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Abstract: This paper proposes a unified optimization model and algorithm for assessing Available Transfer Capability (ATC) and carrying out Congestion Management (CM) in a Deregulated power system handling both pool and bilateral transactions. It uses a power injection model for Unified Power Flow Controller (UPFC), DC load flow model for power network and repeated linear programming technique for optimization. The DC model enforces the line operating lines in MW. A computer package has been developed and the effectiveness of the proposed unified method has been verified by solving 4 bus and an IEEE 30 bus systems. The results demonstrate the effectiveness of UPFC control on ATC enhancement and Congestion Management.

Keywords: Available Transfer Capability, Congestion Management, Unified Power Flow Controller.

1 Introduction

In a restructured power system, it is the Independent System Operator (ISO) that schedules power transactions in a day-ahead market. It is a two step-process. The first step is to announce a day-ahead predicted hourly ATC between various source-sink node pairs to enable the market participants to enter into transaction contracts. The second step is to regulate the proposed contracts so as to avoid violation of any of the operating limits of the system. For this purpose, ISO has to update periodically a real-time index termed Available Transfer Capability (ATC). Available Transfer Capability is a measure of the transfer capability remaining in the physical transmission network for further commercial activity over and above already committed uses without violating security and operating conditions [1]. The ATC information should be made available on a publicly accessible Open Access Same Time Information System

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(OASIS). Congestion may occur when the dispatch of all pool and bilateral and multilateral transactions in full result in the violation of operational constraints. It is the ISO that has to carry out the Congestion Management process and effectively cut the proposed transactions.

Reference [2] uses a dc load flow model for computing ATC between any two locations in the transmission system and ATC’s for selected transmission path between them. Feasibility assessment of simultaneous bilateral transactions in a Deregulated environment using dc load flow model is discussed in [3].

The usage of UPFC in interconnected power systems facilitates transfer of more bulk power between interconnected networks, and enable neighbouring utilities and regions to economically and reliably exchange power [4]. As UPFC’s are capable of directing active and reactive power flows through the designated paths, they can be used to increase ATC and manage congestion. Reference [5] discusses on ATC enhancement with UPFC using repeated power flow approach. Reference [6] focuses on the evaluation of the impact of FACTS control on ATC enhancement using AC load flow model and Optimal Power Flow approach.

The problem of Congestion Management transmission has been singled out as one of crucial importance for smooth functioning of competitive markets. Reference [7] compares various Congestion Management approaches so as to assess their efficiency and the effectiveness of the market signals provided to the market participants. Reference [8] proposes a two-stage transmission dispatch model to deal with Congestion Management problem.

This paper proposes a unified model in OPF framework for the assessment of Available Transfer Capability and Congestion Management using UPFC. This optimization approach uses a DC load flow model [9] and a repeated linear programming.

2 OPF Framework for the Assessment of ATC and CM

Available Transfer Capability (ATC) is defined [2] as the Total Transfer Capability (TTC) minus the sum of Existing Transmission Commitments (ETC), minus the Transmission Reliability Margin (TRM), and minus Capacity Benefit Margin (CBM). Mathematically ATC can be represented as

\[ \text{ATC} = \text{TTC} - \text{ETC} - \text{TRM} - \text{CBM} \]

However, in this paper, TRM and CBM have been excluded when computing ATC.

Congestion occurs whenever the transmission network is unable to accommodate all the proposed bilateral transactions in addition to the ETC, due to the violation of one or more operating constraints like line thermal/stability...
A Unified Optimization Approach for the Enhancement of Available Transfer... limits, bus voltage limits, voltage stability limits and transient stability limits. In this paper, the problem of assessing both ATC and CM is solved by using a unified OPF framework and DC Power flow model, thereby taking into consideration only the line operating limits in MW.

2.1 Problem formulation – the assessment of ATC and CM without UPFC

The decision vector $X$ is defined as

$$X = \begin{bmatrix} X_T \\ X_F \end{bmatrix}^T, \quad (1)$$

where $X_T$ is subvector refers to transfers between source-sink-node pairs in assessment of ATC or proposed bilateral transactions in CM $\begin{bmatrix} T_1 \cdots T_{NT} \end{bmatrix}^T$.

$T_i = T_{i(p,q)}$ - $i^{th}$ transfer or transaction between source node $p$ and sink node $q$,

$NT$ - total number of transfers or transactions considered,

$X_F$ - subvector comprising UPFC decision variables to be defined later.

First, the problems of assessment of ATC and CM are formulated without UPFC. In this case the decision vector $X = X_T$.

The DC load flow model is given by

$$B \theta = P. \quad (2)$$

The bus injection vector $P$ is expressed in terms of the decision vector $X$ as

$$P = M X, \quad (3)$$

where $M$ is power injection vector - Decision vector relation matrix of dimension $(N-1) \times (NX)$

In the base case state $(\theta^0, P^0)$,

$$P^0 = M X^0 = M X_T^0,$$

where

$$X_T^0 = T^0 = \begin{bmatrix} T_1^0 \cdots T_{NT}^0 \end{bmatrix}^T$$

In the assessment of ATC, $T^0$ comprises only Existing Transmission Commitments (ETC) $T^C$. In Congestion management, $T^0$ comprises ETC plus bilateral transactions proposed by various GENCO-DISCO pairs, i.e. $T^0 = T^C + T^P$, where $T^P$ is the vector of proposed bilateral transactions.

In both problems, a new state $(\theta, P)$ which maximizes the decision vector $X$ (the vector of transfers/transactions, $T$) without violating the line loading limits is computed. The decision vector $X$ is given by $X = X^0 + \Delta X = T = T^0 + \Delta T$.
When assessing ATC, $\Delta T$ obtained is positive and it gives the values of ATC. In CM, $\Delta T$ obtained is negative which implies that cuts are to be made in the proposed bilateral transactions.

2.1.1 LP model for Assessment of ATC

The problem of assessment of ATC may be stated as:

**Given:** A base case state $(\theta^0, P^0)$ comprising only ETC during a specific hour in a day-ahead market

**To determine:** The maximum values of transfers (ATC),

$$\Delta X = \Delta T = [\Delta T_1 \ldots \Delta T_{NT}]^T$$

without violating the operating limits (MW) of lines/transformers.

This problem is formulated as an LP optimization problem. Referring to equations (3) and (4), the incremental power flow constraint is as follows:

$$B\Delta \theta = \Delta P = M\Delta X$$

$$\Delta \theta = B^{-1}\Delta P = BIM\Delta X = S\Delta X$$

where $BI = B^{-1}$ and $S = BIM$.

Expressing the line flow in the $i^{th}$ line, $L_i$ p.u. MW, in terms of the line-phase angle $\Psi_i$ rad and line reactance $x_i$ p.u. as

$$L_i = \frac{\Psi_i}{x_i}$$

and noting that the line MW rating is $L_i^{rat}$, the incremental line flow constraints can be written as

$$-L_i^{rat} \leq \frac{\Psi_i^0 + \Delta \Psi_i}{x_i} \leq L_i^{rat}; \quad i = 1, 2, \ldots, NL.$$  

Equation (6) can be written as

$$\Delta \Psi_i^L \leq \Delta \Psi_i \leq \Delta \Psi_i^{U}; \quad i = 1, 2, \ldots, NL,$$

where

$$\Delta \Psi_i^U = x_i L_i^{rat} - \Psi_i^0 \quad \text{and} \quad \Delta \Psi_i^L = -x_i L_i^{rat} - \Psi_i^0.$$ 

The limits on the incremental decision variables are

$$\Delta X_i^L \triangleq (-X_i^0 - X_i^L) \leq \Delta X_i \leq (X_i^U - X_i^0) \triangleq X_i^U; \quad i = 1, 2, \ldots, NY$$

Using the element–node incidence matrix $A$ and equation (5), $\Delta \Psi$ in (7) can be written as
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$$\Delta \Psi = A \Delta \Theta = AS \Delta X$$

(9)

Substituting (9) in (7) the LP model is obtained as

$$\text{Max} : \sum_{i=1}^{NT} w_i \Delta T_i = \sum_{i=1}^{NX} w_i \Delta X_i$$

subject to

$$\Delta \Psi^L \leq [A][S] \Delta X \leq \Delta \Psi^U$$

and

$$X^L \leq \Delta X \leq X^U$$

(10)

Since the \textit{i}\textsuperscript{th} transfer $\Delta T_i$ is between source node $p$ and sink node $q$, the matrix $\mathbf{S} = \mathbf{BIM}$ can be obtained noting that the \textit{i}\textsuperscript{th} column of matrix $\mathbf{M}$ is given by

$$\mathbf{M}_i = \begin{bmatrix} 0 & \cdots & 1 & \cdots & -1 & \cdots & 0 \end{bmatrix}^T.$$  

The upper limit of \textit{i}\textsuperscript{th} transfer $X_i^U$ in equation (8) is chosen as the infinity and the lower limit of \textit{i}\textsuperscript{th} transfer $X_i^L$ is chosen as $T_i^C$. Assuming equal weigage for all transfers, $w_i$ in (10) is set as a unity for $i = 1, 2, \ldots, NT$.

\section*{2.1.2 LP model for CM}

The model is identical to the one proposed for the assessment of ATC, except for the following changes:

(i) The objective function (10) is to be minimized to keep the cuts in transaction as minimum as possible.

(ii) The weightage for the \textit{i}\textsuperscript{th} transaction $w_i$ in equation (10) is chosen as "willingness to pay charges" [8].

(iii) The upper limit of \textit{i}\textsuperscript{th} transaction $X_i^U$ in equation (8) is chosen as ETC plus proposed bilateral transactions ($T_i^C + T_i^P$), and the lower limit of \textit{i}\textsuperscript{th} transaction $X_i^L$ in equation (8) is chosen as committed transactions.

\section*{3 Power Injection Model of UPFC}

UPFC consists of two linked self-commutating converters sharing a common DC capacitor, connected to the ac system through series and shunt...
coupling transformers. The schematic diagram of \( j^{th} \) UPFC (lossless) inserted at the \( k^{th} \) end of line k-m is shown in Fig. 1. As DC load flow model is used only line reactance \( x_{k,m} \) is considered, neglecting the line-charging susceptance.

![Fig. 1 – Schematic diagram of UPFC.](image)

The equivalent circuit of this (lossless) UPFC-embedded transmission line is shown in Fig. 2. It comprises a voltage source in a series with a reactance for each converter.

![Fig. 2 – Equivalent circuit of Lossless UPFC embedded line.](image)

The controllable voltages of the converters are \( U_j = U_j \angle \delta_j \) and \( E_j = E_j \angle \beta_j \); \( j = 1, 2, \ldots, NU \), where \( NU \) is the total number of UPFCs introduced into the system. The bus voltages are \( V_k = V_k \angle \theta_k \), \( V_m = V_m \angle \theta_m \). The voltage source model shown in Fig. 2 is converted into an equivalent current source model as shown in Fig. 3. \( P_{m,j}^{sc} \), \( P_{k,j}^{sh} \), \( V_k \angle \theta_k \), \( V_m \angle \theta_m \). Assuming that all the bus voltage magnitudes are 1.0 p.u even after the simplification, the current source model leads to the Power Injection Model (PIM) [4] of lossless UPFC embedded line k-m shown in Fig. 4.
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\[ I_{k,j}^{sh} = \frac{jE_{j} \angle \beta_{j}}{x_{shj}} \]

\[ I_{k,j}^{se} = \frac{-jU_{j} \angle \delta_{j}}{x_{j}} \]

**Fig. 3 – Current source model of UPFC.**

\[ P_{s, kj}^{se} \]

\[ P_{s, mj}^{se} \]

\[ P_{s, kj}^{se} = \text{Real} \{ (V_{k} \angle \theta_{k}) I_{k,j}^{se} \} = \frac{E_{j}}{x_{shj}} \sin(\theta_{k} - \beta_{j}) ; \ j = 1,2,\ldots,NU \]  \hspace{1cm} (11)

\[ P_{s,mj}^{se} = \text{Real} \{ (V_{m} \angle \theta_{m}) I_{m,j}^{se} \} = \frac{U_{j}}{x_{j}} \sin(\delta_{j} - \theta_{m}) ; \ j = 1,2,\ldots,NU \]  \hspace{1cm} (12)

\[ P_{s, mj}^{se} = \text{Real} \{ (V_{m} \angle \theta_{m}) I_{m,j}^{se} \} = \frac{U_{j}}{x_{j}} \sin(\delta_{j} - \theta_{m}) ; \ j = 1,2,\ldots,NU \]  \hspace{1cm} (13)

**3.1 Power exchange constraint**

Due to the fact that the active power needed by the series converter is provided from ac power system by the shunt converter through the dc link (power exchanged between converters), the active power drawn from the grid by
the shunt converter \((P_{j}^{\text{ex,sh}})\) must be equal to the active power delivered into the network by series converter \((P_{j}^{\text{ex,se}})\),

\[
P_{j}^{\text{ex,sh}} = P_{j}^{\text{ex,se}}. \tag{14}
\]

From Fig. 2,

\[
P_{j}^{\text{ex,sh}} = \text{Real} \{ E_{j} \angle \beta_{j} I_{j}^{*} \} = \frac{E_{j}}{x_{sh_{j}}} \sin(\theta_{k} - \beta_{j}), \tag{15}
\]

\[j = 1,2,\ldots,NU,\]

\[
P_{j}^{\text{ex,se}} = \text{Real} \{ U_{j} \angle \delta_{j} I_{kmj}^{*} \} = \frac{U_{j}}{x_{j}} \sin(\theta_{k} - \delta_{j}) - \frac{U_{j}}{x_{j}} \sin(\theta_{m} - \delta_{j}); \tag{16}
\]

\[j = 1,2,\ldots,NU.\]

From equations (11) and (15), \(P_{j}^{\text{ex,sh}} = P_{k,j}^{\text{sh}}\) and from equations (12), (13) and (16),

\[
P_{j}^{\text{ex,se}} = -(P_{k,j}^{\text{se}} + P_{m,j}^{\text{se}}) \tag{17}
\]

Hence equation (14) becomes

\[
P_{k,j}^{\text{sh}} = -(P_{k,j}^{\text{se}} + P_{m,j}^{\text{se}}) \tag{18}
\]

From equation (18),

\[
P_{m,j}^{\text{se}} = -(P_{k,j}^{\text{se}} + P_{k,j}^{\text{sh}}) \tag{19}
\]

Hence PIM model of UPFC with the satisfaction of power exchange constraint is given by the Fig. 4 and equations (11), (12), (13) and (19).

4 The Assessment of ATC and CM with UPFC

While formulating the LP problem UPFC is represented by the PIM model (Fig. 4). Out of the three power injections \(P_{k,j}^{\text{se}}, P_{k,j}^{\text{sh}} \text{ and } P_{m,j}^{\text{se}}\), the first two injections being chosen as independent decision variables. In order to satisfy the power exchange constraint equation (19), the third injection \(P_{m,j}^{\text{se}}\) is expressed in terms of the two chosen decision variables as

\[
P_{m,j}^{\text{se}} = -(P_{k,j}^{\text{se}} + P_{k,j}^{\text{sh}}). \tag{19}
\]

Unified LP model for the problem of assessment of ATC and CM with UPFC is the same as stated in equation (10), except for the following changes:

(i) The decision vector \(X\) is redefined with extra decision variables corresponding to the UPFC
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\[ X = \left( X_T X_F \right)^T = \left( T P_{se}^P \right)^T, \]  
\[(20)\]

where \( P_{se} \) = vector of injections \( P_{se}^{k,j} ; j = 1,2,\ldots,NU \).

\( P_{sh} \) = vector of injections \( P_{sh}^{k,j} ; j = 1,2,\ldots,NU \).

(ii) The Power Injection vector - Decision vector relation matrix \( M \) in equation (5) is given below for a system with the \( i^{th} \) transfer/transaction \( T_i \) between node pair \((p,q)\) and with \( j^{th} \) UPFC inserted in line \( k-m \)

\[ T_i \quad P_{se}^{k,j} \quad P_{sh}^{k,j}. \]

\[
\begin{bmatrix}
0 & +1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\end{bmatrix}
\]

\[(21)\]

(iii) The limits on UPFC incremental decision variables are

\[
-P_{se,U}^{k,j} \leq (P_{se,0}^{k,j} + \Delta P_{se}^{k,j}) \leq P_{se,U}^{k,j} \leq P_{se,0}^{k,j} 
\]

\[
(-P_{se,U}^{k,j} - P_{se,0}^{k,j}) \leq \Delta P_{se}^{k,j} \leq (P_{se,0}^{k,j} - P_{se,0}^{k,j}) \leq P_{se,U}^{k,j} + \Delta P_{se}^{k,j} \leq P_{se,0}^{k,j} 
\]

\[
(-P_{sh,U}^{k,j} - P_{sh,0}^{k,j}) \leq \Delta P_{sh}^{k,j} \leq (P_{sh,0}^{k,j} - P_{sh,0}^{k,j}) \leq P_{sh,U}^{k,j} + \Delta P_{sh}^{k,j} \leq P_{sh,0}^{k,j} 
\]

The unified LP model for the problem of assessing ATC and CM with UPFC is given by equations (10), (20), (21), (22) and (23).

5 Solution Approach

The solution to the above problem of assessment of ATC and CM is obtained in two phases.

Phase I:

Given: (i) the base case transfers/transactions \( T_i^0 ; i = 1,2,\ldots,NT \) and
(ii) the maximum values of the UPFC decision variables, $P_{k,j}^{se,U}$ and $P_{k,j}^{sh,U}$, $j = 1, 2, \ldots, NU$

To determine: the optimal values of decision variables $T_i^*$, $i = 1, 2, \ldots, NT$ and $P_{k,j}^{se,*}$ and $P_{k,j}^{sh,*}$, $j = 1, 2, \ldots, NU$ using LP solution.

Phase II

Given: the optimal values of decision variables obtained from Phase I.

To determine: the corresponding control parameters of UPFC $U_j$, $\delta_j$, $E_j$, $\beta_j$; $j = 1, 2, \ldots, NU$ satisfying the following constraints:

(i) UPFC steady-state equations (11), (12) and (13) as well as the power exchange constraint equation (19).

(ii) The ranges of control parameters of UPFC

$$U_j^L \leq U_j \leq U_j^U$$
$$E_j^L \leq E_j \leq E_j^U$$
$$0 \leq \delta_j \leq 2\pi$$
$$0 \leq \beta_j \leq 2\pi$$

(24)

The necessity for repeating Phase I and Phase II:

In phase I, $P_{k,j}^{sh,U}$ is chosen as the minimum of the rating of the shunt and series converters. Since $P_{k,j}^{se}$ is a fictitious variable, its maximum value required in Phase I can only be estimated approximately from the specified maximum values of control parameter $U_j$. Owing to this approximation, the optimum solution $T_i^*$, $i = 1, 2, \ldots, NT$, $P_{k,j}^{se,*}$ and $P_{k,j}^{sh,*}$, $j = 1, 2, \ldots, NU$ obtained in phase I when used in phase II to compute $U_j$ may give a value exceeding the limit $U_j^U$. In such a case, phases I and II are to be repeated after suitable correction of the maximum value of $P_{k,j}^{se}$; $j = 1, 2, \ldots, NU$ until convergence is reached.

Details of phase I

The initial value of $P_{k,j}^{se,U}$ is chosen as follows:

From the power exchange constraint equation (19), the approximate relation between the maximum values of power injections is

$$P_{m,j}^{se,U} = -(P_{k,j}^{se,U} + P_{k,j}^{sh,U})$$

(25)

and the estimated maximum value of the decision variable $P_{k,j}^{se}$ is obtained as

$$P_{k,j}^{se,U} = -(P_{k,j}^{sh,U} + P_{m,j}^{se,U})$$

(26)
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In equation (26), the value of $P_{m,j}^{se,U}$ is chosen as $U_j^U/x_j$ by setting $(\theta_m - \delta_j)$ in equation (13) as $\pi/2$ rad.

**Details of phase II**

For the optimum values of variables $T_i^*$, $P_{i,j}^{se,*}$ and $P_{i,j}^{sh,*}$; $i, j = 1, 2, ..., NU$ obtained in phase I, a power flow analysis is carried out and the results $\theta$ obtained are used to compute the corresponding control parameters of UPFC by solving simultaneously UPFC steady state equations (11), (12) and (13), the power exchange constraint equation (19) and the inequalities (24), as explained below.

The control parameter $E_j$ is fixed as $E_j^U$ and $\beta_j$ is obtained from equation (11) as

$$\beta_j = \theta_k - \sin^{-1} \left( \frac{P_{k,j}^{sh,*} x_{shj}}{E_j^U} \right). \quad (27)$$

$U_j$ and $\delta_j$ are obtained by solving simultaneously equations (28) and (29). Equation (28) is obtained from equation (12), whereas equation (29) is obtained by substituting equation (19) in (13).

$$f_{1j} = \frac{U_j}{x_j} \sin(\delta_j - \theta_k) - P_{k,j}^{se,*} = 0 \quad (28)$$

$$f_{2j} = \frac{U_j}{x_j} \sin(\theta_m - \delta_j) + (P_{k,j}^{sh,*} + P_{k,j}^{se,*}) = 0. \quad (29)$$

Since $f_{1j}$ and $f_{2j}$ are non-linear functions, Newton’s algorithm is used to solve iteratively equations (28) and (29). The initial values of $U_j$ is chosen as $U_j = U_j^U$ and $\delta_j$ is computed from equation (12) as

$$\delta_j = \theta_k + \sin^{-1} \left( \frac{P_{k,j}^{se,*} x_{j}}{U_j} \right). \quad (30)$$

If the value of $U_j$ computed from equations (28) and (29) is less than or equal to $U_j^U$, the optimum solution is reached. Otherwise $P_{k,j}^{se,U}$ is reset as given below and Phase I and Phase II are repeated

$$P_{k,j}^{se,U} = c \cdot P_{k,j}^{se,*}, \quad (31)$$

where $c = \left( U_j^U / U_j \right)$.

6 **Algorithm**

1. Run a load flow for the given base case state.
2. Set iteration index \( h = 1 \).
Choose \( P_{k,j}^{sh,U} \) as the minimum of the rating of the shunt and series converters and the initial values of \( P_{k,j}^{sc,U} \) using equation (26).

3. Setup and solve LP problem, equations (10), (20), (21), (22) and (23), so as to get the optimum values \( T_i^* \), \( i = 1, 2, \ldots, NT \), \( P_{k,j}^{sc,*} \) and \( P_{k,j}^{sh,*} \), \( j = 1, 2, \ldots, NU \)

4. Perform a load flow for the new state using decision variables \( T_i^* \); \( i = 1, 2, \ldots, NT \), \( P_{k,j}^{sc,*} \) and \( P_{k,j}^{sh,*} \), \( j = 1, 2, \ldots, NU \)

5. Using the load flow solution obtained and \( P_{k,j}^{sc,*} \), \( P_{k,j}^{sh,*} \), \( j = 1, 2, \ldots, NU \) compute the set of control parameters of UPFC \( U_j, \delta_j, E_j, \beta_j \); \( j = 1, 2, \ldots, NU \) satisfying the power exchange constraint of UPFC using Newton’s algorithm.

6. If \( U_j < U_j^U \) for all \( j = 1, 2, \ldots, NU \), go to step 8. Otherwise go to step 7.

7. Recompute \( P_{k,j}^{sc,U} \), \( j = 1, 2, \ldots, NU \) using equation (31), set iteration index \( h = h + 1 \), and go to step 3.

8. Print the transfers/transactions \( T_i \), \( i = 1, 2, \ldots, NT \) and the UPFC control parameters
\[
U_j, \delta_j, E_j, \beta_j, \quad j = 1, 2, \ldots, NU
\]

7 Results and Discussion

7.1 The assessment of ATC

Four bus system

A computer package for the proposed unified algorithm for the assessment of ATC and Congestion Management with and without UPFC has been developed and the effectiveness of the proposed method has been verified by analyzing two test systems, i.e. a 4 bus system [4] and an IEEE 30 bus system [10] and [11]. The 4 bus system together with generator and load data are shown in Appendix A. Line data and UPFC data are given in Appendix B. Non simultaneous and Simultaneous ATC are computed for a particular hour in a day-ahead market. Results obtained using the proposed method with and without UPFC are discussed below.

Non-simultaneous ATC

Using the package, ATC between nodes 2-3, \( T_{2-3} \) was 23.5 MW with the line 2-3 hitting the limit. In order to enhance ATC \( T_{2-3} \), an UPFC with the data
A Unified Optimization Approach for the Enhancement of Available Transfer... given in Table B2 (Appendix B) is inserted into the critical line 2-3 at bus 2. With this UPFC, the algorithm converged into one iteration gives an increased value of 167.68 MW for $T_{2-3}$. The line 2-3 is once more found to be the critical one. The enhancement in ATC is 613.5%, the obtained power injections being $P_{2}^{se} = 95.17$ MW and $P_{2}^{sh} = 4$ MW. The corresponding control parameters of UPFC are obtained in 2 Newton’s iterations given below

$$U = 0.2 \text{ p.u, } \delta = 1.305 \text{rad, } E = 1.1 \text{p.u and } \beta = -0.335 \text{ rad.}$$

Simultaneous ATC

Simultaneous ATC (SATC) for 4 bus system is determined by considering 4 transfers $T_{1-3}$, $T_{1-4}$, $T_{2-3}$ and $T_{2-4}$ with equal weightage. Table 1 illustrates the results obtained for SATC with and without UPFC. SATC without UPFC is given in column 2 and the total SATC is found to be 106.96 MW. The critical lines are 1-3, 2-3 and 2-4. When only one UPFC is used, placing of the same UPFC in one of the critical lines (line 2-3) gives the best total SATC of 206.17 M, as shown in column 3, lines 1-3, 2-3 and 2-4 being the critical ones.

<table>
<thead>
<tr>
<th>Transfer Source-Sink</th>
<th>Simultaneous ATC (SATC) in MW</th>
<th>Without UPFC</th>
<th>UPFC in 2-3</th>
<th>UPFC in 2-3 and 1-3</th>
<th>UPFC in 2-3, 1-3 and 2-4</th>
<th>UPFC in 2-3, 1-3, 2-4 and 3-4</th>
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<tbody>
<tr>
<td>1-3</td>
<td>20.3</td>
<td>37</td>
<td>119.5</td>
<td>32.4</td>
<td>76.3</td>
<td></td>
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<td>1-4</td>
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<td>33.33</td>
<td>120.2</td>
<td>76.39</td>
<td></td>
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<tr>
<td>2-3</td>
<td>20</td>
<td>135.84</td>
<td>118.9</td>
<td>168.85</td>
<td>181.96</td>
<td></td>
</tr>
<tr>
<td>2-4</td>
<td>0</td>
<td>33.33</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Total SATC (MW)</td>
<td>106.96</td>
<td>206.17</td>
<td>271.73</td>
<td>321.45</td>
<td>334.65</td>
<td></td>
</tr>
<tr>
<td>Critical lines</td>
<td>1-3, 2-3, 2-4</td>
<td>1-3, 2-3, 2-4</td>
<td>1-3, 2-3, 2-4</td>
<td>1-3, 2-3, 3-4</td>
<td>1-3, 2-3, 2-4</td>
<td></td>
</tr>
<tr>
<td>ATC (%)</td>
<td>–</td>
<td>92.75</td>
<td>154</td>
<td>200</td>
<td>213</td>
<td></td>
</tr>
</tbody>
</table>

Thereby, the enhancement of ATC is 92.75%. The combinations of UPFC showing the greatest ATC enhancement are given in columns 4, 5 and 6. When two UPFC’s are connected between 2-3 and 1-3, the total SATC reaches 271.73 MW, as shown in column 4, the critical lines being 1-3, 2-3 and 2-4. Presented in figures, the increase in ATC is by 154 %. When three UPFC’s are connected between 2-3, 1-3 and 2-4, the total SATC increases to 321.45 MW, as shown in column 5, the critical lines being 1-3, 2-3 and 3-4. Presented in figures, the increase in ATC is by 200 %. When four UPFC’s are connected between 2-3, 1-3, 2-4 and 3-4 the total SATC amounts to 334.65 MW, as shown in
column 6, the critical lines being 1-3, 2-3 and 2-4. Presented in figures, the increase in ATC is by 213%. The results for different cases given in Table 1 are all obtained in a single iteration. It has also been observed that the transfer in certain pairs is zero, as ATC depends on system configuration, committed loading and UPFC location.

Table 2 shows the power injections, control parameters of UPFC’s and the number of Newton’s iterations taken for convergence for Simultaneous transfers.

Table 2

Power injections and control parameters of UPFC for SATC for a 4 bus system.

<table>
<thead>
<tr>
<th>Location of UPFC</th>
<th>( P_{k,j}^{w} ) (MW)</th>
<th>( P_{k,j}^{d} ) (MW)</th>
<th>( U_j ) (p.u)</th>
<th>( \delta_j ) (rad)</th>
<th>( E_i ) (p.u)</th>
<th>( \beta_i ) (rad)</th>
<th>Newton’s Iterations</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-3</td>
<td>95.17</td>
<td>4</td>
<td>0.199</td>
<td>1.26</td>
<td>1.1</td>
<td>-0.372</td>
<td>2</td>
</tr>
<tr>
<td>2-3 and 1-3</td>
<td>94.98</td>
<td>4</td>
<td>0.199</td>
<td>1.16</td>
<td>1.1</td>
<td>-0.472</td>
<td>2</td>
</tr>
<tr>
<td>1-3</td>
<td>61.77</td>
<td>4</td>
<td>0.197</td>
<td>1.21</td>
<td>1.1</td>
<td>-0.372</td>
<td>2</td>
</tr>
<tr>
<td>2-3</td>
<td>94.60</td>
<td>4</td>
<td>0.198</td>
<td>1.16</td>
<td>1.1</td>
<td>-0.472</td>
<td>2</td>
</tr>
<tr>
<td>1-3</td>
<td>61.60</td>
<td>4</td>
<td>0.197</td>
<td>1.21</td>
<td>1.1</td>
<td>-0.372</td>
<td>2</td>
</tr>
<tr>
<td>2-4</td>
<td>59.54</td>
<td>4</td>
<td>0.191</td>
<td>1.11</td>
<td>1.1</td>
<td>-0.472</td>
<td>3</td>
</tr>
<tr>
<td>2-3</td>
<td>94.70</td>
<td>4</td>
<td>0.198</td>
<td>1.16</td>
<td>1.1</td>
<td>-0.472</td>
<td>2</td>
</tr>
<tr>
<td>1-3</td>
<td>61.66</td>
<td>4</td>
<td>0.197</td>
<td>1.21</td>
<td>1.1</td>
<td>-0.372</td>
<td>2</td>
</tr>
<tr>
<td>2-4</td>
<td>59.19</td>
<td>4</td>
<td>0.190</td>
<td>1.10</td>
<td>1.1</td>
<td>-0.472</td>
<td>3</td>
</tr>
<tr>
<td>3-4</td>
<td>-45.21</td>
<td>-4</td>
<td>0.20</td>
<td>-2.32</td>
<td>1.1</td>
<td>0.072</td>
<td>4</td>
</tr>
</tbody>
</table>

IEEE 30 Bus system

The proposed method was also tested with IEEE 30 bus system. The data for the system was taken from reference [10] and [11]. The line diagram for IEEE 30 bus system is given in Appendix C. Table 3 shows the values of ATC \( T_{22-8} \) obtained using the package with and without UPFC for the IEEE 30 bus system.

Table 3

NSATC \( T_{22-8} \) for IEEE 30 Bus system.

<table>
<thead>
<tr>
<th>Location of UPFC</th>
<th>Number of iterations</th>
<th>Critical Lines</th>
<th>ATC (MW)</th>
<th>Percentage enhancement of ATC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without UPFC</td>
<td></td>
<td>22-21, 6-8</td>
<td>30.2</td>
<td></td>
</tr>
<tr>
<td>22 – 21</td>
<td>1</td>
<td>6 – 8, 22 – 21</td>
<td>30.5</td>
<td>1.0</td>
</tr>
<tr>
<td>6 – 8</td>
<td>1</td>
<td>6 – 8, 22 – 21</td>
<td>31.6</td>
<td>4.6</td>
</tr>
<tr>
<td>6 – 8 and 22 – 21</td>
<td>4</td>
<td>10 – 21, 22-24</td>
<td>55.48</td>
<td>83.7</td>
</tr>
<tr>
<td>6 – 8, 22-21 and 10-21</td>
<td>2</td>
<td>10-21, 22-24</td>
<td>73.41</td>
<td>143</td>
</tr>
<tr>
<td>6-8, 22-21 10– 21 and 22-24</td>
<td>3</td>
<td>6-8, 10-21, 8-28</td>
<td>89.8</td>
<td>197</td>
</tr>
</tbody>
</table>
A Unified Optimization Approach for the Enhancement of Available Transfer...

The location of UPFC chosen in Table 3 gives the highest ATC value. It has been found that the ATC cannot be substantially enhanced when using only one UPFC, since the two critical lines (6-8 and 22-21) are located in the least impedance path between the node pairs 22-8.

Table 4 illustrates the results obtained for SATC between 4 transfers \( T_{22-8} = T_{22-3} = T_{23-8} \) and \( T_{13-2} \) for the IEEE 30 bus system.

**Table 4**

<table>
<thead>
<tr>
<th>Location of UPFC</th>
<th>Number of iterations</th>
<th>Critical lines</th>
<th>SATC (MW)</th>
<th>Total SATC (MW)</th>
<th>ATC (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without UPFC</td>
<td>–</td>
<td>22-21, 12-13, 6-8</td>
<td>0, 19.26, 31.17, 10.99</td>
<td>61.42</td>
<td>–</td>
</tr>
<tr>
<td>22-21</td>
<td>2</td>
<td>12-13, 10-22, 15-23, 6-8</td>
<td>10.06, 61.01, 22.38, 11.00</td>
<td>104.45</td>
<td>70</td>
</tr>
<tr>
<td>22-21 and 12-13</td>
<td>2</td>
<td>4-12, 10-22, 6-8, 12-13, 10-21, 15-23</td>
<td>2.5, 64.49, 30.76, 48.06</td>
<td>145.81</td>
<td>137.4</td>
</tr>
<tr>
<td>22-21, 12-13 and 4-12</td>
<td>2</td>
<td>10-22, 12-13, 23-24</td>
<td>0, 64.98, 32.5, 91.57</td>
<td>189.05</td>
<td>207.8</td>
</tr>
<tr>
<td>22-21, 12-13, 4-12 and 10-22</td>
<td>3</td>
<td>12-13, 24-25</td>
<td>0, 99.08, 24.2, 89.57</td>
<td>212.85</td>
<td>246.5</td>
</tr>
</tbody>
</table>

**7.2 Congestion Management**

**4 Bus System**

The developed package is also used for solving congestion management problem. The package was tested for the same 4 bus system and the IEEE 30 bus system. Table 5 shows the results obtained for 4 bus system. Bilateral transactions proposed between 1-3, 1-4, 2-3 and 2-4 are shown in column 2. Column 3 gives the “willingness to pay charges” declared by the parties. The location of UPFC given in Table 5 gives the best value of the assigned transactions. In order to see the impact of “willingness to pay charges” on the resulting assigned transactions, in the results obtained with UPFC in the line 2-3 (column 5 of Table 5) the charges for transaction 1-4 are raised from 20 $/MWh to 40$/MWh, which led to the increase in the assigned transaction 1-4, i.e. from 0 to 33.33 MW, and decrease in the assigned transaction 2-4, i.e. from 33.33 MW to 0MW. Hence it is obvious that the transactions are less curtailed if the “willingness to pay charge” is higher. The results for all cases given in Table 5 are obtained in a single iteration.
Table 5

Congestion Management with and without UPFC for 4 bus system.

<table>
<thead>
<tr>
<th>Transactions Source-Sink nodes</th>
<th>Proposed Transaction $T''$ (MW)</th>
<th>Willing-ness to pay charges $$/MWh</th>
<th>Assigned Transaction in MW</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Without UPFC</td>
<td>UPFC in 2-3</td>
</tr>
<tr>
<td>1-3</td>
<td>150</td>
<td>20</td>
<td>20.3</td>
</tr>
<tr>
<td>1-4</td>
<td>150</td>
<td>20</td>
<td>66.66</td>
</tr>
<tr>
<td>2-3</td>
<td>200</td>
<td>20</td>
<td>19.99</td>
</tr>
<tr>
<td>2-4</td>
<td>50</td>
<td>20</td>
<td>0.0</td>
</tr>
<tr>
<td>Total assigned Transaction (MW)</td>
<td></td>
<td></td>
<td>106.95</td>
</tr>
<tr>
<td>Critical Lines</td>
<td></td>
<td>1-3, 2-3, 2-4</td>
<td>1-3,2-3, 2-4</td>
</tr>
<tr>
<td>Enhancement of Assigned Transactions (%)</td>
<td></td>
<td></td>
<td>85</td>
</tr>
</tbody>
</table>

Table 6 shows the line flows in all lines both for the case with proposed transactions and the one with assigned transactions during congestion management without and with UPFC in line 2-3.

Table 6

Line flows without and with UPFC during CM for 4 bus system.

<table>
<thead>
<tr>
<th>Line No.</th>
<th>Rating (MW)</th>
<th>Line flows in MW</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Without UPFC</td>
</tr>
<tr>
<td></td>
<td></td>
<td>With proposed transactions (MW)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>With proposed Transactions (MW)</td>
</tr>
<tr>
<td>1-2</td>
<td>70</td>
<td>112.3</td>
</tr>
<tr>
<td>1-3</td>
<td>100</td>
<td>250.7</td>
</tr>
<tr>
<td>2-3</td>
<td>100</td>
<td>276.9</td>
</tr>
<tr>
<td>2-4</td>
<td>150</td>
<td>265.3</td>
</tr>
<tr>
<td>3-4</td>
<td>70</td>
<td>84.6</td>
</tr>
</tbody>
</table>

IEEE 30 Bus system

For the IEEE 30 bus system, bilateral transactions proposed between $T_{22-8} = T_{22-3} = T_{23-8}$ and $T_{13-2}$ are shown in column 2 of Table 7. The data for
A Unified Optimization Approach for the Enhancement of Available Transfer Capabilities

“willingness to pay charges” are taken from Table 5. Table 7 shows the location of UPFC for which best assigned transactions are obtained.

### Table 7

**Congestion management for IEEE 30 bus system.**

<table>
<thead>
<tr>
<th>Transaction Source-Sink nodes</th>
<th>Proposed Trans. $I^p$ (MW)</th>
<th>Assigned Transaction in MW</th>
<th>Enhanced Assigned transaction (%)</th>
<th>Critical lines</th>
<th>Number of iterations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Without UPFC</td>
<td>UPFC in 22-21</td>
<td>UPFC in 22-21 and 12-13</td>
<td>UPFC in 22-21, 12-13, and 4-12</td>
<td>UPFC in 22-21, 12-13, 4-12 and 10-22</td>
</tr>
<tr>
<td>22-8</td>
<td>25</td>
<td>22-8</td>
<td>22-13</td>
<td>12-13</td>
<td>22-21</td>
</tr>
<tr>
<td>22-3</td>
<td>150</td>
<td>22-3</td>
<td>12-13</td>
<td>10-22</td>
<td>12-13</td>
</tr>
<tr>
<td>23-8</td>
<td>50</td>
<td>23-8</td>
<td>12-13</td>
<td>10-22</td>
<td>12-13</td>
</tr>
<tr>
<td>13-2</td>
<td>150</td>
<td>13-2</td>
<td>12-13</td>
<td>10-22</td>
<td>12-13</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>6-8</td>
<td>10-22</td>
<td>12-13</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>15-23</td>
<td>15-23</td>
<td>12-13</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total assigned Transaction (MW)</td>
<td>–</td>
<td>61.43</td>
<td>104.37</td>
<td>145.81</td>
<td>174.12</td>
</tr>
<tr>
<td>Enhancement of assigned transaction (%)</td>
<td>–</td>
<td>–</td>
<td>70</td>
<td>137</td>
<td>183</td>
</tr>
<tr>
<td>Critical lines</td>
<td>–</td>
<td>22-21</td>
<td>12-13</td>
<td>4-12</td>
<td>12-13</td>
</tr>
<tr>
<td>Number of iterations</td>
<td>–</td>
<td>–</td>
<td>6-8</td>
<td>10-22</td>
<td>12-13</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15-23</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 8 Conclusion

A unified optimization approach is proposed for assessing Available Transfer Capability and solving Congestion Management problem in deregulated power system without and with UPFC. The method uses DC load flow model and repeated LP routine. A generalized program has been developed implementing the proposed solution method. The validity of the proposed method and developed program was tested using a 4 bus and the IEEE 30 bus systems. The introduction of UPFCs at proper locations leads to considerable increase of the ATC and assigned transactions during congestion management. In IEEE 30 bus system, ATC and the assigned transactions in Congestion Management were enhanced by 247% and 217% respectively. The proposed method enables rapid application to a large-scale system. It can be used as an online tool for both assessment of ATC and CM by the system operator. The
proposed method can be extended readily to the problem of Assessment of ATC and CM with additional security related constraints.

9 Symbols

\[ \begin{align*}
N &= \text{Total number of buses in the system} \\
NL &= \text{Total number of lines} \\
NT &= \text{Total number of transfers or transactions} \\
NX &= \text{Total number of decision variables} \\
NU &= \text{Total number of UPFC’s introduced into the system} \\
A &= \text{Element - node incidence matrix of dimension NL x (N-1)} \\
B &= \text{DC load flow matrix} \\
P &= \text{Bus power injection vector} \\
\theta &= \text{Bus phase angle vector} \\
\psi_i &= \text{Line phase angle of } i^{th} \text{ line in radians} \\
\chi_i &= \text{Line reactance in p.u}
\end{align*} \]

10 References


A Unified Optimization Approach for the Enhancement of Available Transfer...


Appendix A

Fig. A1 – Four bus system.

Appendix B

Table B1
Line data for 4 bus system.

<table>
<thead>
<tr>
<th>Line No.</th>
<th>Line reactance $x$ (p.u)</th>
<th>Thermal Rating (MW)</th>
<th>Base MVA</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-2</td>
<td>0.2</td>
<td>70</td>
<td></td>
</tr>
<tr>
<td>1-3</td>
<td>0.2</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>2-3</td>
<td>0.1</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>2-4</td>
<td>0.2</td>
<td>150</td>
<td></td>
</tr>
<tr>
<td>3-4</td>
<td>0.3</td>
<td>70</td>
<td></td>
</tr>
</tbody>
</table>

Table B2
UPFC Data.

<table>
<thead>
<tr>
<th>Series reactance $x_{se}$ (p.u)</th>
<th>Shunt reactance $x_{sh}$ (p.u)</th>
<th>Voltage magnitude series $U_s^L$ (p.u)</th>
<th>Voltage magnitude shunt $E_s^L$ (p.u)</th>
<th>Rating of Shunt converter (MW)</th>
<th>Rating of Series converter (MW)</th>
<th>Base MVA</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>10</td>
<td>0.0</td>
<td>0.0</td>
<td>1.1</td>
<td>4</td>
<td>6</td>
</tr>
</tbody>
</table>
Appendix C

Fig. C1
Line diagram of IEEE 30 Bus System.