International Journal of Electrical and Power Engineering 1 (5): 501-511, 2007
ISSN: 1990-7958

A Multi-Transaction Based Security Constrained Optimal Power Flow Tool for Assessment of Available Transfer Capability and Congestion Management

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Abstract: With the recent trend towards deregulating power systems around the world, assessment of Available Transfer Capability (ATC) and Congestion Management have become key requirements for the smooth running of power markets with multiple transactions. This study proposes an unified model with multi transaction based Security Constrained Optimal Power flow for the assessment of ATC and Congestion Management in deregulated system. It uses an AC load flow model and Successive Linear Programming (SLP) approach enforcing operating constraints imposing limits on both loading of transmission lines (either in MW or MVA) and bus voltage limits. It also enforces security constraints arising out of line outages and generator outages. The use of control such as generator bus voltages, reactive powers of switchable VAR sources and tap setting of on-load tap changing transformers enhances ATC and gives an improved Congestion Management solution. Two possible market policies, policy 1 with fixed fractions assigned to participants and policy 2 with flexible fractions are considered. A computer package has been developed in MATLAB and its effectiveness of the proposed method has been verified by solving modified IEEE 24 bus Reliability Test System and a 119 bus Indian Utility System. The results demonstrate the monotonic and reliable convergence of the proposed method satisfying effectively all the operating and security constraints. Security constrained ATC values and assigned transactions in Congestion Management obtained are enhanced due to the use of system controls.

Key words: Available transfer capability, congestion management, successive linear programming, multi-transaction based security constrained optimal power flow

INTRODUCTION

Power utilities around the world are slowly undergoing a significant transformation towards a deregulated environment. The driving forces of deregulation are aiming to establish a more competitive market in order to achieve lower rates for the consumers and higher efficiency for the suppliers. In this restructured power system, it is the responsibility of Independent System Operator (ISO) to announce the previous day, the information about the predicted hourly Available Transfer Capability (ATC) on a publicly accessible Open Access Same time Information System (OASIS) (NERC, 1996). ATC between a source-sink node pairs is defined by FERC as the amount of transfer capability between the source and sink nodes that is available at a given time for purchase or sale of electric power under anticipated system conditions. Such information will help power marketers, sellers and buyers in reserving transmission services and finalizing bilateral transactions.

Congestion occurs whenever the transmission network is unable to accommodate all the desired transactions due to the violation of one or more operating constraints under the predicted base case state as well as under the contingency states. The task of congestion management requires the ISO to identify and relieve such situations through the deployment of various physical and financial mechanisms, before permitting the hour-ahead transactions.

A number of methods and algorithms have been reported in literature for assessment of ATC and Congestion Management (CM). Ejebe *et al*. (1998) uses Continuation Power Flow (CPF) method for the assessment of ATC. The computational effort is large and time requirement is severe. The dc load flow based methods (Hamoud, 2000a, b) are a bit faster than their ac counterparts, but considers only operating limits on real power flow in MW but not the limit on bus voltage.

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The methods based on power transfer/outage distribution factors (Ejebe *et al.*, 2000; Kumar and Srivastave, 2002) can cater to only the scenarios that are too close to the base case from which the factors are derived. Yan (2002) has proposed Security Constrained Optimal Power Flow approach for assessment of TTC including TRM and CBM but used only Repeated Power Flow approach. Li used Benders decomposition method for assessing static security constrained ATC. All the above methods have not incorporated controls like generator bus voltages, reactive powers of switchable VAR sources and tap setting of on-load tap changing transformers.

Several optimal power flow based Congestion Management schemes have been proposed. An approach for relieving congestion using the minimum total modifications to the desired transactions was presented in Galiane and Illic (1998). A willingness to pay premium (Fang and David, 1999) has also been suggested to avoid curtailment to the transactions. Ettore *et al.* (2003) compared the various congestion management approaches in different electricity markets of England and Wales, Norway, Sweden, PJM and California and developed an unified framework for the mathematical representation of the market dispatch and re-dispatch problems that ISO must solve in congestion management. In this framework, the impact of security constraints are not considered.

This study formulates an unified approach for both assessment of ATC and Congestion Management using a Multi-transaction based Security Constrained Optimal Power Flow method. The method uses Successive Linear Programming (SLP) approach and ac load flow solution (FDPF) enforcing security constraints on line flow limits (either in MVA or MW) and bus voltage limits. The use of controls such as generator bus voltages, reactive powers of switchable VAR sources and tap setting of on-load tap changing transformers enhances ATC and gives an improved Congestion Management solution.

SECURITY CONSTRAINED OPF IN A MULTI-TRANSACTION FRAMEWORK FOR ASSESSMENT OF ATC AND CM

Multi-transaction framework: A multi-transaction framework used in Shu and George (2002) is adapted in this paper. A multi-transaction with a set of transaction M can be described by a triplet denoted by

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

Where, $S^{(m)}$, $m \varepsilon M$ denotes a set of selling buses supplying a specified amount of real power $t^{(m)}$ to a set of buying buses $B^{(m)}$.

In the triplet, the set $S^{(m)}$ is a collection of 2-tuples

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

with the selling bus $s_i^{(m)}$ supplying $\sigma_i^{(m)}$ $t^{(m)}$ MW of the transaction amount. $N_s^{(m)}$ is the number of selling buses in transaction m. The fraction $\sigma_i^{(m)}$ must satisfy the constraint

$$\sum_{i=1}^{N_s^{(m)}} s_i^{(m)} = 1$$
$$\text{with} \quad s_i^{(m)} \text{ e} \left[0,1\right] \quad , i = 1,2.....N_s^{(m)}$$

Similarly the set $B^{(m)}$ is the collection of 2-tuples

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

Where the buying bus $b_j^{(m)}$ receives $\beta_j^{(m)}$ $t^{(m)}$ MW of the transaction amount. $N_b^{(m)}$ is the number of buying buses in transaction m. The fraction $\beta_j^{(m)}$ must satisfy the constraint

$$\sum_{j=1}^{N_b^{(m)}} \beta_j^{(m)} = 1$$
$$\text{with} \quad \beta_j^{(m)} \text{ e} \left[\ 0,1\right], \ j = 1,2...N_b^{(m)}$$

In certain markets the fractions associated with transactions, σ_i and β_j, remain constant making $t^{(m)}$, m = 1, ….NT as the only variables . This is referred as policy 1 in this paper. In certain other markets, fractions σ_i and β_j are flexible in which case the variables are

$$G_i^{(m)} = s_i^{(m)} t^{(m)} ; i = 1, 2....N_s^{(m)} \text{ and}$$
$$L_j^{(m)} = \beta_j^{(m)} t^{(m)} \ ; \ j = 1, 2....N_b^{(m)}$$

This is referred as policy 2 in this study. The OPF formulation for policy 1 is developed below.

Development of OPF model for ATC and CM-policy 1: ATC is defined as the Total Transfer Capability (TTC) less the sum of Existing Transmission Commitments (ETC) less the Transmission Reliability Margin (TRM) and the Capacity Benefit Margin (CBM). However, in this study ATC is computed ignoring TRM and CBM.

Congestion occurs whenever the transmission network is unable to accommodate all the proposed multiransactions 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 study, both the problems of assessment of ATC and CM are solved using a unified OPF framework and AC Power flow model. The study considers realistic ratings, for the transmission lines, either MW rating (stability limit for long lines) or MVA rating (thermal limit for short/medium lines) and bus voltage limits. This method also adjusts the available controls like generator bus voltages, reactive powers of switchable VAR sources and tap setting of on-load tap changing transformers for enhancing ATC as well as assigned transactions in Congestion Management.

Problem formulation: ATC assessment and congestion management for a set of transactions M is posed as a security constrained OPF problem in a multi- transaction framework by defining the decision vector x as

$$X = \left[X_t^T \;\; X_c^T\right]^T = [t \;\; V_G^T \;\;\; A^T \;\; Q_s^T]^T \tag{4}$$

Where

X_t = Sub-vector comprising transactions t between GENCO-DISCO groups.

X_c = Sub-vector comprising control variables like generator bus voltages V_G, tap setting of on-load tap changing transformers A and reactive powers of switchable VAR sources Q_s.

Statement of the problem:
To determine: The decision vector X

To maximize: wTt (5)

Where,

$$w^T = (w_1 \ldots\ldots\ldots w_{NT}) \tag{6}$$

and $t = t^{(m)} = (t^{(t)} \ldots\ldots\ldots t^{(NT)})$; NT is the number of transactions

Subject to:
Base case Power Flow Constraints

$$F(\theta, V_L, X) = 0 \tag{7}$$

Contingency case Power Flow Constraints

$$F_{(c)}(\theta, V_L, X) = 0; \; c = 1,2\ldots\ldots NC \tag{8}$$

Line flow constraints in MVA/MW under base case

$$\begin{aligned} &f(\theta, V_L, X) \le f^U && \text{(for MVA)} \\ &fL \le f(\theta, VL, X) \le f^U && \text{(for MW)} \end{aligned} \tag{9}$$

Line flow constraints in MVA/MW under contingency case

$$\begin{aligned} &f_{(c)}(\theta, V_L, X) \le f^U && \text{(for MVA)} \\ & && ; c = 1, 2\ldots\ldots\ldots NC \\ &f^L \le f_{(c)}(\theta, V_L, X) \le f^U && \text{(for MW)} \end{aligned} \tag{10}$$

Base case bus voltage limits

$$v^L \le v_L \le v^U \tag{11}$$

Contingency case bus voltage limits

$$v^L \le v_{L(c)} \le v^U \quad ; c = 1,2\ldots\ldots NC \tag{12}$$

and the operating limits on decision vector

$$X^L \le X \le X^U \tag{13}$$

Linearized OPF model: The OPF problem in Eq. 5-13 is linearized around an operating state to obtain an incremental OPF model which is given below. This OPF problem is a non-linear programming problem which is solved through Successive Linear Programming(SLP) technique. From equality constraints (7) and (8), linearized relation of state vector in terms of decision vector is obtained and this is substituted in inequality constraints (9) to (12), thereby reducing the number of constraints.

Relations between the state and decision vector are derived in Appendix A. The mismatch vector ΔP in equation (A4) contains GENCO and DISCO participants and is made up of change in multi-transaction given by

$$\Delta P = \sum_{m \in M} \Delta P^{(m)} \tag{14}$$

For each transaction m, the injection vector $\Delta P^{(m)}$ in (14) is given by

Where

$$y_n^{(m)} = \left\{ \begin{array}{ll} \dfrac{s_i^{(m)}}{V_i} & \text{if } n = s_i^{(m)} \;\; ; i = 1,2 \ldots N_s^{(m)} \\ -\dfrac{\beta_j^{(m)}}{V_j} & \text{if } n = b_j^{(m)} \;\; ; j = 1,2 \ldots N_b^{(m)} \\ 0 & \text{otherwise} \end{array} \right\} ; n = 1 \ldots\ldots N \text{ and } m = 1,2 \ldots NT \tag{15}$$

Substituting (14) and (15) in (A4) we get the relation between Δθ and ΔX

$$\Delta\theta = [B']^{-1} \sum_{m\in M} y^{(m)}\Delta t^{(m)} = [B']^{-1}\left[y^{(1)}.......y^{(NT)}\right]\Delta t^{(m)}$$

$$= [B']^{-1}\,[Y]\,\Delta t^{(m)}$$

$$\Delta\theta = [D1]\,\Delta t^{(m)}$$

Where $[D1] = [B']^{-1}\,[Y]$

$$\Delta\theta = [D1 \quad D2 \quad D3 \quad D4]\,\Delta X$$

$$\Delta\theta = [D]\,\Delta X \tag{16}$$

Where, D1 is of dimension N×NT and D2, D3, D4 are null matrices of dimension N×NV, N×NTR, $N\times NQ_s$, respectively and ΔX is of dimension NX where $NX=NT+NV+NTR+NQ_s$

$$\left(\frac{\Delta QL_L}{V}\right)$$

vector in (A6) contains DISCO participants of the transactions $\Delta Q^{(m)}$ and is denoted by ΔQ.

The mismatch vector $\Delta t^{(m)}$ is made up of change in multi-transaction given by

$$\Delta Q = \sum_{m\in M} \Delta Q^{(m)} \tag{17}$$

For each transaction m, vector $\Delta Q^{(m)}$ in (17) is given by

$$\Delta Q^{(m)} \triangleq z^{(m)}\Delta t^{(m)} \tag{18}$$

Where,

$$z_n^{(m)} = \left\{\begin{array}{ll} -\dfrac{r_j^{(m)}\beta_j^{(m)}}{V_j} & \text{if } n = b_j^{(m)}\ ;\ j = 1.....N_b^{(m)} \\ 0 & \text{otherwise} \end{array}\right\};\ n = 1, 2......NQ$$

$r_j^{(m)}$ denotes the ratio of reactive power demand to real power demand at the respective buyer buses.

Substituting (18) in (17)

$$\Delta Q = \sum_{m\in M} Z^{(m)}\Delta t^{(m)}$$
$$= \left[Z^{(1)}\ ....Z^{(NT)}\right]\Delta t^{(m)}$$
$$= [Z]\Delta t^{(m)} \tag{19}$$

$\Delta QG_L/V$ of (A6) is a NQ dimension vector containing non zero elements of $\Delta Q_{Si}/V_i$ corresponding to the switchable sources ΔQ_{Si} at the i^{th} bus and for all other buses the elements are zero. Let [R] be a matrix such that

$$\frac{\Delta QG_L}{V} = [R]\Delta Q_S \tag{20}$$

Substituting (19) and (20) in (A6)

$$\Delta V_L = \left[B''\right]^{-1}\left[Z\ -J_{LG}\ -J_{LA}\ \ R\right]\Delta X$$
$$= \left[E_1 \quad E_2 \quad E_3 \quad E_4\right]\Delta X$$
$$\Delta V_L = [E]\Delta X \tag{21}$$

Where,

$$[E_1] = \left[B''\right]^{-1}[Z];[E_2] = \left[B''\right]^{-1}[-J_{LG}]$$
$$[E_3] = \left[B''\right]^{-1}[-J_{LA}];[E_4] = \left[B''\right]^{-1}[R]$$

The linearized OPF model is as follows.

Maximize:

$$w^T\,\Delta t \tag{22}$$

Subject to:

Base case line flow constraints using equation (B4)

$$\Delta f = [K]\,\Delta X \le\ \le f^U \qquad \text{(for MVA)}$$
$$\Delta f^L \le \Delta f = [K]\,\Delta X \le\ \le f^U \qquad \text{(for MW)} \tag{23}$$

Contingency case line flow constraints

$$\Delta f_{(c)} = [K]_{(c)}\,\Delta X \le\ \le f^U_{(c)} \qquad \text{(for MVA)}$$
$$;\ c = 1, 2....\ NC \tag{24}$$
$$\Delta f^L_{(c)} \le \Delta f_{(c)} = [K]_{(c)}\,\Delta X \le\ \le f^U_{(c)} \qquad \text{(for MW)}$$

Base case bus voltage limits

$$\Delta V^L \le \Delta V_L \le \Delta V^U$$

Substituting Eq. 21 in the above equation we get

$$\Delta V^L \le [E]\,\Delta X \le \Delta V^U \tag{25}$$

Contingency case bus voltage limits

$$\Delta V^L_{(c)} \le [E]_{(c)}\,\Delta X \le \Delta V^U_{(c)} \tag{26}$$

Operating limits on decision vector

$$\Delta X^L \le \Delta X \le \Delta X^U \tag{27}$$

LP model comprises objective function (22) and inequalities, (23) to (27).

OPF Model for policy 2: The following are the changes required for policy 2.

- In the decision vector X defined in Eq. 4 t is replaced by the bus power injection vector I which is defined as $I^T = (G^T \quad L^T)$ where vector G comprises $G_i^{(m)}$; i = 1, 2.....$N_s^{(m)}$ and m = 1, 2....NT and vector L comprises $L_j^{(m)}$; j = 1, 2.....$N_b^{(m)}$ and m = 1, 2....NT. I is of dimension NI where

$$NI = \sum_{m \in M} N_s^{(m)} + \sum_{m \in M} N_b^{(m)}$$

- The D matrix used in Eq. 16 is derived for Policy 2 as follows. Equation A4 is modified as

$$\Delta\theta = \left[B'\right]^{-1} \sum_{m=1}^{NT} \sum_{i=1}^{N_s^{(m)}} \Delta P_{(i)}^{(m)} + \sum_{m=1}^{NT} \sum_{j=1}^{N_b^{(m)}} \Delta P_{(j)}^{(m)} \tag{28}$$

Where,

$$\begin{aligned} \Delta P_{(i)}^{(m)} &= y_{(i)}^{(m)} \Delta G_{(i)}^{(m)} \\ \Delta P_{(j)}^{(m)} &= y_{(j)}^{(m)} \Delta L_{(j)}^{(m)} \end{aligned} \tag{29}$$

and

$$y_{i(n)}^{(m)} = \begin{Bmatrix} \frac{1}{V_i} & \text{if } n = s_i^{(m)} \;; i = 1, 2....N_s^{(m)} \\ 0 & \text{otherwise} \end{Bmatrix}; \; n = 1, 2......N$$

$$y_{j(n)}^{(m)} = \begin{Bmatrix} \frac{-1}{V_j} & \text{if } n = b_j^{(m)} \;; \; j = 1.....N_b^{(m)} \\ 0 & \text{otherwise} \end{Bmatrix}; \; n = 1, 2......N$$

Substituting (29) in (28) the following equation can be obtained $\Delta\theta = [D]\,\Delta X$.

- The E matrix used in Eq. (21) is derived for Policy 2 as follows Eq. 17 is given by

$$\Delta Q = \sum_{m=1}^{NT} \left[\sum_{j=1}^{N_b^{(m)}} \Delta Q_{(j)}^{(m)} \right] \tag{30}$$

Where,

$$\Delta Q_{(j)}^{(m)} = Z_{(j)}^{(m)} \Delta L_{(j)}^{(m)} \tag{31}$$

and

$$z_{(j)n}^{(m)} = \begin{Bmatrix} -\frac{r_j^{(m)}}{V_j} & \text{if } n = b_j^{(m)} \;; \; j = 1.....N_b^{(m)} \\ 0 & \text{otherwise} \end{Bmatrix}; n = 1, 2......NQ$$

Substituting (30) and (31) in (A6) the following equation can be obtained $\Delta V_L = [E]\,\Delta X$.

Differences in the assessment of ATC and CM: The model is the same for ATC and Congestion management. However the following differences exist.

Assessment of ATC:

- The weightage for the m^{th} transaction w_m, m=1,2….NT in Eq. 6 is chosen as unity.
- The lower limit X_t^L in Eq. 13 is chosen as committed transactions and the upper limit of m^{th} transaction X_t^U is chosen as infinity.

Congestion management:

- The objective function (5) is to be minimized to keep the cuts in transaction as minimum as possible.
- The weightage for the m^{th} transaction w_m, m=1.2…NT in Eq. 6 is chosen as “willingness to pay charges” of the m^{th} transaction.
- The lower limit of m^{th} transaction X_t^L in Eq. 13 is chosen as committed transactions and the upper limit of m^{th} transaction X_t^U is chosen as the sum of committed and proposed transactions.

APPENDIX A-RELATION BETWEEN STATE AND DECISION VECTOR

Successive linear programming (Sadasivam and Abdullah, 1990)is used to solve the NLP optimization problem stated in 2.2.1. For the purpose of developing linearized model for SLP, the base case power flow Eq. 7 is linearized around the operating state and decoupled to obtain incremental relations between state vector and decision vector.

$$\begin{aligned} \Delta\theta &= [D]\,\Delta X \\ \Delta V_L &= [E]\,\Delta X \end{aligned} \tag{A1}$$

The details are given below.

Equation 7 is written in expanded form splitting into four groups represented by suffixes 1, P,G and L denoting slack bus, buses other than the slack bus, generator buses and load buses, respectively.

$$\begin{bmatrix} F_1 \\ F_P \\ F_G \\ F_L \end{bmatrix} = \begin{bmatrix} P_1(\theta, V_G, V_L, A) \\ P_P(\theta, V_G, V_L, A) \\ Q_G(\theta, V_G, V_L, A) \\ Q_L(\theta, V_G, V_L, A) \end{bmatrix} = \begin{bmatrix} PG_1 - PL_1 \\ PG_P - PL_P \\ QG_G - QL_G \\ QG_L - QL_L \end{bmatrix} \quad \text{(A2)}$$

Where functions P and Q denote the real and the reactive powers flowing from the buses into the connected lines. PG, QG, PL and QL denote the real and reactive power generations and loads, respectively. Equation A2 is linearized to get

$$\begin{bmatrix} \left[\frac{\partial P_1}{\partial \theta}\right]^T & \left[\frac{\partial P_1}{\partial V_G}\right]^T & \left[\frac{\partial P_1}{\partial V_L}\right]^T & \left[\frac{\partial P_1}{\partial A}\right]^T \\ \frac{\partial P_P}{\partial \theta} & \frac{\partial P_P}{\partial V_G} & \frac{\partial P_P}{\partial V_L} & \frac{\partial P_P}{\partial A} \\ \frac{\partial Q_G}{\partial \theta} & \frac{\partial Q_G}{\partial V_G} & \frac{\partial Q_G}{\partial V_L} & \frac{\partial Q_G}{\partial A} \\ \frac{\partial Q_L}{\partial \theta} & \frac{\partial Q_L}{\partial V_G} & \frac{\partial Q_L}{\partial V_L} & \frac{\partial Q_L}{\partial A} \end{bmatrix} \quad \text{(A3)}$$

$$\begin{bmatrix} \Delta\theta \\ \Delta V_G \\ \Delta V_L \\ \Delta A \end{bmatrix} = \begin{bmatrix} \Delta PG_1 - \Delta PL_1 \\ \Delta PG_P - \Delta PL_P \\ XQG_G - \Delta QL_G \\ \Delta QG_L - \Delta QL_L \end{bmatrix}$$

Let the partial derivative sub-matrices of (A3) be denoted as $[j'_{ij}]$ where i is the row index from the set {1, P, G, L } and j is the column index from the set {θ, G, L, A }. In the second Eq. A3 the weak submatrices $[j'_{PL}]$, $[j'_{PG}]$, $[j'_{PA}]$ are deleted and the elements of $[j'_{P\theta}]$ are divided by the respective voltage magnitudes giving rise to $[j'_{P\theta}]$ where,

$$[J_{P?}] = \left(\frac{1}{V}\right)[J'_{P?}]$$

Using decoupling assumptions (Stott and Alsac, 1974) the matrix $[j'_{P\theta}]$ is replaced by [B'] matrix resulting in

$$\Delta\theta = \left[B'\right]^{-1}\left[\frac{(\Delta PG_P - \Delta PL_P)}{V}\right] = \left[B'\right]^{-1}\Delta P \quad \text{(A4)}$$

Similarly neglecting $[j'_{L\theta}]$ in the fourth Eq. A3 and dividing each of the reactive power equations of the load buses by their respective voltage magnitudes

$$J_{LG}\Delta V_G + J_{LL}\Delta V_L + J_{LA}\Delta A = \left(\frac{\Delta QG_L - \Delta QL_L}{V}\right) \quad \text{(A5)}$$

Using decoupling assumptions (Stott and Alsac, 1974) the matrix $[j_{LL}]$ is replaced by the constant matrix [B"] and Eq. A5 becomes

$$\Delta V_L = \left[B''\right]^{-1}\left[\left(\frac{\Delta QG_L - \Delta QL_L}{V}\right) - J_{LG}\,\Delta V_G - J_{LA}\,\Delta A\right] \quad \text{(A6)}$$

ALGORITHM AND COMPUTATIONAL DETAILS

To make the linearized model more accurate in representing the non-linear model and to overcome the oscillatory convergence behaviour of SLP optimization, the movement of LP decision variables (Δt, ΔV_G, ΔQ_S, ΔA) are restricted within a maximum step size (Sadasivam and Abdullah, 1990). The flow chart for the proposed algorithm for assessment of ATC and Congestion management is presented in Fig. 1 which is self explanatory. The flow chart consists of repeated LPMOVES. An LPMOVE comprises setting up and solving of the linearized problem, updating the decision vector and obtaining new state vector by solving power flow problem. In congestion management problem, initially if the congestion is very severe, that is violation in many operating limits exists, LP solution becomes infeasible. This is because violations of too many operating constraints demands too large change in decision variable which is not permitted by the maximum step size. In that case, the proposed transactions are reduced by a fixed percentage to get a starting feasible LP solution.

The terms "Violation" and "Margin" used in the flow chart are defined as follows. For violated inequalities pertaining to line flows and bus voltages under base case and contingency cases, "Violation" is defined as the deviation of the respective variable from the operating limits (either lower or upper) in percentage of rating. If Violation of line flows or bus voltages are greater than 2% it is referred as "Severe violation" and if Violation lies within the range of 1-2% it is referred as "Correctable violation" and if it is less than 1% it is referred as "acceptable violation" (Appendix B). In the case of "Severe violation" the LP problem is re-solved after reverting to the previous state and using reduced step size. In the case of "Correctable violation" LP problem is solved with reduced step size.

For the line flows and bus voltages which are closer to the operating limits (either lower or upper), the term "Margin" is defined as Margin = abs (Rating-Actual) Margin is acceptable if it is less than 1%. The convergence of the iterative process is reached when the following conditions are satisfied.

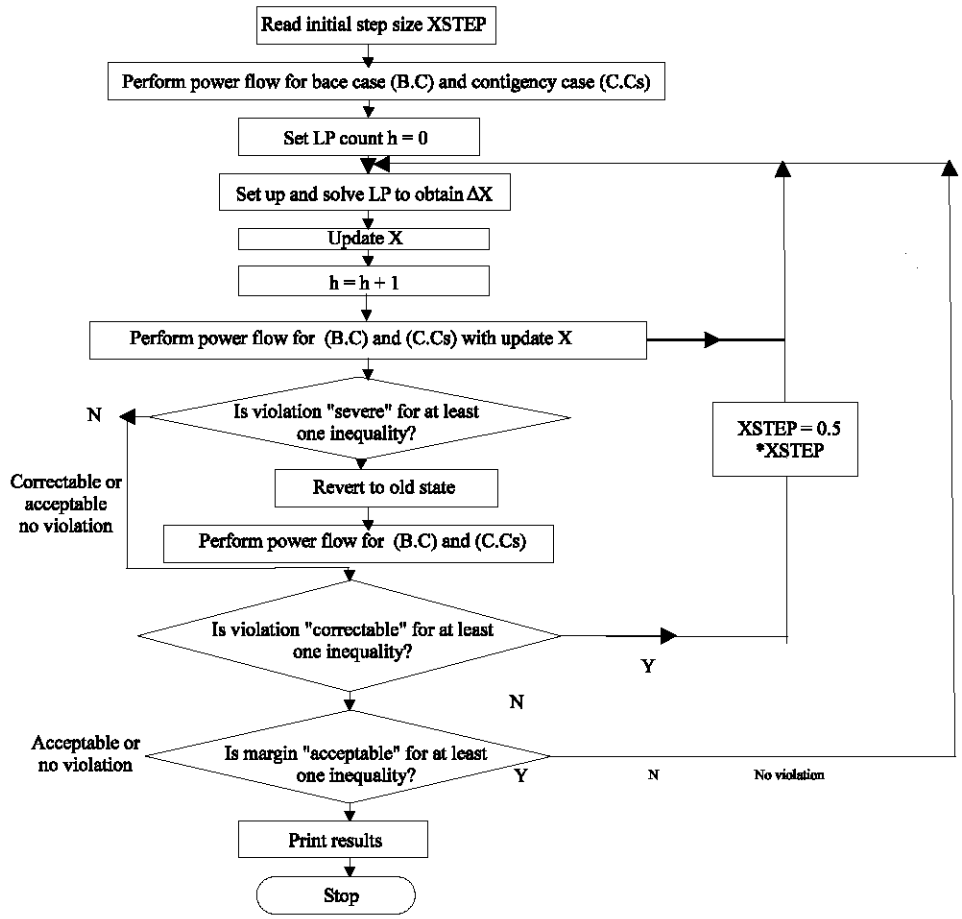

Fig. 1: Flow chart for assessment of ATC and CM

- No violations or acceptable violations in the inequality.
- Margin acceptable for at least one inequality.

APPENDIX B- SENSITIVITY RELATIONS BETWEEN LINE FLOW AND DECISION VECTOR

Let $\Delta\theta$ and ΔV_L be the changes in state which causes the corresponding change in line flow $f_{k\text{-}m}$ either in MVA or MW.

$$\Delta f_{k\text{-}m} = \left[\frac{\partial f_{k\text{-}m}}{\partial \delta}\right]^t \Delta\theta + \left[\frac{\partial f_{k\text{-}m}}{\partial V}\right]^t \Delta V_L \tag{B1}$$

$$\Delta f_{k\text{-}m} = \begin{array}{c} \\ \left[\begin{array}{ccccccccc} 0 & \frac{\partial f_{k\text{-}m}}{\partial \delta_k} & 0 & \frac{\partial f_{k\text{-}m}}{\partial \delta_m} & 0 & \frac{\partial f_{k\text{-}m}}{\partial V_k} & 0 & \frac{\partial f_{k\text{-}m}}{\partial V_m} & \\ & k & & m & & k & & & m \end{array}\right] \end{array} \begin{bmatrix} \Delta ? \\ \Delta V_L \end{bmatrix} \tag{B2}$$

Generalizing Eq. B2 for all NL lines

$$\Delta f = \left[f1\ \ f2\right]\begin{bmatrix} \Delta ? \\ \Delta V_L \end{bmatrix} \tag{B3}$$

Substituting (16) and (21) in (B3)

$$\Delta f = \{[f1][D] + [f2][E]\}\Delta X = [K]\Delta X \tag{B4}$$

RESULTS AND DISCUSSION

Assessment of ATC: In order to demonstrate the effectiveness of the proposed method, modified IEEE 24 bus Reliability Test System (RTS) and a 119 bus Indian Utility System are used . The data pertaining to the multi-transactions for 24 bus system and 119 bus system are given in Appendix C.

24 bus system: The 24 bus RTS is divided into three areas (Yan, 2002). The data for 24 bus system is taken from (Yan, 2002; IEEE, 1996). The following two transfers are considered.

Table 1: ATC values for 24 bus RTS with line /generator contingencies

	ATC, MW					
	Without security			With security		
Case	T1	T2	Total ATC	T1	T2	Total ATC
Policy1 (without controls)	231	209	440	150	150	300
Policy 1 (with controls)	240	218	458	165	169	334
Policy2 (without controls)	326	150	476	290	129	419
Policy 2 (with controls)	405	145	550	318	121	439

T1 : Area 1 to Area 2

T2 : Area 1 to Area 3

The results obtained for ATC (policy 1 and policy 2) without and with security constraints are given in Table 1. The contingency cases considered are outage of lines CC1: 11-13, CC2: 17-22, CC3:19-20,CC4: 21-22 , CC5: outage of generator with 272 MW at bus 18 in area 1 and CC6: outage of generator with 212 MW at bus 23 in area 2. The maximum step size for the LP decision variables are chosen after a trial study. The maximum step size for control variables (ΔV_G, ΔQ_S, ΔA) are 0.007, 0.10 and 0.01 p.u, respectively. Maximum step size for transactions are chosen for policy 1 and policy 2 based on the level of transactions. For policy 1,maximum step size chosen for Δt are 0.8 p.u for ATC without security and 0.3 p.u for ATC with security. For policy 2, the maximum step size chosen for (ΔG or ΔL) is 0.3 p.u for ATC without security and 0.25 p.u for ATC with security.

ATC obtained using Policy 1 without controls is 440 MW .However if control settings are used, ATC is increased to 458 MW(4.09% increase). When all security constraints are taken, ATC obtained, without controls, is 300 MW and when control settings are used ATC value is increased to 334 MW(11.33% increase).

Markets using Policy 2 gives a higher ATC as illustrated in Table 1. This is because Policy 1 is conservative since the control variable Δt is distributed among GENCOS and DISCOS in certain fixed fractions. ATC obtained without security using Policy 2 without controls is 476 MW and if control settings are used, the value is increased to 550 MW(15.54% increase). When all security constraints are considered, ATC without controls is 419 MW and this value is increased to 439 MW(4.77% increase) if control settings are used. Figure 2 (a and b) show the convergence behaviour of the proposed method, variation of ATC T1 and T2 with LPMOVE for Policy 1 with controls. Figure 2c shows corresponding critical line flows.

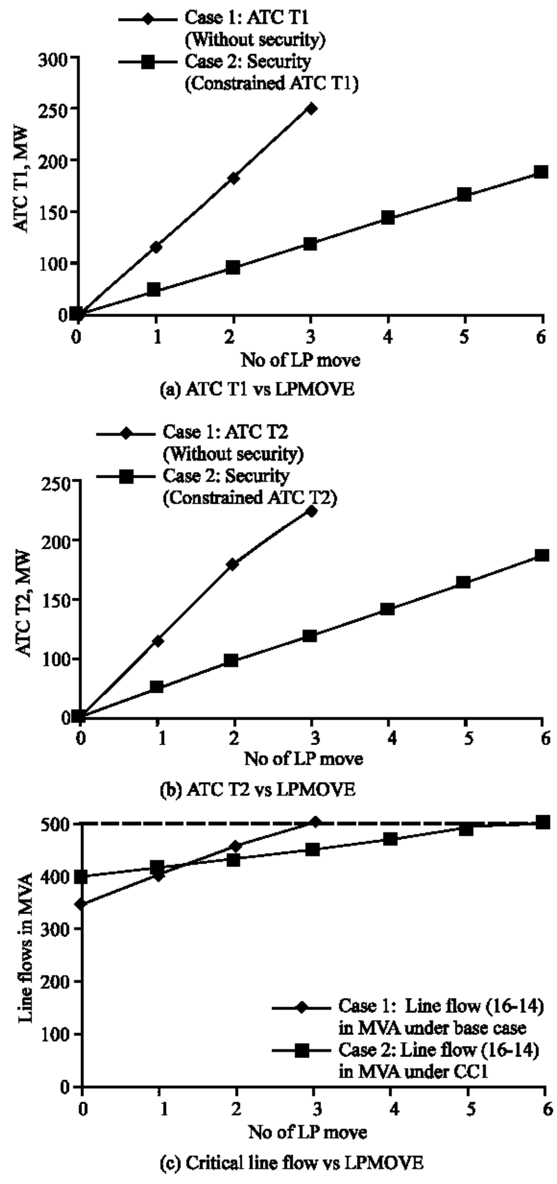

Fig. 2: Results for Policy 1 with control

119 bus system: The algorithm is then applied to a practical system, 119 bus Indian utility system. The system consist of 25 generators, 168 transmission lines. 26 transformers and 3 shunt reactors and 4 shunt capacitors. The total load of the system is 7636 MW and 4527 MVAR. 119 bus system is divided into 5 regions. The following two transfers are considered.

Table 2: ATC values for 119 bus Indian Utility system with line/generator contingencies

	ATC, MW					
	Without security			With security		
Case	T1	T2	Total ATC	T1	T2	Total ATC
Policy1(without controls)	116	106	222	60	60	120
Policy 1(with controls)	120	120	240	65	73	138
Policy2 (without controls)	73	224	297	74	168	242
Policy 2 (with controls)	104	257	361	80	193	273

Table 3: Congestion management for 24 bus system

	Proposed transactions: T1 = 300MW, T2 = 150MW, T3 = 100MW, T4 = 50 MW total proposed transactions = 600 MW									
	Without security					With security				
	Assigned transactions (MW)				Total assigned transactions	Assigned transactions (MW)				Total assigned transactions
Case	T1	T2	T3	T4	(MW)	T1	T2	T3	T4	(MW)
Policy1(without controls)	244	150	20	13	427	178	71	34	9	292
Policy 1(with controls)	297	118	20	10	445	182	74	38	10	304
Policy2(without controls)	230	108	72	36	446	149	80	50	26	305
Policy 2(with controls)	257	108	84	36	485	152	80	58	28	318

Table 4: Congestion management for 119 bus system

	Proposed transactions: T1 = 200MW, T2 = 150MW, T3 = 100MW, T4 = 50 MW total proposed transactions = 600 MW									
	Without security					With security				
	Assigned transactions (MW)				Total assigned transactions	Assigned transactions (MW)				Total assigned transactions
Case	T1	T2	T3	T4	(MW)	T1	T2	T3	T4	(MW)
Policy1(without controls)	145	65	70	94	374	80	56	30	56	222
Policy 1(with controls)	129	98	68	99	394	82	58	34	58	232
Policy2(without controls)	196	156	70	96	518	104	68	67	103	346
Policy 2 (with controls)	188	157	82	118	545	115	76	68	105	364

T1 : Region 1 to Region 3
T2 : Region 2 to Region 5

The results obtained for ATC (policy 1 and policy 2) without and with security constraints are given in Table 2. The contingency cases considered are CC1: Outage of two parallel units of transformers between buses 2029 and 1109,CC2: outage of two parallel units of transformers between buses 2021 and 1110, CC3: outage of single circuit line between buses 2060 and 2120, CC4: outage of single circuit line between buses 2012 and 2087and CC5: outage of generator with 53 MW at bus 1001 in area 1. The maximum step size for control variables (ΔV_G, ΔQ_S, ΔA) are same as chosen for 24 bus system. For policy 1 and 2 maximum step size chosen for $\Delta t/(\Delta G$ or $\Delta L)$ are 0.3 p.u for ATC without security and 0.2 p.u for ATC with security constraints. In policy 1, ATC obtained without controls is 222 MW which is increased to 240 MW (8.1% increase) when controls are used. ATC obtained with security constraints is 120 MW and when control settings are used it is increased to 138 MW (15% increase). In policy 2, ATC obtained without controls is 297 MW which is increased to 361 MW (21.55% increase) when control settings are used. ATC obtained with security constraints is 242 MW which is increased to 273 MW (12.81% increase) when control settings are used. Results given in Table 1 and 2 are obtained in 3-6 LPMOVES.

Congestion management

Bus system: The algorithm is also used to solve congestion management problem. It is tested for the same 24 bus system and IEEE 119 bus system. The following four transactions are considered. T1: Area 1 to Area 2; T2: Area 1 to Area 3; T3: Between bus 3 -14; T4: Between bus 15-4. The results obtained for Congestion Management (policy 1 and policy 2) without and with security constraints are given in Table 3. In policy 1 and 2 maximum step sizes chosen for decision variables for congestion management without and with security constraints are the same as that chosen for ATC assessment for 24 bus system. It is found from Table 3 that total assigned transactions without controls for policy 1 is 427 MW which is increased to 445 MW (4.22% increase) when control settings are used. When all security constraints are considered, the assigned transactions obtained without controls is 292 MW which is increased to 304 MW (4.11% increase) when controls

APPENDIX C-DATA PERTAINING TO MULTI-TRANSACTIONS FOR TEST SYSTEMS

Table C1: The Transaction Profile -24 Bus system

Transactions	Transaction amount (MW)	Willingness to pay charges $/Mw-hr	$S^{(m)}$	$B^{(m)}$
Multi-lateral transaction T1	300	20	(18,0.5), (21, 0.5)	(9, 0.2) , (10,0.3), (13, 0.2), (20,0.3)
Multi-lateral transaction T2	150	40	(16,0.5), (15, 0.5)	(2,0.3), (3,0.3), (4,0.2) , (7,0.2)
Bilateral transaction T3	100	50	(23,1)	(14,1)
Bilateral transaction T4	50	60	(15,1)	(4,1)

Table C2: The Transaction Profile- 119 Bus system

Transactions	Transaction amount (MW)	Willingness to pay charges $/Mw-hr	$S^{(m)}$	$B^{(m)}$
Multi-lateral transaction T1	200	20	(401,0.1), (407, 0.2), (2001, 0.1), (2002, 0.1), (1001, 0.1), (1002, 0.05), (2003, 0.05), (409, 0.3)	(2086, 0.1) , (424,0.3), (2082, 0.1), (2084,0.1), (2087,0.1), (2088,0.1), (2089,0.1), (2090,0.1)
Multi-lateral transaction T2	150	40	(404, 0.2), (2006, 0.2), (1003,0.1), (2004, 0.2), (428, 0.1),(2005, 0.1), (403, 0.1)	(2111,0.1), (2113,0.1), (2114,0.1), (2116,0.1), (2117,0.1), (2118,0.1), (2119,0.1), (2120,0.1), (2122,0.2)
Bilateral transaction T3	100	50	(406,1)	(2046,1)
Bilateral transaction T4	150	60	(1004,1)	(2064,1)

are used. In policy 2 the assigned transaction without controls obtained is 446 MW which is more than obtained in policy 1 and when control settings are used the value is increased to 485 MW(8.74% increase). When security constraints are taken, assigned transactions obtained is 305 MW which is increased to 318 MW(4.26% increase) when controls are used.

119 bus system: Table 4 shows the results obtained for congestion management for 119 bus system. The following four transactions are considered.

T1 : Region 1 to3
T2 : Region 2 to 5
T3 : Between bus 406-2046
T4 : Between bus1004-2064

The results shows that the proposed algorithm is reliable and converging in 3-6 LPMOVES for all the cases. It is also found to be effective in enhancing the ATC as well as improving Congestion Management solution with the use of extra controls.

CONCLUSION

An unified framework with Multi-transaction based Security Constrained Optimal Power Flow method using SLP technique has been proposed for the assessment of ATC and congestion management. It uses an AC load flow model and enforces operating limit constraints on line flows(either MVA or MW) and bus voltages. It also enforces security constraints arising out of line outages and generator outages. Two possible market policies, policy 1 with fixed fractions assigned to participants of multi-transactions and policy 2 with flexible fractions are considered. A computer package is developed in MATLAB for the proposed method and models, and its effectiveness is tested using modified IEEE 24 bus Reliability Test System and an 119 bus Indian Utility System. Results obtained confirm that the proposed algorithm has monotonic and reliable convergence satisfying effectively all the operating and security constraints. The results show that security constrained ATC values and assigned transactions obtained in congestion management are enhanced if available system controls like V_G, Q_S asd A are effectively used.

Nomenclature:

w : A vector of weightage given to the transactions
N : The number of buses except slack bus
NQ : The number of load buses
NC : The number of contingencies
f^U : The upper limit of the line flows in MVA/MW
f^L : The lower limit of the line flows in MW
V^L : The lower limit of bus voltages taken as 0.9 p.u
V^U : The upper limit of bus voltages taken as 1.05 p.u
NV : The number of voltage controlled bus
NTR : The number of transformers
NQ_S : The number of switchable VAR sources

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