

VOLTAGE STABILITY BASED AVAILABLE TRANSFER CAPABILITY ENHANCEMENT IN COMPETITIVE ELECTRICITY MARKET USING UPFC

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ABSTRACT

Voltage instability has been considered as a major threat to power researchers and utilities for more than three decades. In competitive electricity market, a number of generating companies may use same transmission corridor to supply power to consumers. This may reduce Available Transfer Capability (ATC) of transmission network. ATC reduction may lead to shrinkage of nose curve, thus causing the danger of voltage instability. In this paper, determination of ATC has been proposed based on voltage stability criterion for bilateral and multilateral contracts. Placement of Unified Power Flow Controller (UPFC) in optimal location has been suggested for voltage stability based ATC enhancement. Optimal location of UPFC has been found using a sensitivity based approach. Case studies performed on IEEE 14-bus system establish the effectiveness of UPFC placement in voltage stability based ATC enhancement.

KEYWORDS: Voltage Stability, Available Transfer Capability, Loading Margin, Unified Power Flow Controller

INTRODUCTION

Due to increase in power demand, modern power system networks are being operated under highly stressed conditions. This causes difficulty in maintaining bus voltages within acceptable limits. Several incidences of voltage collapse caused by voltage instability has been observed in different parts of the world [1]. In competitive electricity market, a number of independent power producers may use same transmission network to transfer power to consumers. This overloading of line may reduce its Available Transfer Capability (ATC) which may ultimately lead to reduction in maximum loadability, thus creating voltage instability problem. Available Transfer Capability (ATC) is defined as [2]:

$$ATC = TTC - TRM - \{ETC + CBM\} \quad (1)$$

where,

TTC= Total Transfer Capability

TRM=Transmission Reliability Margin

=Existing Transfer Commitments

CBM=Capacity Benefit Margin

A method has been proposed in [3] for determining ATC between any two locations in a transmission system (single-area or multi-area) under a given set of system operating conditions. Many technical challenges including total transfer capability calculation, transient stability constraint handling, transmission capability margins and probabilistic ATC calculation has been proposed in [4]. A novel formulation of the ATC problem based on full AC power flow solution to incorporate the

effects of reactive power flows, voltage limits voltage collapse as well as the traditional line flow (thermal loading) effect has been considered [5]. An application of bifurcation criterion has been proposed for determination of ATC in [6]. In [7], determination of total transfer capability considering line flow limits, bus voltage magnitudes, generated reactive powers, voltage stability and line outages, has been proposed..

Most of the research on ATC determination has mainly concentrated on finding available power of the line for future transactions. Very limited effort seems to be made in determining ATC based on voltage stability criterion. In this paper, a new concept of voltage stability based ATC based on loading margin (distance between the base case operating point and the maximum loadability point) has been proposed. Voltage stability based ATC have been obtained for bilateral and multilateral contracts.

The advent of Flexible AC Transmission System (FACTS) controllers [8] has created new opportunities for increasing power system stability margin including voltage stability margin. Unified Power Flow Controller (UPFC) seems to be most promising FACTS controller due to its ability to control series and shunt variables, simultaneously. However, due to its high cost, and for maximum benefit, it should be placed optimally in the system. In this paper, attempt has been made for optimal placement of UPFC to enhance voltage stability based ATC for bilateral and multilateral transactions. Sensitivity of loading factor with respect to reactive power flowing through lines has been used to decide optimal location for the placement of UPFC. Case studies have been performed on IEEE 14-bus system.

PROPOSED METHODOLOGY FOR ATC DETERMINATION

In this work, loading margin (distance between the base case operating point and the maximum loadability point) of P-V and Q-V curves have been computed, separately, for the system intact case and single line outage cases, for bilateral and multilateral transactions. The loading margin of P-V curve corresponding to most critical contingency (contingency having least loading margin) represents real power that can be safely transferred to load for future transactions without causing voltage instability, and therefore, has been taken as voltage stability based real power ATC. The loading margin of Q-V curve corresponding to most critical contingency (contingency having least loading margin) represents reactive power that can be safely transmitted to load for future transactions without causing voltage instability, and therefore, has been considered as voltage stability based reactive power ATC of the system.

Voltage stability based real power ATC and reactive power ATC have been computed for bilateral as well as multilateral contracts. For obtaining P-V and Q-V curves, real power generations have been varied at seller buses (except at slack bus), and real and reactive power demands have been varied at buyer buses as per followings:

$$PG_i = PG_{ib} (1 + \lambda) \quad (2)$$

where,

PG_i = Real power generation at seller bus-i

PG_{ib} = Real power generation at seller bus-i at the base case operating point.

λ = Loading factor

$$PD_i = PD_{ib} (1 + \lambda) \quad (3)$$

where,

PD_i = Real power demand at buyer bus-i

PD_{ib} = Real power demand at buyer bus-i at the base case operating point

$$QD_i = QD_{ib}(1 + \lambda) \quad (4)$$

where,

QD_i =Reactive power demand at buyer bus-i

QD_{ib} = Reactive power demand at buyer bus-i at the base case operating point

UPFC MODEL

In the present work, UPFC has been represented by steady-state injection model [9]. The UPFC consists of two switching converters operated from a common DC link, as shown in figure-1. In this figure, Converter 2 performs the main function of the UPFC by injecting an AC voltage with controllable magnitude and phase angle in series with the transmission line. The basic function of Converter 1 is to supply or absorb the active power demanded by Converter 2 at the common DC link. This is represented by the current, I_p . Converter 1 can also generate or absorb controllable reactive power and provide independent shunt reactive compensation for the line. This is represented by the current, I_q .

The UPFC circuit arrangement has been shown in figure 2. The series converter is represented by an AC voltage source in series with a reactance X_s , as shown in figure 2.

The series voltage source \bar{V}_s is controllable in magnitude and phase i.e:

$$\bar{V}_s = r \bar{V}_i e^{j\gamma} \quad (5)$$

where, $0 < r < r_{\max}$ and $0 < \gamma < 2\pi$

The steady-state injection model of UPFC has been derived from figure 2 [9] and has been shown in figure 3. In figure 3, UPFC has been represented as controllable loads connected at the two ends of the line.

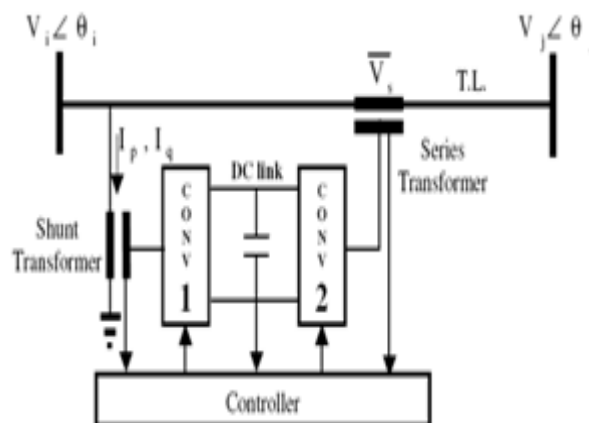


Figure 1: UPFC Schematic Diagram

Φ_i = power factor angle of the increased load at i^{th} bus

$V_i \angle \delta_i$ = Complex voltage at bus i

$Y_{ij} \angle \theta_{ij} = G_{ij} + jB_{ij}$ = ij th element of the bus admittance matrix

n = Total number of the buses in the system

Differentiating equation (6) with respect to Q_{ik} provides the expression for the sensitivity factor,

$$\frac{\partial \lambda}{\partial Q_{ik}} = Y^{-1} [Z^{-1} (1 - X) - 1] \quad (7)$$

where,

$$X = \sum_{\substack{j=1 \\ \neq k}}^n \left\{ \begin{array}{l} \left[V_i \frac{\partial V_j}{\partial Q_{G_i}} + V_j \frac{\partial V_i}{\partial Q_{G_i}} \right] Y_{ij} \sin(\delta_i - \delta_j - \theta_{ij}) \\ + V_i V_j Y_{ij} \cos(\delta_i - \delta_j - \theta_{ij}) \left[\frac{\partial \delta_i}{\partial Q_{G_i}} - \frac{\partial \delta_j}{\partial Q_{G_i}} \right] \end{array} \right\} \quad (8)$$

$$Y = K_{Di} S_{\Delta base} \sin \phi_i \quad (9)$$

$$Z = \frac{\partial Q_{ik}}{\partial Q_{G_i}} = \left[V_i \frac{\partial V_k}{\partial Q_{G_i}} + V_k \frac{\partial V_i}{\partial Q_{G_i}} \right] Y_{ik} \sin(\delta_i - \delta_j - \theta_{ij}) \\ + V_i V_j Y_{ik} \cos(\delta_i - \delta_j - \theta_{ik}) \left[\frac{\partial \delta_i}{\partial Q_{G_i}} - \frac{\partial \delta_k}{\partial Q_{G_i}} \right] \quad (10)$$

The sensitivity factor $\frac{\partial \lambda}{\partial Q_{ik}}$, which relates changes in loading factor with respect to change in reactive power

flowing from bus- i to bus- k , can be computed using (7) for the most critical contingency for bilateral and multilateral

transaction cases. Each line is having two such sensitivity values ($\frac{\partial \lambda}{\partial Q_{ik}}$ and $\frac{\partial \lambda}{\partial Q_{ki}}$). Based on maximum absolute value of

sensitivity factors computed under most critical contingency for bilateral and multilateral transactions, priority lines for the

placement of UPFC have been determined. Depending upon magnitude of $\frac{\partial \lambda}{\partial Q_{ik}}$ and $\frac{\partial \lambda}{\partial Q_{ki}}$ corresponding to priority lines,

bus- i or bus- k can be considered as priority buses. The real power ATC (the distance between the base case operating point

and the maximum loadability point of P-V curve under most critical contingency) and the reactive power ATC

(the distance between the base case operating point and the maximum loadability point of Q-V curve) can be computed

after UPFC placement at each of the priority locations. The combination of priority line and priority bus producing

maximum enhancement in real power ATC and reactive power ATC for majority of transactions has been selected as the

optimal site for UPFC placement.

CASE STUDIES

Proposed approach of voltage stability based ATC determination and its enhancement using UPFC has been tested

on an IEEE 14-bus system [11]. IEEE 14-bus system has two generators (at buses 1 & 2), three synchronous condensers (at buses 3, 6 & 8) and 20 transmission lines (including 3 transformers).

In order to calculate ATC of the system under bilateral and multilateral contracts, bilateral transaction was considered between seller bus-2 and buyer bus-13, whereas, multilateral transaction was considered between group of seller buses 1,2 and group of buyer buses 9,13. P-V and Q-V curves of buyer buses were plotted for the system intact case and all the single line outage cases under bilateral and multilateral transactions. For obtaining P-V and Q-V curves of buyer buses, starting from the base case operating point, loading factor (λ) was gradually increased in the steps of 0.01, until load flow diverged. Loading factor was increased in the steps of 0.001 near the point of divergence to get more accurate estimate of the loading margins. For obtaining P-V curve of buyer buses, Real power generation were varied at seller buses (except at the slack bus) as per (2), whereas, real power demands were varied at buyer buses as per (3), keeping all other generations and demands constants. For obtaining Q-V curve of buyer buses, reactive power demands were varied at buyer buses as per (4), reactive power generation of seller buses at each of loading factor were obtained from load flow results, all other loads and generations were considered constant while running load flow at different loading factors.

Real power loading margins (the distance between the base case operating point and the maximum loadability point of the P-V curve) and reactive power loading margins (the distance between the base case operating point and the maximum loadability point of Q-V curve) were computed from P-V curves and Q-V curves, respectively, for the system intact case and all the single line outage cases under bilateral and multilateral transactions. Real and reactive power loading margins under bilateral and multilateral transactions, for the system intact case and ten critical line outage cases, have been shown in Table-I. It is observed from Table-I that outage of line 5-6 results in lowest value of real power loading margin (63.26 MW) as well as lowest value of reactive power loading margin (32.20 MVAR) for bilateral transaction between seller bus-2 and buyer bus-13. It is also observed from Table-I that outage of same line 5-6 results in lowest value of real power loading margin (66.87 MW) as well as lowest value of reactive power loading margin (36.17 MVAR) for multilateral transaction between group of seller buses 1,2 and group of buyer buses 9,13. Therefore, voltage stability based real power ATC for bilateral transaction was considered as 63.26 MW. Voltage stability based real power ATC for multilateral transaction was considered as 66.87 MW. Voltage stability based reactive power ATC for bilateral transaction was considered as 32.20 MVAR. Voltage stability based reactive power ATC for multilateral transaction was considered as 36.17 MVAR.

In order to find optimal location for the placement of UPFC to enhance voltage stability based ATC, sensitivity of loading factor with respect to reactive power flowing through lines, were calculated under outage of line 5-6, for bilateral and multilateral transaction cases. Absolute value of sensitivity factor for two most priority lines have been shown in Table 2 for bilateral and multilateral transactions. It is observed from Table-II that line 8-7 (towards bus-7) and line 4-9 (towards bus-9) are two most sensitive lines for bilateral as well as multilateral transactions.

Voltage stability based real power ATC (real power loading margin of P-V curve under outage of line 5-6) and voltage stability based reactive power ATC (reactive power loading margin of Q-V curve under outage of line 5-6) were computed for bilateral and multilateral transaction cases, after UPFC placement in each of the two priority locations (i.e. in line 8-7, towards bus-7, and in line 4-9, towards bus-9). Voltage stability based real and reactive power ATC without UPFC in the system, with UPFC placed in line 8-7 (towards bus-7) and with UPFC placed in line 4-9 (towards bus-9), have been shown in Table 3. It is observed from Table-III that UPFC placement in line 8-7 (towards bus-7) causes

maximum enhancement in voltage stability based real power as well as reactive power ATC for bilateral transaction, whereas, UPFC placement in line 4-9 (towards bus-9) results in maximum enhancement in voltage stability based real as well as reactive power ATC for multilateral transaction. However, UPFC placement in line 8-7 (towards bus-7) is also very effective in voltage stability based real power as well as reactive power ATC enhancement in case of multilateral transaction. Therefore, line 8-7 (towards bus-7) has been selected as the optimal location for the placement of UPFC in this work, to enhance voltage stability based ATC for the considered transactions in IEEE 14-bus system.

Table 1: Real and Reactive Power Loading Margins under Bilateral and Multilateral Transactions (IEEE 14-Bus System)

Line outage	Bilateral Transaction		Multilateral Transaction	
	Real Power Loading Margin (MW)	Reactive Power Loading Margin (MVAR)	Real Power Loading Margin (MW)	Reactive Power Loading Margin (MVAR)
Intact	211.04	110.29	168.66	91.22
5-6	63.26*	32.20**	66.87***	36.17****
1-2	127.76	66.89	97.72	51.80
7-9	151.99	79.04	83.32	45.06
4-7	168.73	83.48	101.91	55.12
2-4	172.49	90.14	160.70	52.04
2-5	173.66	90.76	140.31	75.88
2-3	177.89	92.96	139.12	75.24
1-5	185.67	97.03	142.38	77.00
4-5	211.11	110.32	159.63	86.33
3-4	203.04	106.11	166.46	90.03

* Voltage stability based real power ATC for bilateral transaction between seller bus 2 and buyer bus 13

** Voltage stability based reactive power ATC for bilateral transaction between seller bus2 & buyer bus13

*** Voltage stability based real power ATC for multilateral transaction between group of seller buses 1,2 and group of buyer buses 9,13

**** Voltage stability based reactive power ATC for multilateral transaction between group of seller buses 1,2 and group of buyer buses 9,13

Table 2: Absolute Value of $\frac{\partial \lambda}{\partial Q_{ik}}$ for Two Most Sensitive Lines for Bilateral and Multilateral Transactions under Outage of Line 5-6 (IEEE 14-Bus System)

Transaction	Line (towards bus)	$\frac{\partial \lambda}{\partial Q_{ik}}$	Line (towards bus)	$\frac{\partial \lambda}{\partial Q_{ik}}$
Bilateral	8-7 (7)	294.63	4-9 (9)	179.78
Multilateral	8-7 (7)	483.61	4-9 (9)	188.57

Table 3: Voltage Stability Based Real and Reactive Power ATC with and without UPFC, for Bilateral and Multilateral Transactions (IEEE 14-Bus System)

	Voltage Stability Based Real Power ATC		Voltage Stability Based Reactive Power ATC	
	Bilateral Transaction	Multilateral Transaction	Bilateral Transaction	Multilateral Transaction
Without UPFC	63.26	66.87	32.20	36.17
With UPFC in line 8-7 (towards bus-7)	79.20	108.87	41.39	60.70
With UPFC in line 4-9 (towards bus-9)	96.69	104.46	50.53	56.50

CONCLUSIONS

An approach for determination of ATC based on voltage stability criterion has been suggested in this paper. The real power loading margin computed from P-V curve under most critical contingency has been taken as voltage stability based real power ATC. The reactive power loading margin computed from Q-V curve under most critical contingency has been taken as voltage stability based reactive power ATC. Voltage stability based real and reactive power ATC have been computed for bilateral and multilateral transactions. A sensitivity based approach has been proposed for optimal placement of UPFC to enhance voltage stability based real and reactive power ATC under bilateral and multilateral transactions. Case studies performed on IEEE 14-bus system show that proposed approach of optimal placement of UPFC is quite effective in voltage stability based ATC enhancement in competitive electricity market.

REFERENCES

1. P. Kundur, "*Power System Stability and Control*", Mc Graw Hill, New York, 1994.
2. North American Electric Reliability Council (NERC), "*Available Transfer Capability Definitions and Determination*", NERC Report, June 1996.
3. G. Hamoud, "Assessment of Available Transfer Capability of Transmission Systems", *IEEE Transactions on Power Systems*, Vol. 15, No. 1, pp. 27-32, February 2000.
4. Xuemin Zhang, Y. H. Song, Qiang Lu and Shengwei Mei, "Dynamic Available Transfer Capability (ATC) Evaluation by Dynamic Constrained Optimization", *IEEE Transactions on Power Systems*, Vol. 19, No. 2, May 2004.
5. G. C. Ejebe, J. Tong, J. G. Waight, J. G. Frame, X. Wang, W. F. Tinney, "Available Transfer Capability Calculations", *IEEE Transactions on Power Systems*, Vol. 13, No. 4, pp. 1521-1527, November 1998.
6. Ashwani Kumar, S. C. Srivastava and S. N. Singh, "Available Transfer Capability Assessment in a Competitive Electricity Market Using a Bifurcation Approach", *IEE Proc.-Generation Transmission Distribution*, Vol. 151, No. 2, pp. 133-140, March 2004.
7. Liang Min and Ali Abur, "Total Transfer Capability Computation for Multi-Area Power Systems", *IEEE Transactions on Power Systems*, Vol. 21, No. 3, pp. 1141-1147, August 2006.
8. N G. Hingorani, and L. Gyugyi, "*Understanding FACTS: Concepts and Technology of Flexible AC Transmission Systems*", IEEE Press, New- York, 2000.
9. M. Noroozian, L. Anguist, M. Ghandhari and G. Andersson, "Use of UPFC for optimal power flow control", *IEEE Transactions on Power Delivery*, Vol. 12, No. 4, pp. 1629-1634, October 1997.
10. Sreekanth Reddy Donapati and M. K. Verma, "An Approach for Optimal Placement of UPFC to Enhance Voltage Stability Margin Under Contingencies", *Proc. of the 15th National Power System Conference*, Paper No.230, I.I.T. Bombay, India, December 16-18, 2008.
11. "Power systems test case archive" available at http://www.ee.washington.edu/research/pstca/pf14/pg_tca14bus.htm