congestion management on the reliability of power transactions. Int. J. Electrical Power and Energy Sys., 25: 113-122.

Ge, S.Y. and T.S. Chung, 1999. Optimal active power flow incorporating power flow control needs in flexible AC transmission systems. IEEE Trans. Power Sys., 14: 738-744.

Li, N.,Y. Xu and H. Chen, 2000. FACTS-based power flow control in interconnected power systems. IEEE. Trans. Power Sys., 15: 257-262.

Rau, N.S., 2000. Transmission loss and congestion cost allocation- an approach based on responsibility. IEEE. Trans. Power Sys., 15: 1401-1409.

Mesut E. Baran, 2000. Venkat Banunarayanan and Kenneth E.Garren, Equitable allocation of Congestion Relief cost to Transactions. IEEE. Trans. Power Sys., 15: 579-585.

Wu, Z.O., Y.N. Wang, H.S. Qing and Y.X. Ou Yang, 2004. Continuous integration congestion cost allocation based on sensitivity. IEEE. Proc-Generation, Trans. Distribut., 151: 421-426.

Tao S. and G. Gross, 2002. A Congestion-Management allocation Mechanism for Multiple Transaction Networks. IEEE. Trans. Power Sys., 17: 826-833.

Alomoush, M., 2003. Derivation of UPFC DC load flow model with examples of its use in restructured power systems. IEEE. Trans. Power Sys., 18: 1173-1180.

Glatvitsch, H. and F. Alvarado, 1998. Management of multiple congested conditions in unbundled operation of a power system. IEEE. Trans. Power Sys., 13: 1013-1019.

The IEEE Reliability Test System, 1996. A report prepared by the Reliability Test System Task Force of the Application of Probability Methods Subcommittee. IEEE. Trans. Power Sys., 14: 1010-1020.