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Application of FACTS Devices for ATC Enhancement in Competitive Power Market

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Abstract - **With the recent trends towards deregulating power systems around the world, transfer capability computation emerges as the key issue to a smoothly running power market with multiple transactions. In deregulated power systems, Available Transfer Capability analysis is presently a critical issue. This paper presents the calculation of ATC using DC and AC distribution factors. Flexible AC transmission system devices can be alternative to reduce the flows in heavily loaded lines, resulting in an increased transfer capability, low system loss, improved stability of the network and reduced cost of production by controlling the power flows in the network. Two types of FACTS are used in this study namely Thyristor Controlled Series Capacitor(and Unified Power Flow Controller for enhancing the available transfer capability of the interconnected power system. The ATC is computed for different transactions of IEEE 24-bus (single area) system.**

Index Terms - **Available Transfer Capability, electricity market, flexible ac transmission systems, TCSC, UPFC.**

I. INTRODUCTION

The concept of competitive industries rather than regulated ones has become prominent in the past few years. Economists and political analysts have promoted the idea that free markets can drive down costs and prices thus reducing inefficiencies in power production. This change in the climate of ideas has fostered regulators to initiate reforms to restructure the electricity industry to achieve better service, reliable operation and competitive rates. Deregulation of the power industry was first initiated in United Kingdom. The U.S electricity industry has reportedly taken the plunge towards deregulation. The Federal Energy Regulatory commission (FERC) has mandated that transmission must be open to all customers and Available Transfer Capability (ATC) information be made available on a publicly accessible open access same time information system (OASIS)[1]. Utility engineers must continuously compute and update hourly ATC values to be made available in the web.

Due to deregulation, power wheeling transactions have become a very important issue. Generally power wheeling is defined as the power transmitted from a power producer to a customer through transmission systems and distribution facilities of third party. Since the transmission facilities have their physical limitation, not all of the power wheeling transaction can be accepted and carried out in power market. Thermal limits of transmission facilities, voltage limits at each bus, reactive power constraints of generating units and net interchange constraints do limit the feasibility of power transfer.

Transfer capability is the measure of the ability of interconnected electric systems to reliably move or transfer power from one area to another over all transmission lines (or paths) between those areas under specified system conditions. The units of transfer capability are in terms of electric power, generally expressed in mega watts (MW). in this context, “area” may be an individual electric system, power pool , control area , sub region or north American electric reliability council (NERC) region[1], or a portion of any of these. Transfer capability is also directional in nature. that is , the transfer capability from area A to area B is not generally equal to the transfer capability from Area B to Area A .

Total Transfer Capability (TTC) is the largest value of electric power that can be transferred over the interconnected transmission network in a reliable manner without violation of specified constraints. TTC is the key component for calculating Available Transfer Capability (ATC).

The ATC of a transmission network has been defined as the unutilized transfer capability of the transmission network for the transfer of power for further commercial activity, over and above already committed usage[1]. Power transactions between a specific seller bus/area and buyer bus/area can be committed only when sufficient ATC is available for that interface. Thus such transfer capability can be used for reserving transmission services, scheduling firm and non - firm transactions and for arranging emergency transfers between seller bus/areas or buyer bus/areas of an interconnected power system network. ATC among areas of an interconnected power system network and also for critical transmission paths between areas are required to be continuously computed , updated and posted to OASIS following any changes in the system conditions.

Genetic Algorithms (GAs) are probabilistic heuristic search procedures based on natural genetic system. It uses probabilistic transition rules, not deterministic rules. GA is highly multi-direction, parallel and rather robust method in searching global optimal solution of complex optimization problems. By using random choice as a tool in the search process, it possesses the advantage to help preventing the algorithm getting stuck in a local minimum. Power system researchers have implemented the technique broadly in recent areas [8].

This paper presents the calculation of ATC using DC and AC power transfer distribution factors. Two types of FACTS devices are used in this study namely Thyristor Controlled Series Capacitor (TCSC) and Unified Power Flow Controller (UPFC) for enhancing the available transfer capability of the interconnected power system. A method to determine the optimal locations of TCSC and UPFC has been suggested in this paper. The proposed method is tested on IEEE 24 bus system for different transactions.

II. AVAILABLE TRANSFER CAPABILITY

Mathematically, ATC is defined as[4], the Total Transfer Capability (TTC) less the Transmission Reliability Margin (TRM), less the Capacity Benefit Margin (CBM) and the sum of existing transmission commitments(TC) which includes retail customer service.

Transmission Reliability Margin (TRM)[4] is defined as that amount of transmission transfer capability necessary to ensure that the interconnected transmission network is secure under a reasonable range of uncertainties in system conditions.

Capacity Benefit Margin (CBM)[4] is defined as that amount of transmission transfer capability reserved by load serving entities to ensure access to generation from interconnected systems to meet generation reliability requirements.

$$ATC = TTC - TRM - CBM - TC \qquad (1)$$

In this paper, the margins such as TRM and CBM are not considered. Therefore ATC here can be expressed as:

$$ATC=TTC-TC \qquad (2)$$

The procedure proposed involves the method based on multiple load flow runs AC load flow for each increment of transaction between an interface and checks whether any of the operating conditions such as line flow limit or bus voltage limit is violated . the minimum out of the two critical transaction values is taken as the TTC for the system in that condition.

A method based on continuation power flow[4] incorporating limits of reactive power flows , voltage limits as well as voltage collapse and line flow limits is described . However, with this method the computational effort and time requirement are large. The topological information of a system is stored in matrix form and constants for different simultaneous cases and critical contingencies have been calculating before hand and used for determination of ATC values. For very large systems, the method may be quite cumbersome. The localized linearity of the system is assumed and additional load required to hit the different limits are separately calculated and the minimum of all these is taken as ATC.

Method based on linear sensitivity factors offer a great potential for real time calculation of ATC . Use of these factors offers an approximate but extremely fast model for the static ATC determination . The DC power transfer distribution factors are derived (DCPTDFs) based on DC load flow assumptions and hence are provide less accurate results. The new set of AC power transfer distribution factors[2] (ACPTDFs) to determine static ATC more accurately.

It is highly recognized that FACTS devices, specially the series devices such as thyristor controlled series capacitor (TCSC) , thyristor controlled phase angle regulator (TCPAR), the unified power flow controller (UPFC) etc. can be applied to increase the ATC of power network.

If FACTS device is placed randomly in any line , the ATC between seller bus/area and the buyer bus/ area will increase. But if FACTS device is placed at a particular line [7], ATC of that line will be increased.

III. COMPUTATIONAL METHODS

A. *ATC Determination using DC power transfer distribution factors*

1) Computation of DC Distribution Factors:

A method based on DC power transfer distribution factors is proposed. From the power flow point of view, a transaction of a specified amount of power that is injected into the system at one zone by a generator and removed at another zone by a load. The linearity property of the DC power flow model can be used to find the transaction amount that would give rise to a specified power flow, such as an interface limit. The coefficient of the linear relationship between the amount of a transaction and the flow on a line is called the power transfer distribution factor (PTDF). PTDF is also called sensitivity because it relates the amount of one change transaction amount to another change line power flow.

The PTDF is the fraction of amount of a transaction from one zone to another that flows over a given transmission line. PTDF $_{iij-mn}$ is the fraction of a transaction from zone m to zone n that flows over a transmission line connecting zone i to zone j . The equation for the PTDF is

$$\mathrm{PTDF}_{ij\text{-}mn} = (X_{im} - X_{jm} - X_{in} + X_{in})/X_{ij} \qquad (3)$$

Where X_{ij} - reactance of the transmission line connecting zone i and zone j.

X_{im} - entry in the ith row and the mth column of the bus reactance matrix X .

2) ATC Determination using DC power transfer distribution factors:

The ATC from seller bus/area to buyer bus/ area could be found using a DC power flow by varying the amount of transaction until a limit is reached, but this is computationally inefficient . Instead, the DC power transfer distribution factors described above can be used to quickly calculate the maximum allowable flow .

The PTDF can be used to directly calculate the ATC. A transaction from zone m to zone n creates a change in the flow on a line from zone i to zone j of ΔP_{ij}. . The new flow on the line is the sum of the original flow p_{ij}^0 and the change , and it must be less than the line's flow limit P_{ij}^{max} .

$$P_{ij}^{new} = P_{ij}^{0} + \Delta P_{ij} \leq P_{ij}^{max} \qquad (4)$$

Applying equation(4) and solving for the transaction amount,

$$P^{max}_{mn,ij} < (P_{ij}^{Max} - P^{0}_{ij})/\mathrm{PTDF}_{ij,mn} \qquad (5)$$

$P^{max}_{ij,mn}$ is the maximum allowable transaction amount from zone m to zone n constrained by the line from zone i to zone j is the minimum of the maximum allowable transaction over all lines

$$ATC_{mn} = \min\{P^{max}_{mn,ij}\} \quad (6)$$

B. *ATC Determination using AC Distribution Factors*

Consider a bilateral transaction t_p between a seller bus, m and buyer bus, n. Further consider a line l, carrying a part of the transaction power. Let the line be connected between a bus-i and a bus-j. For a change in real power transaction between the above seller and buyer say by Δt_p MW, if the change in transmission line quantity q_l is Δq_l, the AC power transfer distribution factors can be defined as:

$$(ACPTDF)_{ql\text{-}tp} = \frac{\Delta q_l}{\Delta t_p} \quad (7)$$

In this paper, the transmission quantity q_l is taken as real power flow from bus-i to bus-j.

1) Computation of AC Distribution Factors:

The distribution factors have been computed with the base case load flow results using the sensitivity properties of the NRLF Jacobean. The procedure for calculation of these distribution factors is described below.

Consider the sensitivity relationship provided by the Newton-Raphson load flow equations in the polar coordinates for a base case load flow as:

$$\begin{bmatrix}\Delta\delta \\ \Delta V\end{bmatrix} = [S_T]\begin{bmatrix}\Delta P \\ \Delta Q\end{bmatrix} \quad (8)$$

Where, $S_T = [J_T]^{-1}$ is a sensitivity matrix and J_T is the full Jacobean defined for all the buses except for the slack bus.

At a base case load flow, if only one of the bilateral transactions, say the p^{th} transaction, between a seller bus, m and a buyer bus, n is changed by Δt_p, only the following two entries in the mismatch vector $[\Delta P, \Delta Q]^T$ of (8) will be non-zero.

$$\Delta P_m = \Delta t_p, \ \Delta P_n = -\Delta t_p$$

With the above mismatch vector, changes in the voltage angle and voltage magnitude at all the buses can be computed from (8), and hence, a new voltage profile can be calculated. These can be utilized to compute new values of transmission quantity q_l and thus the change in the quantity Δq_l from the base case. Once Δq_l is known for all the lines and change in the voltage magnitude is computed at all the buses corresponding to a transaction Δt_p, the ACPTDFs for each line and buses, respectively, can be obtained from (7).

2) ATC Determination using AC Distribution Factors:

ATC from a bus/zone m to another bus/zone n can be found using the AC load flow by varying the amount of transaction until one or more line flows in the transmission system considered or a bus voltage at some bus reaches the limiting value. However this method is computationally involved. Instead, the distribution factors described above can be used to quickly calculate ATC considering both the line flow limits and voltage limits, as follows.

ATC for base case, between bus/zone m and bus/zone n using the line flow limit criterion has been calculated using ACPTDFs as,

$$ATC_{mn} = \min\left\{\frac{(P_{ij}^{\max} - P_{ij}^{0})}{PTDF_{ij,mn}} ij \in N_l\right\} \quad (9)$$

Where, P_{ij}^{max} is the MW power flow limit of a line between bus-i and bus-j.

P_{ij}^{0} is the base case power flow in the line between bus-i and bus-j.

$PTDF_{ij\text{-}mn}$ is the Power Transfer Distribution Factor for the line between bus-i and bus-j, when N_l is the total no. of lines**.**

IV. MODELLING OF TCSC

Transmission lines are represented by lumped π equivalent parameters. The series compensator TCSC is simply a static capacitor/reactor with impedance jx_c. Figure 1 shows a transmission line incorporating TCSC

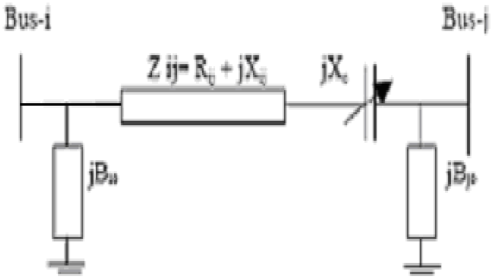

Fig. 1 Equivalent circuit of a line with TCSC

Where X_{ij} is the reactance of the line, R_{ij} *is* the resistance of the line, B_{io} and B_{jo} are the half-line charging susceptance of the line at bus-i and bus-j.

A. Representation of TCSC for power flow

The difference between the line susceptance before and after the addition of TCSC can be expressed as:

$$\Delta y_{ij} = y'_{ij} - y_{ij} = (g'_{ij} + jb'_{ij}) - (g_{ij} + jb_{ij}) \quad (10)$$

$$g_{ij} = \frac{r_{ij}}{\sqrt{r_{ij}^{2} + x_{ij}^{2}}},\ b_{ij} = -\frac{x_{ij}}{\sqrt{r_{ij}^{2} + x_{ij}^{2}}} \quad (11)$$

$$g'_{ij} = \frac{r_{ij}}{\sqrt{r_{ij}^{2} + (x_{ij} + x_c)^2}},\ b'_{ij} = -\frac{x_{ij} + x_c}{\sqrt{r_{ij}^{2} + (x_{ij} + x_c)^2}} \quad (12)$$

After adding TCSC on the line between bus i and bus j of a general power system, the new system admittance matrix Y_{bus}' can be updated as:

$$\mathbf{Y_{bus}' = \ Y_{bus} +} \begin{bmatrix} 0 & 0 & 0 & & 0 & 0 & 0 \\ 0 & \Delta Y_{ij} & 0 & \cdots & 0 & -\Delta Y_{ij} & 0 \\ 0 & 0 & 0 & & 0 & 0 & 0 \\ & \vdots & & \ddots & & \vdots & \\ 0 & 0 & 0 & & 0 & 0 & 0 \\ 0 & -\Delta Y_{ij} & 0 & \cdots & 0 & \Delta Y_{ij} & 0 \\ 0 & 0 & 0 & & 0 & 0 & 0 \end{bmatrix}$$

Because the Y_{bus} has to be updated for each of different locations and the amount of compensation of TCSC, the above formulation is applied in each iteration.

B. Power flow procedure with UPFC

The procedure for the proposed algorithm using TCSC can be summarized as:

Step 1: Read the system line data, bus data and TCSC data

Step 2: Form Y_{bus} using sparsity technique.

Step 3: Modify the Y_{bus} elements with the value of TCSC reactance.

Step 4: Form conventional Jacobean matrix.

Step 5: Use the Jacobean matrix to solve bus voltage until the convergence is achieved. When the mismatch at every bus is less than prescribederror, the power flow converges.

Step 6: Output system voltages and line flows.

V. MODELLING OF UPFC

The unified power flow controller concept was proposed by gyugyi in 1991. the UPFC was devised for the real time control and dynamic compensation of transmission systems, providing multifunctional flexibility required to solve many of the problems facing the power delivery industry. Within the frame work of traditional power transmission concepts, the UPFC is able to control, simultaneously or selectively all the parameters effecting power flow in the transmission line (i.e., voltage, impedance and phase angle), and this unique capability is signified by the adjective unified in its name. Alternatively, it can independently control both real and reactive power flow in the line.

UPFC is considered as a universal tool for power flow control because it has an ability to simultaneously and independently control all the three parameters which affect power flow, i.e., transmission angle, terminal voltage and system reactance. According to its impact on the system it might be modeled as a combination of a series voltage source, an active and a reactive current source.

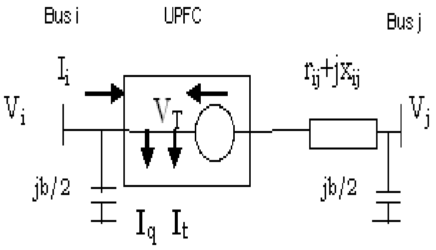

Fig. 2.Power injection model of UPFC

The equivalent circuit of UPFC placed in line k, which is connected between bus-i, and bus-j is shown in Fig. 2. According to its structure, UPFC resemble phase shifting transformers, however, when active and reactive losses are neglected, their apparent power is not balanced. The active power inserted into the system via V_T is balanced by the current source I_T. Here Iq represents a reactive current source and is independent of V_T. The control parameters of the UPFC are the voltage (V_T), current (I_q) and the phase angle (Φ_T). The two voltage source model of the UPFC is converted into two power injections in polar form for power flow studies.

The advantage of power injection representation is that it does not destroy the symmetric characteristics of the admittance matrix.

A. Representation of UPFC for power flow

UPFC modified Jacobean matrix elements In power flow, the two power injections (P_{is},Q_{is}) and (P_{js},Q_{js}) of a UPFC can be treated as generators. However, because they vary with the connected bus bar voltage amplitudes and phases, the relevant elements of the jacobean matrix will be modified at each iteration. The formation of the jacobean matrix is

$$\begin{bmatrix} H & N \\ M & L \end{bmatrix}$$

The following equations are representing the additional elements of the jacobean matrix owing to the injections of the UPFC at the bus bars i and j.

$H_{i,j}$=-2$V_iV_TG_{ij}$ sin(Φ_T-δ_j) + V_jV_T (G_{ij} sin(Φ_T-δ_j)- B_{ij} cos (Φ_T-δ_j)

$H_{j,j}$= V_jV_T(G_{ij}sin(Φ_T-δ_j)+B_{ij}cos(Φ_T-δ_j))

N_{ii}=-2 $V_iV_TG_{ij}$cos(Φ_T-δ_j)

$N_{i,j}$=V_jV_T(G_{ij}cos(Φ_T-δ_j)-B_{ij}sin(Φ_T-δ_j))

$M_{i,i}$= V_iV_T(-G_{ij} cos(Φ_T-δ_i)+(B_{ij}+B/2)sin(Φ_T-δ_i)

$M_{j,j}$=-V_jV_T(-G_{ij} cos(Φ_T-δ_i)+B_{ij}sin(Φ_T-δ_i))

$L_{i,i}$=V_iI_q+V_iV_T(G_{ij}sin(Φ_T-δ_i)+(B_{ij}+B/2)cos(Φ_T-δ_i))

$L_{j,j}$== -V_jV_T(G_{ij} sin(Φ_T-δ_j)+ B_{ij} cos(Φ_T-δ_j))

B. Power flow procedure with UPFC

The procedure for the proposed algorithm can be summarized as:

Step 1: Input data needed by the conventional power flow, form the admittance matrix, input the parameters of the UPFC i.e., V_T , Φ_T and I_q.

Step 2: Form conventional Jacobean matrix; modify the jacobean matrix using UPFC injection elements to become the enhanced jacobean matrix according to the above equations.

Step 3: Use the enhanced jacobean matrix to solve bus Voltage until the convergence of all power injections are achieved. When the mismatch at every bus is less than prescribed error , the power flow converges. Otherwise go to step2.

Step 4: Output system voltages and line flows.

VI. FACTS DEVICES LOCATION

A. Objectives

The objectives for the placement of FACTS devices in the power system may be one of the following:

1. Reduction in the real power loss of a particular line
2. Reduction in the total system real power loss
3. Reduction in the total system reactive power loss
4. Maximum relief of congestion in the system

For the first three objectives, methods based on the sensitivity approach may be used. If the objective of FACTS device placement is to provide maximum relief of congestion, the devices may be placed in the most congested lines or, alternatively, in locations determined by genetic algorithm.

B. Genetic Algorithm

In genetic algorithms, individuals are simplified to a chromosome that codes the control variables of the problem. The strength of an individual is the objective function (fitness) that must be optimized. A random start function might generate the initial population size. After the start, successive populations are generated using the GA iteration process, which contains three basic operators: reproduction, crossover and mutation. Finally, the population stabilizes, because no better individual can be found. When algorithm converges and most of the individuals in the population are almost identical, it represents a sub-optimal solution. A genetic algorithm has three parameters: the population size, crossover rate and mutation rate. These parameters are important to determine the performance of the algorithm. The detailed description can be found in [8].

VII. CASE STUDIES AND RESULTS

The IEEE 24-bus system is adopted as the test system. The ATC has been determined using AC power transfer distribution factors, DC power transfer distribution factors based on the line flow limit. Further ATC values are also determined for all the transactions using repetitive NRLF. ATC for the 24-bus system is determined for ten transactions, which are given in table1. Results obtained from repetitive AC load flow NRLF are also given for comparison. To determine ATC with the repetitive AC load flow, the NRLF was run for each increment of the transaction over its base value until any of the line flows or the bus voltages hit the limiting value. Results obtained from DC load flows are also included in table 1.

TABLE11
ATC VALUES BASED ON THE LINE FLOW LIMIT FOR 24-BUS SYSTEM

S.no	Trans action	ATC from AC distribution factors	ATC from DC distribution factors	NRLF
1	23-15	7.6416	7.8363	7.6
2	10-3	2.9372	3.6876	2.8
3	22-9	4.0696	3.4903	3.4999
4	21-6	1.0437	1.0797	0.9999
5	18-5	2.5686	2.6504	2.4999
6	20-8	0.4614	0.337	0.4
7	19-5	2.5379	2.6076	2.5
8	10-6	0.9539	0.9896	0.9
9	22-5	2.5663	2.6513	2.4998
10	14-8	0.4617	0.3372	0.4

The proposed method has been applied to sample system i.e., IEEE 24- bus system. By placing TCSC and UPFC at appropriate location, more power can be transferred.

TABLE 2
ATC ENHANCEMENT USING TCSC FOR 24- BUS SYSTEM

S.no	Transaction	ATC without TCSC	ATC with TCSC	TCSC location (optimal)
1	22-9	4.0443	4.2010	line-28
2	18-5	2.5589	2.672	line-9
3	19-5	2.5262	2.6387	line-9
4	21-6	1.0398	1.1929	line-10
5	10-6	1.9532	1.5700	line-10

TABLE 3
ATC ENHANCEMENT USING UPFC FOR 24- BUS SYSTEM

S.no	Transaction	ATC without UPFC	ATC with UPFC	UPFC location (Optimal)
1	22-9	4.0474	4.2399	line-28
2	18-5	2.5951	2.999	line-3
3	19-5	2.5647	3.1	line-3
4	21-6	1.8672	2.199	line-10
5	10-6	1.5956	1.9	line-10

Table-2 presents details on the location of the TCSC and the corresponding ATC for IEEE 24 –bus (single area) system. Table-3 presents details on the location of the UPFC and the corresponding ATC for IEEE 24 –bus (single area) system.

The base case ATC values are also shown in the above tables to observe the improvement with the placement of FACTS devices. The results in table– 2 shows that a significant improvement of ATC can be achieved using TCSC. The result in table-3 shows the enhancement of ATC by placing UPFC at optimal locations.

VIII. CONCLUSION

The ATC is computed for different transactions of IEEE 24- bus system using power transfer distribution factor methods. AC and DC power transfer distribution factor (PTDF) methods have been used for ATC determination and the results are compared with the repeated NRLF method.

The distribution factors can be recalculated at a base case operating point and can be utilized for determining ATC values based on line flow. The studies conducted on the two systems reveal that ATC determined using AC power transfer distribution factors method are quite accurate as compared to the DC power transfer distribution factors method and are close to those from AC load flows.

In deregulated power systems, Available Transfer Capability (ATC) analysis is presently a critical issue in the operating or planning because of increased area interchanges among utilities. Flexible AC transmission system devices can be an alternative to reduce the flows in heavily loaded lines, resulting in an increased transfer capability.

FACTS devices can be effectively used to overcome some of the limitations of electric power transfer. The ATC enhancement using TCSC and UPFC has been analyzed for different transactions, and results are compared with and without FACTS devices for the IEEE -24 bus reliability test system. Test results illustrate the effectiveness of the UPFC.

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