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LOPTDF & OTDF Formulation for ATC with Line Outage Contingencies

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ABSTRACT: Deregulation of the electricity industry throughout the world aims at creating a competitive market to trade electricity, which generates a host of new technical challenges to market participants and power system researchers. For transmission systems, it requires non-discriminatory open access to transmission resources. Therefore, for better transmission services support and full utilisation of transmission assets, one of the major challenges is to accurately gauge the transfer capability remaining in the system for further transactions, which is termed Available Transfer Capability (ATC). It is crucial to develop an appropriate ATC determination methodology that enables one to evaluate the realistic transmission transfer capability by accounting for all related important requirements. This paper describes the evaluation of single area ATC using Power Transfer Distribution Factors ATC is calculated with (PTDFs) in Combined Economic Emission Dispatch (CEED) environment. Simultaneous bilateral and multilateral wheeling transactions have been carried out on IEEE 30 bus and IEEE 118 bus systems for the assessment of ATC for both normal and line outage contingencies. The obtained ATC results are compared with Power World Simulator to justify its accuracy. The solutions obtained are quite encouraging and useful in the present restructuring environment.

KEYWORDS: Available Transfer Capability, Wheeling transactions, Combined Economic Emission Dispatch, Power Transfer Distribution Factors, Participation Factors, Line Outage Power Transfer Distribution Factors

1. INTRODUCTION

Restructuring process of the electrical industry throughout the world aims at creating competitive markets to trade electricity [1-5]. In order to have open access in the restructured power market, a transparent knowledge about the generation capacity and the transmission capability of the system has to be determined. In the power market, the Independent System Operator (ISO) can check the capability of the transmission paths. The transactions in the open access market could be two types, either involving just one buyer-seller pair (even if their physical injection and utilization points are multiple) and known as bilateral transactions, or bringing together a multiple buyers and sellers who group themselves together to enter in to a multilateral transaction.

Since many utilities provide transaction services for wholesale customers, they must know about the post information on ATC of their transmission networks. Such information will help power marketers, sellers and buyers in reserving transmission services. ATC must be rapidly updated for new capacity reservations, schedules or transactions, various mathematical models have been developed by the researchers to determine the ATC of the transmission system [6-10]. The computation of ATC has been carried out by the various researchers. Yan-ou and Chanan Singh demonstrated on IEEE 24 bus reliability test system [11]. The linear ATC has been demonstrated using DC Power Transfer Distribution Factors (DCPTDF) and used to allocate real power flows on the transmission lines [12]. However, this method has a poor accuracy due to the assumption involved in the DC power flow model.

Researchers have proposed the computation of ATC using AC Power Transfer Distribution Factors (ACPTDF) [13-15]. The new methods to evaluate ATC in competitive environment are proposed in [16-18].
In this paper, ATC is computed using PTDF in CEED environment for IEEE test systems. Before computing the ATC, the basic optimal power flow solution has to be determined. Researchers proposed a price penalty factor for solving the CEED problem, which blends the emission costs with the normal fuel costs [19]. Yurevich et al. validated evolutionary programming (EP) algorithm to solve optimal power flow problem with quadratic and sine component cost functions [20]. Evolutionary computation methods have been applied for solving EP based CEED problem with non-linear scaling factor and demonstrated on various IEEE test systems [21]. CEED problem is formulated as a multi-objective problem by considering both economy and emission simultaneously. This bi-objective problem is converted in to single objective function using price penalty approach.

The assessment of ATC in CEED environment using PTDF are demonstrated on IEEE 30 bus and IEEE 118 bus systems with line flow constraints. Simultaneous bilateral and multilateral transactions have been carried out in the test systems for the assessment of ATC for both normal and contingency modes. The obtained results are compared with Power World Simulator package [22].

II. AVAILABLE TRANSFER CAPABILITY

Available Transfer Capability (ATC) is a measure of the transfer capability remaining in the physical transmission network for further commercial activity over and above the already committed uses [23]. ATC evaluation is important because it is the point where power system reliability meets electricity market efficiency. ATC can have a huge impact on market outcomes and system reliability, so the results of ATC are of great interest to all involved. ATC can be expressed as:

$$ATC = TTC - \text{Existing Transmission Commitments} \qquad (1)$$

Where, Total Transfer Capability (TTC) is defined as the amount of electric power that can be transferred over the interconnected transmission network or particular path or interface in a reliable manner while meeting all of a specific set of defined pre and post contingency conditions. Existing transaction is the power flow over the transmission paths at the desired time at which ATC should be calculated. This is the already committed used power on the transmission path. Utilities would have to determine adequately their ATC's to insure that system reliability is maintained while serving a wide range of transmission transactions. ATC between and within areas of the interconnected power system and ATC for critical transmission paths between these areas would be continuously updated and posted changes in scheduled power transfers between the areas [1-5].

The information of ATC, as an important indicator of the system performance, is useful in restructured energy market in many ways.

ATC at base case, between bus m and bus n using line flow limit (thermal limit) criterion is mathematically formulated using PTDF as

$$ATC_{mn} = \min\{\, T_{ij,\,mn} \,\},\ ij \in N_L \qquad (2)$$

Where $T_{ij,mn}$ denotes the transfer limit values for each line in the system. It is given by

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$$T_{ij,\,mn} = \begin{cases} \dfrac{(P_{ij}^{\max} - P_{ij}^{0})}{PTDFij,\,mn} & PTDF_{ij,mn} > 0 \\ \alpha \text{ (infinite)} & PTDF_{ij,\,mn} = 0 \\ \dfrac{(-P_{ij}^{\max} - P_{ij}^{0})}{PTDF_{ij,\,mn}} & PTDF_{ij,\,mn} < 0 \end{cases} \qquad (3)$$

Where

P_{ij}^{max} is the MW power limit of a line between bus i and j. P_{ij}^{o} is the base case power flow in line between bus i and j.

$PTDF_{ij,mn}$ is the power transfer distribution factor for the line between bus i and j when a transaction is taking place between bus m and n.
N_L is the total number of lines.
In this paper, the optimal settings of generators under CEED environment are considered as a base case power flow. The PTDF may be either DCPTDF or ACPTDF and it depends on the method of formulation and it is explained in the section III.

2.1 CEED Problem Formulation

Optimization of CEED problem has been mathematically formulated and is given by the following equation

$$\phi = min \sum_{i=1}^{Ng} f\,(FC, EC) \qquad (4)$$

Where

ϕ is the optimal cost of generation (US$/h).
FC and EC total fuel cost and total emission of generators respectively.
N_g represents the number of generators connected in the network.
The cost is optimized within the following power system constraint

$$\sum_{i=1}^{Ng} P_{gi} = P_d + P_l \qquad (5)$$

Where
P_d is the total load of the system and
P_l is the transmission losses of the system.

The bi-objective combined economic emission dispatch problem is converted into single optimization problem by introducing price penalty factor h [24] and the CEED optimization problem is solved using evolutionary programming and the more information is also available in the paper [6-10].

III. PTDF CALCULATION

PTDFs determine the linear impact of a transfer (or changes in power injection) on the elements of the power system.

These values provide a linearized approximation of how the flow on the transmission lines and interfaces change in response to transaction between the seller and buyer.

3.1 DCPTDF Formulation

The linear DC Power Transfer Distribution Factors (DCPTDF) are used to allocate MW flows on the lines for a transaction in the system and they are based on DC power flow equations [11-15]. These equations are simply the real part of decoupled power flow equations in which voltages and reactive powers are ignored and only angle and real powers are solved by iterating
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$$[\Delta\delta] = [B]^{-1} \ \Delta P \qquad (6)$$

Where B is bus susceptance matrix and ΔP is the change in power at base case. However, this has a poor accuracy due to assumption involved in the DC power flow

model [12].

3.2 ACPTDF Formulation

The AC power transfer distribution factors proposed for calculation of ATC [13] were used to find various transmission system quantities for a change in MW transaction at different operating conditions.

Consider a bilateral transaction t_k between a seller bus *m* and buyer bus *n*. Line l carries the part of the transacted power and is connected between buses *i* and *j*. For a change in real power, transaction among the above buyer and seller by Δt_k MW, if the change in a transmission line quantity q_1 is Δq_1 , power transfer distribution factors can be defined as,

$$PTDF_{ij,mn} = \frac{\Delta q_l}{\Delta t_k} \qquad (7)$$

The transmission quantity q_l can be either real power flow from bus *i* to *j* (P_{ij}) (or) real power flow from bus *j* to bus *i* (P_{ji}). The above factors have been proposed to compute at a base case load flow with results using sensitivity properties of NRLF Jacobian. Consider full Jacobian in polar coordinates $[J_T]$, defined to include all the buses except slack (including ΔQ-ΔV equations also for PV buses).

$$\begin{bmatrix} \Delta\delta \\ \Delta V \end{bmatrix} = \begin{bmatrix} \frac{\partial P}{\partial \delta} & \frac{\partial P}{\partial V} \\ \frac{\partial Q}{\partial \delta} & \frac{\partial Q}{\partial V} \end{bmatrix}^{-1} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = [J_T]^{-1} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \qquad (8)$$

In a base case load flow, if only one of the k^{th} bilateral transactions is changed by Δt_k MW, only the following two entries in the mismatch vector on RHS of (8) will be non zero.

$$\Delta Pi = \Delta t_k \qquad \Delta Pj = -\Delta t_k \qquad (9)$$

With the above mismatch vector elements, the change in voltage angle and magnitude at all buses can be computed from (8) & (9) and, hence, the new voltage profile can be calculated. These can be utilized to compute all the transmission quantities q_l and hence the corresponding in these quantities Δq_l from the base case. Once the Δq_l for all the lines corresponding to a change in transaction Δt_k is known, PTDFs can be obtained from (7). These ACPTDFs, which are computed at a base load flow condition, have been utilized for computing change in transmission quantities at other operating conditions as well.

ACPTDF is also calculated for multilateral transaction in which group of sellers have a bilateral contract with group of buyers. The change in multilateral transaction can be assumed to be shared equally by each of the sellers and buyers. However, the transaction amount can be shared in any pre-decided ratio in a deregulated environment. The mismatch vector for the multilateral transactions will have non zero entries corresponding to the buyer and seller buses [16-20]. The rest of the procedure for calculation of ACPTDF will be the same as outlined above the bilateral transaction case.

3.3 Contingency Selection

The severity of the system loading under normal and contingency cases in an area or between areas can be described by a real power line flow Performance Index (PI) [25], as given below.
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$$PI = \sum_{m=1}^{N_l} \frac{w_m}{2n} \left[\frac{P_{lm}}{P_{lm}^{max}} \right]^{2n} \qquad (10)$$

Where P_{lm} is the real power flow and P_{lm}^{max} is the rated capacity of the line l -m, n is the exponent and w_m is a real non-negative weighing coefficient which may be used to reflect the importance of lines. PI will be small when all the lines are within their limits and reach a high value when there are overloads.

3.4 LOPTDF & OTDF formulation for ATC with line outage contingencies

Line Outage Power Transfer Distribution Factor (LOPTDF) is a sensitivity measure of how a change in a line's status affects the flows on other lines in the system. When calculating PTDF values for interfaces that include contingent lines, the PTDF values calculated are actually refer to as an Outage Transfer Distribution Factor (OTDF). An OTDF is similar to PTDF, expect and OTDF provides a linearized approximation of the post-outage change in flow on a transmission line in response to a transaction between the seller and buyer [21-25]. The OTDF value is a function of PTDF values and LOPTDF values.
Consider the outage of a line connected between buses r and s having pre outage real

power flow P_{rs}^{o} and P_{sr}^{o} from bus r to bus s and bus s to bus r respectively. Let $P_{ij,rs}$ be the post outage flow in a line connected between buses i and j. The change in the line flows can

be written as,

$$\Delta P_{ij,rs} = P_{ij,rs} - P_{ij}^{o} \qquad (11)$$

The Line Outage Power Transfer Distribution Factor (LOPTDF) can be defined as the ratio of $P_{ij,rs}$ to the real power flow transmitted in the line taken for outage and connected between the buses r and s.

$$LOPTDF_{ij,rs} = \Delta P_{ij,rs} \Big/ P_{rs}^{o} \qquad (12)$$

The OTDF value for line i-j during outage of line r-s is

$$OTDF_{ij,rs} = PTDF_{ij,mn} + LOPTDF_{ij,rs} \times PTDF_{rs,mn} \qquad (13)$$

Then, for each line during each contingency, determine another transfer limit value

$$T_{ij,\,rs} = \begin{cases} \dfrac{(P_{ij}^{\max} - P_{ij,rs})}{OTDF_{ij,\,rs}} & ; \ OTDF_{ij,rs} > 0 \\ \alpha \text{ (infinite)} & ; \ OTDF_{ij,\,rs} = 0 \\ \dfrac{(-P_{ij}^{\max} - P_{ij,\,rs})}{OTDF_{ij,\,rs}} & ; \ OTDF_{ij,\,rs} < 0 \end{cases} \tag{14}$$

ATC under a line outage condition, for the transaction between *m* and *n*, taking the line flow limit criteria into account can be determined as

$$ATC_{mn,rs} = \min\{T_{ij,\,mn}, T_{ij,rs}\},\ ij \in N_L\ \ \&\ rs \in N_{LC} \tag{15}$$

Where,
N_{LC} is total number of line outage contingencies.
$P_{ij,\,rs}$ is power flow on line *i-j* after outage of the line *r-s*.

$LOPTDF_{ij,rs}$ are line outage power transfer distribution factor for line *i-j* when line *r-s* is out.
$PTDF_{rs,mn}$ is power transfer distribution factor for line *r-s* outage and for transaction between bus *m* and bus *n*.
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IV. ALGORITHM

The basic steps used for computing ATC for each transaction are as follows:
Step 1: Read the system input data.
Step 2: Run a base case load flow in CEED environment and determine the optimal settings of the generators [21].
Step 3: Consider wheeling transactions (t_k).
Step 4: Compute AC power transfer distribution factors as per (7).
Step 5: Take transactions as variables, line flow, real and reactive power limits of generators as constraints and compute the feasible wheeling transactions.
Step 6: Dispatch the possible transactions and determine the ATC as per (2).

Step 7: Is any contingency analysis to be performed, then perform contingency analysis as per (10) and then proceed, otherwise go to step 10
Step 8: Calculate LOPTDF and OTDF as per (12) & (13)

Step 9: Calculate ATC for line outage contingency case as per (15)
Step 10: Is any other transaction has to be carried out, then consider the next transaction and go to step 4, otherwise proceed.
Step 11: Print the value ATC.

V. SIMULATION RESULTS AND DISCUSSIONS

The ATC determination is carried out for the simultaneous bilateral and multilateral transactions. The assessment of ATC using PTDF methods have been conducted on IEEE 30 bus and IEEE 118 bus systems by considering single area for normal and line outage mode operation under restructured environment. Thermal limit of each line is considered as a constraint and reactive power demand at load buses has been taken as constant. In the ATC determination, generator settings are obtained from CEED environment explained by the authors in [26-29]. The simulation studies are carried out on Intel Pentium IV, 2.66 GHz system in MATLAB environment. The results are compared with Power World Simulator (PWS) package. Some of the results are not possible to verify because of the limitation of PWS package. (For example multilateral transactions are not possible to perform using Power World Simulator).

The bus data, line data and CEED base case values of the test systems are taken from [21, 26]. In IEEE 30 bus system, two simultaneous bilateral transactions T_1 (2-28) & T_2 (5-23) and a multilateral transaction T_3 (2, 11 - 28, 26) are considered and the results are given
in Table.1.

Table 1: ATC in MW-IEEE 30 bus system

Transaction	Case	DCPTDF method	DCPTDF method (PWS)	ACPTDF method	ACPTDF method (PWS)	LOPTDF method	LOPTDF method (PWS)
T_1 (2-28)	A	23.65	23.78	24.82	24.87	-	-
	B	18.26	18.04	-	-	18.83	18.34
T_2 (5-23)	A	16.25	17.36	19.35	17.53	-	-
	B	12.16	13.53	-	-	14.18	12.25
T_3 (2, 11 -28, 26)	A	15.56	-	16.95	-	-	-
	B	11.35	-	-	-	12.23	-

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In IEEE 118 bus system, three simultaneous bilateral transactions T_1 (1-118), T_2 (46-80) & T_3 (49-100) and a multilateral transaction T_4 (25, 59, 46 - 89, 100, 103, 111) are considered and the results are given in Table.2.

Table 2: ATC in MW-IEEE 118 bus system

Transaction	Case	DCPTDF method	DCPTDF method (PWS)	ACPTDF method	ACPTDF method (PWS)	LOPTDF method	LOPTDF method (PWS)
T_1(1- 118)	A	216.20	216.96	214.48	212.34	-	-
	B	211.82	212.29	-	-	194.78	193.11
T_2(46-80)	A	425.22	426.54	363.42	360.45	-	-
	B	303.76	305.52	-	-	245.41	243.41
T_3(49-100)	A	440.68	442.14	395.37	393.03	-	-
	B	308.54	310.62	-	-	256.47	254.20
T_4(25, 59, 46 - 89, 100, 103, 111)	A	42.39	-	51.07	-	-	-
	B	12.46	-	-	-	14.79	-

For both the test systems, the ATC calculations are carried out in normal mode operation (case A) and (n-1) line contingency mode operation (case B).

In contingency mode operation, as per (18) outage of line 9-10 is considered for IEEE 30 bus system and outage of line 69-77 is considered for IEEE 118 bus system.

VI. CONCLUSION

The ATC value serves as an important indicator of system performance. This paper presents the determination of ATC using Power Transfer Distribution Factors. ATC determination has been tested on two IEEE test systems with simultaneous bilateral and multilateral wheeling transactions. Line outage contingency is also considered. The obtained results are compared with Power World Simulator. For the various cases considered, the ATC determination using ACPTDF for the base case, LOPTDF for the line outage contingency are found to be more accurate.

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