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A Unified Optimization Approach for the Enhancement of Available Transfer Capability and Congestion Management Using Unified Power Flow Controller

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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 Assessement 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

$$\mathrm{ATC} = \mathrm{TTC} - \mathrm{ETC} - \mathrm{TRM} - \mathrm{CBM}\,.$$

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 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 $\mathbf{X}$ is defined as

$$\boldsymbol{X} = \begin{bmatrix} \boldsymbol{X}_{\mathbf{T}} & \boldsymbol{X}_{\mathbf{F}} \end{bmatrix}^{\mathrm{T}}, \tag{1}$$

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

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

NT - total number of transfers or transactions considered,

$\boldsymbol{X}_{\mathbf{F}}$ - 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 $\boldsymbol{X} = \boldsymbol{X}_{\mathbf{T}}$.

The DC load flow model is given by

$$\boldsymbol{B}\,\theta = \boldsymbol{P}. \tag{2}$$

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

$$\boldsymbol{P} = \boldsymbol{M}\,\boldsymbol{X}, \tag{3}$$

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

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

$$\boldsymbol{P}^0 = \boldsymbol{M}\,\boldsymbol{X}^0 = \boldsymbol{M}\,\boldsymbol{X}_{\mathbf{T}}{}^0,$$

where

$$\boldsymbol{X}_{\mathbf{T}}{}^0 = \boldsymbol{T}^0 = \begin{bmatrix} T_1^0 & \cdots & T_{NT}^0 \end{bmatrix}^{\mathrm{T}}$$

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

In both problems, a new state (θ ,***P***) which maximizes the decision vector, **X** (the vector of transfers/transactions, T) without violating the line loading limits is computed. The decision vector $\boldsymbol{X}$ is given by $\boldsymbol{X} = \boldsymbol{X}^0 + \Delta\boldsymbol{X} = \boldsymbol{T} = \boldsymbol{T}^0 + \Delta\boldsymbol{T}$.

When assessing ATC, $\Delta\boldsymbol{T}$ obtained is positive and it gives the values of ATC. In CM, $\Delta\boldsymbol{T}$ 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 $(\theta^0, \boldsymbol{P}^0)$ comprising only ETC during a specific hour in a day-ahead market

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

$$\boldsymbol{\Delta X} = \boldsymbol{\Delta T} = \begin{bmatrix} \Delta T_1 & \cdots & \Delta T_{NT} \end{bmatrix}^{\mathrm{T}} \tag{4}$$

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:

$$\begin{gathered} \boldsymbol{B}\Delta\theta = \Delta\boldsymbol{P} = \boldsymbol{M}\Delta\boldsymbol{X} \\ \Delta\theta = \boldsymbol{B}^{-1}\Delta\boldsymbol{P} = \boldsymbol{BIM}\Delta\boldsymbol{X} = \boldsymbol{S}\Delta\boldsymbol{X} \end{gathered} \tag{5}$$

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

Expressing the line flow in the i^{th} line, L_i p.u. MW, in terms of the line-phase angle Ψ_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

$$-L_i^{rat} \le \frac{(\Psi_i^0 + \Delta\Psi_i)}{x_i} \le L_i^{rat}\ ; \quad i = 1, 2, \ldots, NL\ . \tag{6}$$

Equationn (6) can be written as

$$\Delta\Psi_i^L \le \Delta\Psi_i \le \Delta\Psi_i^U\ ; \quad i = 1, 2, \ldots, NL\ , \tag{7}$$

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

$$\Delta X_i^L \triangleq \left(-X_i^L - X_i^0\right) \le \Delta X_i \le \left(X_i^U - X_i^0\right) \triangleq X_i^U\ ; \quad i = 1, 2, \ldots, NX \tag{8}$$

Using the element – node incidence matrix $\boldsymbol{A}$ and equation (5), $\boldsymbol{\Delta\Psi}$ in (7) can be written as

$$\Delta\boldsymbol{\Psi} = \boldsymbol{A}\Delta\boldsymbol{\theta} = \boldsymbol{AS}\Delta\boldsymbol{X} \tag{9}$$

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

$$\left.\begin{array}{l} \text{Max}: \sum_{i=1}^{NT} w_i \Delta T_i = \sum_{i=1}^{NX} w_i \Delta X_i \\ \text{subject to} \\ \Delta\boldsymbol{\Psi}^L \le [\boldsymbol{A}][\boldsymbol{S}]\Delta\boldsymbol{X} \le \Delta\boldsymbol{\Psi}^U \\ \text{and} \\ \boldsymbol{X}^L \le \Delta\boldsymbol{X} \le \Delta\boldsymbol{X}^U \end{array}\right\} \tag{10}$$

Since the i^th^ transfer ΔT_i is between source node *p* and sink node *q*, the matrix $\boldsymbol{S} = \boldsymbol{BIM}$ can be obtained noting that the *i*th column of matrix $\boldsymbol{M}$ is given by

$$\boldsymbol{M}_i = \begin{bmatrix} 0 & \cdots & \underbrace{1}_{p^{\text{th}}} & \cdots & \underbrace{-1}_{q^{\text{th}}} & \cdots & 0 \end{bmatrix}^{\text{T}}.$$

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

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 *i*th transaction w_i in equation (10) is chosen as "willingness to pay charges" [8].

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

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 $x_{k\text{-}m}$ is considered, neglecting the line-charging susceptance.

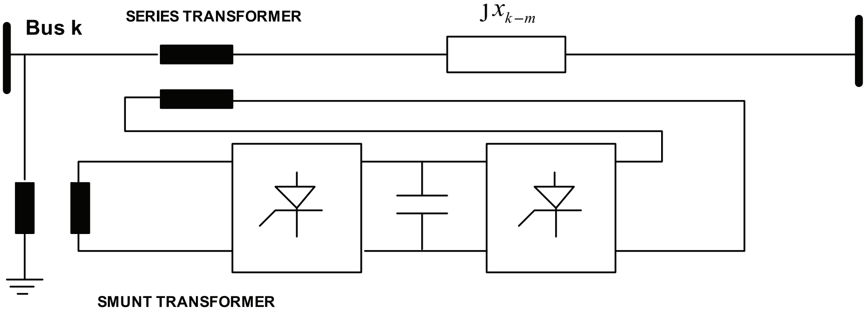

Fig. 1 – *Schematic diagram of* UPFC.

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.

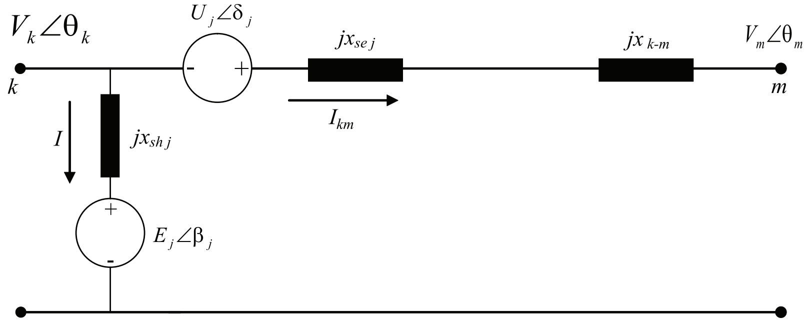

Fig. 2 – *Equivalent circuit of Lossless* UPFC *embedded line.*

The controllable voltages of the converters are $\mathbf{U_j} = U_j \angle \delta_j$ and $\mathbf{E_j} = E_j \angle \beta_j$; $j = 1,2,\ldots,NU$, where NU is the total number of UPFCs introduced into the system. The bus voltages are $\mathbf{V_k} = V_k \angle \theta_k$, $\mathbf{V_m} = V_m \angle \theta_m$. The voltage source model shown in Fig. 2 is converted into an equivalent current source model as shown in Fig. 3. $P_{m,j}^{se}$ $P_{k,j}^{sh}$ $V_k\angle\theta_k$ $V_m\angle\theta_m$ 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

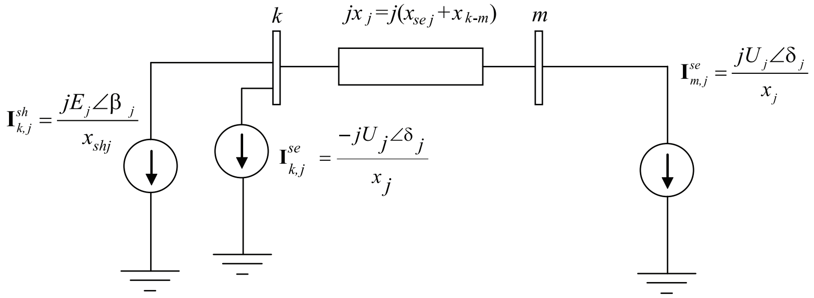

Fig. 3 – *Current source model of* UPFC.

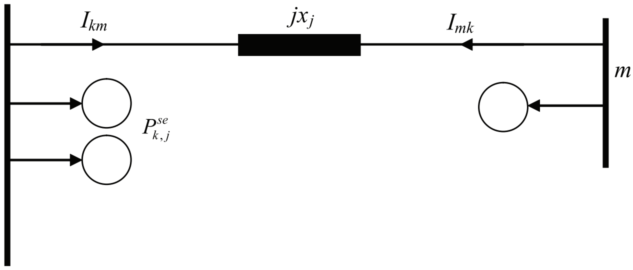

Fig. 4 – PIM *model of* UPFC *embedded line.*

The expressions for $P^{sh}_{k,j}$, $P^{se}_{k,j}$ and $P^{se}_{m,j}$ are derived from Figs. 3 and 4, using $V_k = V_m = 1.0$ p.u.

$P^{sh}_{k,j}$ is power drawn at bus k due to current source.

$$I^{sh}_{k,j} = \text{Real}\,\{\,(V_k\angle\theta_k)\ I^{sh\,*}_{k,j}\} = \frac{E_j}{x_{shj}}\sin(\theta_k - \beta_j)\,;\quad j = 1,2,\ldots,NU \tag{11}$$

$P^{se}_{k,j}$ is power drawn at bus k due to current source $I^{se}_{k,j}$,

$$P^{se}_{k,j} = \text{Real}\,\{\,(V_k\angle\theta_k)\ I^{se\,*}_{k,j}\} = \frac{U_j}{x_j}\sin(\delta_j - \theta_k)\,;\quad j = 1,2,\ldots,NU \tag{12}$$

$P^{se}_{m,j}$ is power drawn at bus m due to current source $I^{se}_{m,j}$,

$$I^{se}_{m,j} = \text{Real}\,\{\,(\mathrm{V_m}\angle\theta_\mathrm{m}\ I^{se\,*}_{m,j}\} = \frac{U_j}{x_j}\sin(\theta_m - \delta_j)\,;\quad j = 1,2,\ldots,NU \tag{13}$$

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 ($P_j^{ex,sh}$) must be equal to the active power delivered into the network by series converter ($P_j^{ex,se}$),

$$P_j^{ex,sh} = P_j^{ex,se} . \qquad (14)$$

From Fig. 2,

$$P_j^{ex,sh} = \text{Real } \{ E_j \angle \beta_j \ I^* \} = \frac{E_j}{x_{shj}} \sin(\theta_k - \beta_j), \qquad (15)$$

$$j = 1, 2, \ldots, NU ,$$

$$P_j^{ex,se} = \text{Real } \{ U_j \angle \delta_j \ I_{km}{}^* \} = -\frac{U_j}{x_j} \sin(\delta_j - \theta_k) - \frac{U_j}{x_j} \sin(\theta_m - \delta_j) ; \qquad (16)$$

$$j = 1, 2, \ldots, NU .$$

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

$$P_j^{ex,se} = -(P_{k,j}^{se} + P_{m,j}^{se}) \qquad (17)$$

Hence equation (14) becomes

$$P_{k,j}^{sh} = -(P_{k,j}^{se} + P_{m,j}^{se}) \qquad (18)$$

From equation (18),

$$P_{m,j}^{se} = -(P_{k,j}^{se} + P_{k,j}^{sh}) \qquad (19)$$

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 $P_{k,j}^{se}, P_{k,j}^{sh}$ and $P_{m,j}^{se}$, the first two injections being chosen as independent decision variables. In order to satisfy the power exchange constraint equation (19), the third injection $P_{m,j}^{se}$ is expressed in terms of the two chosen decision variables as

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

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

$$\boldsymbol{X} = (\boldsymbol{X_T X_F})^{\mathrm{T}} = \left(\boldsymbol{T P}_{se} \boldsymbol{P}_{sh}\right)^{\mathrm{T}}, \tag{20}$$

where

$\boldsymbol{P}_{se}$ = vector of injections $P_{k,j}^{se}$; $j = 1,2,\ldots,NU$.

$\boldsymbol{P}_{sh}$ = vector of injections $P_{k,j}^{sh}$; $j = 1,2,\ldots,NU$.

(ii) The Power Injection vector - Decision vector relation matrix $\boldsymbol{M}$ 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

$$\boldsymbol{M} = \begin{array}{r} \\ \\ p^{th}\{ \\ \\ q^{th}\{ \\ \\ k^{th}\{ \\ \\ m^{th}\{ \\ \\ \end{array} \begin{array}{c} \begin{array}{ccccccc} & T_i & & P_{k,j}^{se} & & P_{k,j}^{sh}. & \end{array} \\ \begin{bmatrix} \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ 0 & +1 & \cdots & 0 & \cdots & 0 & 0 \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ 0 & -1 & & 0 & & 0 & 0 \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ 0 & 0 & \cdots & -1 & \cdots & -1 & 0 \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ 0 & 0 & \cdots & +1 & \cdots & +1 & 0 \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \end{bmatrix} \end{array} \tag{21}$$

(iii) The limits on UPFC incremental decision variables are

$$\begin{gathered} -P_{k,j}^{se,U} \le (P_{k,j}^{se,0} + \Delta P_{k,j}^{se}) \le P_{k,j}^{se,U} \\ (-P_{k,j}^{se,U} - P_{k,j}^{se,0}) \le \Delta P_{k,j}^{se} \le (P_{k,j}^{se,U} - P_{k,j}^{se,0}) \end{gathered} \tag{22}$$

$$\begin{gathered} -P_{k,j}^{sh,U} \le (P_{k,j}^{sh,0} + \Delta P_{k,j}^{sh}) \le P_{k,j}^{sh,U} \\ (-P_{k,j}^{sh,U} - P_{k,j}^{sh,0}) \le \Delta P_{k,j}^{sh} \le (P_{k,j}^{sh,U} - P_{k,j}^{sh,0}) \end{gathered} \tag{23}$$

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 $P_{k,j}^{sh,U}$; $j=1,2,\dots,NU$

To determine: the optimal values of decision variables T_i^* ; $i=1,2,\dots,NT$ and $P_{k,j}^{se,*}$ and $P_{k,j}^{sh,*}$; $j=1,2,\dots,NU$ 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, δ_j , E_j, β_j ; $j=1,2,\dots,NU$ 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

$$\begin{gathered} U_j^L \le U_j \le U_j^U \\ E_j^L \le E_j \le E_j^U \\ 0 \le \delta_j \le 2\pi \\ 0 \le \beta_j \le 2\pi \end{gathered} \tag{24}$$

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^* , $i=1,2,\dots,NT$, $P_{k,j}^{se,*}$ and $P_{k,j}^{sh,*}$, $j=1,2,\dots,NU$ 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 $P_{k,j}^{se}$; $j=1,2,\dots,NU$ 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

$$P_{m,j}^{se,U} = -(P_{k,j}^{se,U} + P_{k,j}^{sh,U}) \tag{25}$$

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

$$P_{k,j}^{se,U} = -(P_{k,j}^{sh,U} + P_{m,j}^{se,U}) \,. \tag{26}$$

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^* ; $P_{k,j}^{se,*}$ and $P_{k,j}^{sh,*}$; $i, j = 1, 2, \ldots, NU$ obtained in phase I, a power flow analysis is carried out and the results θ 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 β_j is obtained from equation (11) as

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

U_j and δ_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).

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

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

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 δ_j is computed from equation (12) as

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

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

$$P_{k,j}^{se,U} = c\, P_{k,j}^{se\,*}, \tag{31}$$

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 $P_{k,j}^{se,U}$ 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^*, $i = 1,2,\ldots,NT$, $P_{k,j}^{se,*}$ and $P_{k,j}^{sh,*}$, $j = 1,2,\ldots,NU$
4. Perform a load flow for the new state using decision variables T_i^*; $i = 1,2,\ldots,NT$, $P_{k,j}^{se,*}$ and $P_{k,j}^{sh,*}$, $j = 1,2,\ldots,NU$
5. Using the load flow solution obtained and $P_{k,j}^{se,*}, P_{k,j}^{sh,*}$, $j = 1,2,\ldots,NU$ compute the set of control parameters of UPFC U_j, δ_j, E_j, β_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 $P_{k,j}^{se,U}$, $j = 1,2,\ldots,NU$ 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 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 $P_k^{se} = 95.17\,\mathrm{MW}$ and $P_k^{sh} = 4\,\mathrm{MW}$. The corresponding control parameters of UPFC are obtained in 2 Newton's iterations given below

$U = 0.2$ p.u, $\delta = 1.305$rad, $E = 1.1$p.u and $\beta = -0.335$ 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 1

SATC *with and without* UPFC *for a* 4 *bus system.*

Transfer Source-Sink	Simultaneous ATC (SATC) in MW				
	Without UPFC	UPFC in 2-3	UPFC in 2-3 and 1-3	UPFC in 2-3, 1-3 and 2-4	UPFC in 2-3, 1-3, 2-4 and 3-4
1-3	20.3	37	119.5	32.4	76.3
1-4	66.66	0	33.33	120.2	76.39
2-3	20	135.84	118.9	168.85	181.96
2-4	0	33.33	0	0	0
Total SATC (MW)	106.96	206.17	271.73	321.45	334.65
Critical lines	1-3, 2-3, 2-4	1-3, 2-3, 2-4	1-3, 2-3, 2-4	1-3, 2-3, 3-4	1-3, 2-3, 2-4
ATC (%)	–	92.75	154	200	213

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 321.45MW, 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 334.65MW, 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.*

Location of UPFC	$P^{se}_{k,j}$ (MW)	$P^{sh}_{k,j}$ (MW)	U_i (p.u)	δ_i (rad)	E_i (p.u)	β_i (rad)	Newton's Iterations
2-3	95.17	4	0.199	1.26	1.1	-0.372	2
2-3 and	94.98	4	0.199	1.16	1.1	-0.472	2
1-3	61.77	4	0.197	1.21	1.1	-0.372	2
2-3	94.60	4	0.198	1.16	1.1	-0.472	2
1-3	61.60	4	0.197	1.21	1.1	-0.372	2
2-4	59.54	4	0.191	1.11	1.1	-0.472	3
2-3	94.70	4	0.198	1.16	1.1	-0.472	2
1-3	61.66	4	0.197	1.21	1.1	-0.372	2
2-4	59.19	4	0.190	1.10	1.1	-0.472	3
3-4	-45.21	-4	0.20	-2.32	1.1	0.072	4

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 $T_{22\text{-}8}$ obtained using the package with and without UPFC for the IEEE 30 bus system.

Table 3

NSATC $T_{22\text{-}8}$ *for* IEEE 30 *Bus system*.

Location of UPFC	Number of iterations	Critical Lines	ATC (MW)	Percentage enhancement of ATC
Without UPFC	–	22-21, 6-8	30.2	–
22 – 21	1	6 – 8, 22 – 21	30.5	1.0
6 – 8	1	6 – 8, 22 – 21	31.6	4.6
6 – 8 and 22 – 21	4	10 – 21, 22-24	55.48	83.7
6 – 8, 22-21 and 10-21	2	10-21, 22-24	73.41	143
6-8, 22-21 10– 21 and 22-24	3	6-8, 10-21, 8-28	89.8	197

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

SATC *for* IEEE 30 *bus system*.

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

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.*

Transactions Source-Sink nodes	Proposed Transaction T_i^p (MW)	Willing-ness to pay charges $/MWh	Assigned Transaction in MW				
			Without UPFC	UPFC in 2-3	UPFC in 2-3 and 1-3	UPFCin 2-3, 1-3 and 2-4	UPFC in 2-3, 1-3,2-4 and 3-4
1-3	150	20	20.3	37	103.45	31.96	75.79
1-4	150	20	66.66	0.0	33.33	103.22	59.78
2-3	200	20	19.99	127.86	108.4	138.7	151.3
2-4	50	20	0.00	33.33	0.0	0.0	0.0
Total assigned Transaction (MW)	–	–	106.95	198.19	245.18	273.88	286.87
Critical Lines	–	–	1-3,2-3, 2-4	1-3,2-3, 2-4	1-3,2-3, 2-4	1-3,2-3,3-4	1-3,2-3, 2-4
Enhancement of Assigned Transactions (%)	–	–	–	85	129	156	168

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.*

Line No.	Rating (MW)	Line flows in MW			
		Without UPFC		UPFC in 2-3	
		With proposed transactions (MW)	With Assigned transactions (MW)	With proposed Transactions (MW)	With Assigned Transactions (MW)
1-2	70	112.3	50.0	75.8	0.0
1-3	100	250.7	100	287.2	100
2-3	100	276.9	100	211.3	100
2-4	150	265.3	150	294.5	150
3-4	70	84.6	66.7	55.5	33.3

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 "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.*

Transaction Source-Sink nodes	Proposed Trans. T_i^p (MW)	Assigned Transaction in MW				
		Without UPFC	UPFC in 22-21	UPFC in 22-21 and 12-13	UPFC in 22-21, 12-13, and 4-12	UPFC in 22-21,12-13, 4-12 and 10-22
22-8	25	0	10.05	2.5	0.47	8.25
22-3	150	19.26	60.94	64.49	64.36	91.3
23-8	50	31.17	22.38	30.76	32.9	25.9
13-2	150	11.00	11.00	48.06	76.37	69.16
Total assigned Transaction (MW)	–	61.43	104.37	145.81	174.12	194.61
Enhancement of assigned transaction (%)	–	–	70	137	183	217
Critical lines	–	22-21 12-13 6-8	12-13 10-22 6-8 15-23	4-12 10-22 12-13 6-8 10-21 10-22 15-23	10-22 12-13 6-8 15-23 23-24	12-13 6-8 10-21 22-21 15-23 24-25
Number of iterations	–	–	2	2	2	3

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

N = Total number of buses in the system

NL = Total number of lines

NT = Total number of transfers or transactions

NX = Total number of decision variables

NU = Total number of UPFC's introduced into the system

$\boldsymbol{A}$ = Element - node incidence matrix of dimension NL x (N-1)

$\boldsymbol{B}$ = DC load flow matrix

$\boldsymbol{P}$ = Bus power injection vector

θ = Bus phase angle vector

ψ_ι = Line phase angle of i^th line in radians

x_i = Line reactance in p.u

10 References

[1] Available Transfer Capability Definition and Determinations: A Framework for Determining available Transfer Capabilities of the Interconnected Transmission Networks for a Commercially viable Electricity Market, NERC, June 1996.

[2] G. Hamoud: Assessment of Available Transfer Capability of transmission Systems. IEEE Trans. on Power Systems, Vol. 15, No. 1, Feb. 2000, pp. 27 – 31.

[3] G. Hamoud: Feasibility Assessment of Simultaneous Bilateral Transactions in a Deregulated Environment, IEEE Trans. on Power Systems, Vol. 15, No. 1, Feb. 2000, pp. 22 – 26.

[4] M..I Alomoush: Derivation of UPFC DC Load Flow Model with Examples of its use in Restructured Power System, IEEE Trans. on Power Systems, Vol. 18, No. 3, Aug. 2003, pp. 1173 – 1181.

[5] H. Sawhney, B. Jeyasurya: Application of Unified Power Flow Controller for Available Transfer Capability Enhancement, Electric Power Systems Research, Vol. 69, No. 2-3, May 2004, pp. 155 – 160.

[6] Y. Xiao, Y.H. Song: Available Transfer Capability Enhancement using FACTS Device. IEEE Trans. on Power Systems, Vol. 18, No. 1, Feb. 2003, pp. 305 – 312.

[7] E. Bompard, P. Correia, G. Gross, M. Amelin: Congestion-Management Schemes: A Comparative Analysis under A Unified Framework, IEEE Trans. on Power Systems, Vol. 18, No. 1, Feb. 2003, pp. 346 – 352.

[8] R.S. Fang, A.K. David: Transmission Congestion Management in Electricity Market, IEEE Trans. on Power Systems, Vol. 14, No. 2, Aug. 1999, pp. 877 – 883.

[9] R. Jayashree, M. Abdullah Khan, K. Kuppusamy, M. Vivek: Transfer Capability Assessment and Congestion Management in a Deregulated Power System, Proceedings of National Systems Conference IIT, Kharagpur, 2003, pp. 381 – 384.

[10] H. Saadat: Power System Analysis, McGraw Hill, New Delhi, 2002.

[11] M. Shaaban, Y. Ni, F.F. Wu: Transfer Capability Computations in Deregulated Power Systems, Proceedings of the 33rd Hawaii International Conference on System Sciences, Vol. 4, 2000.

Appendix A

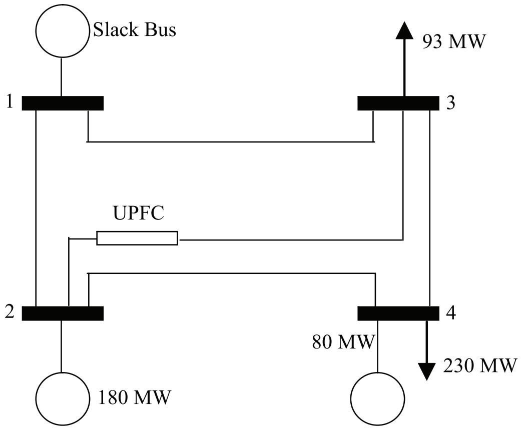

Fig. A1 – *Four bus system.*

Appendix B

Table B1

Line data for 4 *bus system.*

Line No.	Line reactance x (p.u)	Thermal Rating (MW)	Base MVA
1-2	0.2	70	100
1-3	0.2	100	
2-3	0.1	100	
2-4	0.2	150	
3-4	0.3	70	

Table B2

UPFC Data.

Series reactance x_{se} (p.u)	Shunt reactance x_{sh} (p.u)	Voltage magnitude series		Voltage magnitude shunt		Rating of Shunt converter (MW)	Rating of Series converter (MW)	Base MVA
		Lower limit	Upper limit	Lower limit	Upper limit			
		U^L (p.u)	U^U (p.u)	E^L (p.u)	E^U (p.u)			
0.1	10	0.0	0.2	0.0	1.1	4	6	100

Appendix C

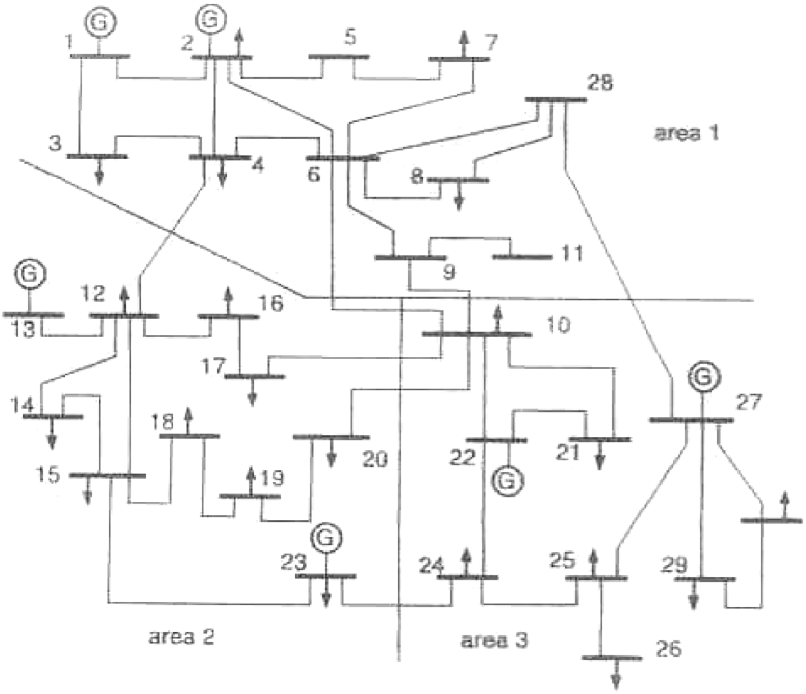

Fig. C1

Line diagram of IEEE 30 *Bus System.*