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ATC determination with FACTS devices using PTDFs approach for multi-transactions in competitive electricity markets

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ABSTRACT

Available transfer capability (ATC) is an important indicator for accommodating further transactions over and above already existing commitments. With flexible AC transmission system (FACTS) deployment in a system for better utilization, the ATC information quantification is essential. ATC enhancement with these devices can play an important role in an efficient and secure operation of competitive markets. The main objective of the paper is: (i) power transfer distribution factors determination with FACTS devices, (ii) ATC determination for bilateral/multi-lateral transactions based on PTDFs with FACTS devices, (iii) optimal location of FACTS devices based on power flow sensitivity corresponding to transactions, and (iv) comparison of ATC obtained with DC PTDF based approach. The results have been determined for intact and line contingency cases without and with FACTS devices. The proposed method have been tested on IEEE 24 bus RTS.

1. Introduction

One of the key features of competitive electricity market is fair and open transmission access of the network to all users. This may result overloading of transmission system facilities more frequently. The assessment of available transfer capability for the economic utilization of the available system components with regard to system security plays a vital role in both operational planning and real time operation of a system. Therefore, secure and reliable operation of transmission network requires the system operator (SO) to determine and update available transfer capability (ATC) at regular intervals for its optimal commercial use. North American Electrical Reliability Council (NERC) in this regard established a framework for determining ATC of the interconnected transmission networks for a commercially viable wholesale market [1,2].

With the introduction of competition in the power industry all over the world, the electricity supply industries are forced to utilize their network facilities in a more economic and secure manner [3]. Thus, the transfer capability determination of transmission system has emerged as a new measure for secure and reliable operation of a system. With established open access nondiscriminatory transmission services policy under FERC orders 888 and 889, ATC is required to be posted on web to make competition reasonable and effective [4]. The information of ATC will help market elements to reserve transmission services well in advance for optimal commercial use of transmission network. Utilities are therefore required to determine their ATC accurately to ensure secure and reliable operation of a system. ATC has to be continuously updated and posted following changes in the system conditions. There are various sources of uncertainties involved in the ATC calculation that can be attributed to weather conditions, forced and scheduled transmission outages, and generation unavailability [5]. A number of software tools, such as continuation power flow (CPFLOW) [6], transmission and voltage limitation program (TVLIM) [7] and TRACE [8] have been developed for transfer capability calculation. However these methods are time intensive for on line implementation.

For fast computation of ATC, the power flow sensitivity based methods have been proposed by many authors. These methods are based on Power Transfer Distribution Factors/Line Outage Factors (PTDFs), (LODFs) using DC load flow approach. The DC load flow based methods utilizing DC power transfer distribution factors are well reported for ATC computation in [8]. The DC load flow based approaches are fast however are based on DC load flow assumptions. More accurate methods based on AC load flow approach for ATC determination using the sensitivity factors has been reported in [9–14]. Ejebe et al. [9] presented a novel formulation of ATC problem based on full AC power flow solution to incorporate the effects of reactive power flows, voltage limits as well as voltage stability and line flow limits. Many authors utilized sensitivity based methods for computation of ATC [10–13]. Greene et al. [12] presented a computationally efficient formula for the first

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Nomenclature

P_i real power injection at bus-i
Q_i reactive power injection at bus-i
n total no of buses
N_l is the total number of lines in the system
P_{gi}, Q_{gi} real and reactive power generation at bus-i
P_{di}, Q_{di} real and reactive power demand at bus-i
V_i, δi voltage magnitude and voltage angle at bus-i
$Y_{ij} = G_{ij} + B_{ij}$ i–jth element of Y-bus matrix
$|Y_{ij}|$, θ_{ij} magnitude and angle of Y_{bus} elements
Y_{sh} shunt charging admittance of line-ij
P_{ij}, Q_{ij} real power flow and reactive power flow in a line-ij
$P_i^{STATCOM}, Q_i^{STATCOM}$ real and reactive power injection at a particular bus with STATCOM
$P_{ij}^{SSSC}, Q_{ij}^{SSSC}$ real and reactive power injection at a particular bus with SSSC
$P_{ij}^{UPFCC}, Q_{ij}^{UPFC}$ real and reactive power injection at a particular bus with UPFC
V_{sh} and δ_{sh} shunt voltage and angle for STATCOM
V_{se} and δ_{se} series injected voltage and angle for SSSC
V_{sh}, δ_{sh} V_{se}, δ_{se} shunt voltage and angle, Series injected voltage and angle for UPFC
$PTDF_{mn,FACTS}^{ij}$ power transfer distribution factors with FACTS devices for transactions between seller bus m and buyer bus n
$LODF_{rs,FACTS}^{ij}$ line outage distribution factors with rs line outage
$Limit\, t_{ij}^{\max}$ is thermal limit of any line i–j

order sensitivity of the transfer capability with respect to the variations in parameters such as operating conditions, other power transfers, and system data and sensitivities can be used to estimate the effect on the transfer capability of variations in parameters. A fast algorithm to incorporate the effect of reactive power flows based on circle equations and mega-Var corrected megawatt limits for ATC determination was presented in [13]. Authors in [14] proposed AC PTDFs based on AC load flow along with voltage sensitivity factors for ATC determination. Othman [15] presented a new computationally fast and accurate method evaluating ATC based on curve fitting technique so called cubic-spline interpolation technique which traces the curves of voltage magnitude and power flow variations with respect to increase of real power transfer. Li and Liu proposed maximum area concept based sensitivity based method for computation of ATC in bilateral and simultaneous transaction environment [16]. A novel method of contingency ATC computation using ac sensitivity factors and a sensitivity analysis of system uncertainties was proposed in [17]. An approach for determination of TCSC reactance based on PTDFs for ATC enhancement is proposed in [18]. Comprehensive approach for ATC determination in multi-transactions environment using DC PTDF based approach is presented in [19]. However, the method is based on DC load flow assumptions. The approach in [19] is extended with AC power transfer distribution factors for multi-transactions environment and comparison of results are presented with both DC and AC methods [20]. However, the role of FACTS devices in ATC enhancement has not been considered in PTDF based approach. Based on the literature available, it is observed that the power transfer distribution factors based approaches which are proved fast can also be implemented with the incorporation of FACTS devices for ATC computation.

In the competitive environment, electricity supply industries all over the world are operating in a manner to utilize their existing infrastructure in a best possible and efficient way. To utilize the power system in a more secure and efficient manner, the FACTS devices have a great role to play. These devices have been installed in a system world wide for better power transfer capabilities of a system, security enhancement, voltage control, and transient and dynamic stability improvements [21,22]. Thus, there is need in a deregulated electricity market to calculate ATC with FACTS controllers using PTDFs based approach. The FACTS technology provides solutions for increasing transmission system capability [23–27]. Zhang and Handschin [23] presented mathematical models of FACTS controllers such as the STATCOM, SSSC, UPFC, and the latest FACTS devices GUPFC and IPFC using a non-linear optimization problem to determine ATC. Xiao and Song et al. presented an OPF based approach for ATC enhancement using FACTS device [24]. Harinder and Jeyasurya [25] presented the application of third generation FACTS controller, the unified power flow controller to improve the transfer capability of the power system. Farahmand et al. described [26] the repeated power flow for enhancement of ATC with FACTS controllers by Genetic algorithm. Menniti et al. proposed a method to determine Static Synchronous Series Compensator (SSSC) best location that maximizes the power system available transfer capability measured as the maximum system load increase before any operating limit is reached [27]. Some of the authors have proposed fuzzy based contingency constrained OPF and artificial intelligence based approach for ATC determination in [28,29]. Sen transformer has emerged as one of the power flow control devices. An analysis of comparison of UPFC and SEN transformer is presented recently in [30]. However, the authors have utilized optimal power flow based methods for ATC enhancement with FACTS devices. The PTDFs with FACTS devices for ATC determination in multi-transaction market environment can be obtained for ATC determination as sensitivity based methods are proven faster.

In this paper, PTDFs with the incorporation of FACTS devices have been determined for ATC calculations. The location of FACTS devices is decided based on the pattern of variation of PTDFs for each line corresponding to different transactions. The line outage distribution factors have been also been determined without and with FACTS devices. The results have also been obtained for single and multi-transactions between seller and buyer buses. The results have also been obtained using PTDFs based on DC load flow approach for line intact and contingency cases for comparison. The results have been obtained for IEEE RTS 24 bus system [31].

2. Model of FACTS devices

2.1. Static compensator (STATCOM)

For the power flow analysis, STATCOM is represented by a synchronous voltage source with magnitude V_{sh} and angle δ_{sh} with its internal impedance Z_{se} connected at any bus i, shown in Fig. 1. The real and reactive power injection at any bus i of the STATCOM are [22]:

$$P_i^{STATCOM} = V_i^2 G_{sh} + V_i V_{sh}[G_{sh}\cos(\delta_i - \delta_{sh}) + B_{sh}\sin(\delta_i - \delta_{sh})] \quad (1)$$

$$Q_i^{STATCOM} = -V_i^2 B_{sh} + V_i V_{sh}[G_{sh}\sin(\delta_i - \delta_{sh}) - B_{sh}\cos(\delta_i - \delta_{sh})] \quad (2)$$

where

$$1/Z_{sh} = G_{sh} + jB_{sh}$$