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Available Transfer Capability Calculation with Transfer based Static Security -Constrained Optimal Power Flow

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Abstract -In power market environment, available transfer capability (ATC) is an important index, indicating the amount of the further usable transmission capacity for commercial trading. ATC calculation is non-trivial when static security constraints are included. In this paper, a novel formulation of the ATC problem has been adopted based on Transfer based Static Security-Constrained Optimal Power Flow (TSSCOPF) solution to incorporate the effects of voltage limits as well as the traditional line flow (thermal loading) effects. This method, calculates ATC problem with static security constraints into a base case master problem and a series of sub problems relevant to various contingencies. The mathematic model is formulated and an improved solution algorithm is presented. Computer testing results on the IEEE 30-bus system show clearly the effectiveness of the proposed method and solution algorithm.

KEYWORDS*:* power market, available transfer capability (ATC), Power System, Static Stability, Optimal Power Flow.

1 Introduction

In recent years, electric power systems are experiencing an epochal revolution due to an increasingly competitive market. Nowadays, more than before, security problems such as overloads, unacceptable transient voltage dips and system instability can occur. In this new business environment it is more and more important for the system operator to know how additional power can be safely transferred across the system. In many power systems, the maximum power transfer across critical corridors or interfaces is limited by stability considerations [1]. If the transfer level increases too much, instability may occur for certain disturbances. A good knowledge of these stability constraints is very important to operate the system close to its stability limits avoiding vulnerable states [2].

These aspects have motivated the development of methodologies to evaluate existing power transfer capabilities and transmission margins with consider of the physical and operational limitations of the transmission system, such as circuit ratings and bus voltage levels. Also, as power systems become more heavily loaded, voltage collapse phenomena are more likely to occur, especially in systems with long-distance lines [3]. Therefore, there is a need for an OPF-based algorithm, which introduces a form of static stability constraints, to computing ATC. This paper presents a new method for computation of ATC that uses the OPF technique solved by evolutionary programming algorithm, which can handle non-smooth fuel cost function of generating units. The technique introduces a form of stability constraint of voltage magnitude and power flow variations with respect to the increase of real power transfer. The transfer capability of the system is analyzed under two different sets of transfer, which are area-to-area ATC and point-to-point ATC. Area to-area ATC is the additional amount of power that is transferred from the seller area to the buyer area. On the other hand, point-to-point ATC is the additional amount of power that is transferred from the seller bus to the buyer bus. ATC is also analyzed and quantified by considering the effect of contingencies, such as line outages. Considering outages of all lines for a large-scale interconnected power system is impractical and, therefore, contingency ranking is used to select the critical lines that may adversely affect the ATC during outages. The accuracy and effectiveness of the ATC method using the Transfer based Security-Constrained Optimal Power Flow (TSSCOPF) technique is verified on the IEEE 30-bus test system.

2. TTC Formulation and Comparison of Methods

2.1 Currently Used TTC Determination Methods

The popularly used methods to calculate TTC can be categorized into the following three types:
1) Continuation power flow (CPF) methods[4];
2) Repeated power flow (RPF) methods;
3) Transfer based security constrained optimal power flow (OPF) methods[5].

Both OPF and RPF enable transfers by increasing the complex load with uniform power factor at every load bus in the sink area and increasing the injected real power at generator buses in the source area in incremental steps until limits are incurred. The mathematical formulation of TTC using OPF and RPF can be expressed as follows:

Maximize λ
Subject to

$$P_{Gi} - P_{Di} - \sum_{j=1}^{n} |U_i||U_j| (G_{ij} \cos\delta_{ij} - B_{ij} \sin\delta_{ij}) = 0 \quad (1)$$

$$Q_{Gi} - Q_{Di} - \sum_{j=1}^{n} |U_i||U_j| (G_{ij} \sin\delta_{ij} - B_{ij} \cos\delta_{ij}) = 0 \quad (2)$$

$$|U_i|_{\min} \le |U_i| \le |U_i|_{\max} \quad (3)$$

$$S_{ij} \le S_{ij\max} \quad (4)$$

Where

λ: scalar parameter representing the increase in bus load or generation. $\lambda =$ 0 corresponds to no transfer (base case) and $\lambda = \lambda_{\max}$ corresponds to the maximal transfer;

P_{Gi}, Q_{Gi} :real and reactive power generation at bus i ;

P_{Di}, Q_{Di} :real and reactive load demand at bus i

n : bus number of the system;

$|U_i|$, $|U_j|$:voltage magnitude at bus i, j ;

$G_{ij} B_{ij}$:real and imaginary part of the ij 'th element of bus admittance matrix;

δ_{ij} : voltage angle difference between bus i and bus j ;

$|U_i|_{\min}$, $|U_i|_{\max}$: lower and upper limits of voltage magnitude at bus i ;

S_{ij} : apparent power flow in line ij ;

$S_{ij\max}$: thermal limit of line ij .

In the above power flow equations (1) and (2), P_{Gi} (generator real output in source area), P_{Di} (real load in sink area), and Q_{Di} (reactive load in sink area) are changed in the following way [2]:

$$P_{Gi} = P_{Gi}^0 (1 + \lambda k_{Gi}) \quad (5)$$

$$P_{Di} = P_{Di}^0 (1 + \lambda k_{Di}) \quad (6)$$

$$Q_{Di} = Q_{Di}^0 (1 + \lambda k_{Di}) \quad (7)$$

Where:

P_{Gi}^0 : original real power generation at bus which is in source area;

P_{Di}^0 , Q_{Di}^0 : original real and reactive load demand at bus which is in sink area;

k_{Gi} , k_{Di} : constants used to specify the change rate in generation and load as λ varies.

TTC level in each case (normal or contingency case) is calculated
as follows:

$$TTC = \sum_{i \in Sink} P_{Di}(\lambda_{\max}) - \sum_{i \in Sink} P_{Di}^0 \quad (8)$$

Where

$\sum_{i \in Sink} P_{Di}(\lambda_{\max})$ sum of load at sink area when $\lambda = \lambda_{\max}$;

$\sum_{i \in Sink} P_{Di}^0$ sum of load at sink area when $\lambda = 0$.

The RPF repeatedly solves conventional power flow equations at a succession of points along the specified transfer directions while CPF solves a set of augmented power flow equations to obtain the solution curve passing through the "nose" point without encountering the numerical difficulty of ill conditioning. There are detailed descriptions about CPF in [6], [7], and [8]. The advantage of CPF is that it will not encounter the numerical difficulty of ill conditioning so that it can get complete –and – curve to calculate voltage stability margins while its disadvantage is that the implementation of CPF involves parameterization, predictor, corrector and step-size control, which are complicated. OPF possesses several advantages. Compared to any RPF method OPF can provide – and – curves for voltage stability study. Adjustment method of control variables in OPF is relatively easier. Compared to CPF The implementation method is much easier and time to convergence is reduced.

2.2 Proposed TTC Determination Method

To overcome the deficiency of the continuation power flow (CPF) and repeated power flow (RPF) methods, a Transfer-Based Static Security-Constrained Optimal Power Flow (TSSCOPF) is proposed in this paper. It assumes that only all

OPF-optimized parameters involving the selected source and sink area can be dispatched, which can be satisfied in decentralized structure. The formulation of TSSCOPF is shown in the Appendix. TSSCOPF is a good method to use in the future application since OPF adjusts the real power output at the source area, the real and reactive load at the sink area in a fixed incremental step while TSSCOPF can adjust those variables in any way. OPF is utilized to determinate TTC in this paper because it is perhaps the most significant technique for obtaining minimum cost generation patterns in a power system with existing transmission and operational constraints. In order to give a complete description of methods to determinate TTC, TSSCOPF is presented in the Appendix and can be used for decentralized application.

3. General Procedure to Determine of TTC

The general procedure to determine TTC (considering TRM) is as follows.

1) Select a case (normal or any contingency case from contingency list).

2) Simulate load level by a normal distribution.

3) Establish and solve the base case power flow (no transfer, $\lambda=0$). If there is no limit violation, go to Step 4). Otherwise, set TTC level for the selected case at that load level
as zero. Return to Step 2) to simulate another load level.

4) Use RPF to make a step increase in transfer power (λ increased by $\Delta\lambda$).

5) Establish and solve the power flow problem.

6) Check the solution to Step 5) whether any limit is violated. If no limit is violated, go to Step 4). If there is any violation, decrease the transfer power by the minimum amount necessary to eliminate the violation and then go to Step 7). The minimum amount is determined by decreasing by 10% of each time and then going to Step 5) until the violation is gone.

7) Compute the TTC level at the maximal. This is the TTC level for the selected case at that load level. Return to Step 2) to simulate another load level until a convergence criterion of the TTC level for the selected case is reached. Then go to Step 8).

8) Return to Step 1) to select the next case. If all cases have been selected, go to Step 9).

9) Compute the TTC for this source/sink transfer case. ATC is the minimal value of all the TTC levels.

When TRM is not considered, ignore Step 2) and after computing TTC level at Step 3) or Step 7), go to Step 8) directly.

4. Case Studies and Results

4.1. Test System

The IEEE 30 bus Reliability Test System (RTS) is used in this paper to demonstrate the proposed methods. The diagram of the RTS system is shown in Fig. 1. In order to study ATC, the RTS system is divided into three areas, which are shown in Table 1 and Fig. 1. Tie lines between areas are listed in Table 2. In this study, the respect voltage violation of each bus is assumed to be ± 0.06p.u. The MVA power flow or the thermal ratings of the line limits are for both contingency and base case conditions.

4.2. Test Results and Discussion

Prior to the ATC calculation, contingency ranking is performed on the 6 lines in the system in which after contingency selection, 3 lines have been identified as critical lines [9]. In this study, these three critical lines which are connected from bus 4 to bus 12 and from bus 9 to bus 10 and from bus 10 to bus 20 are selected as the test case in the determination of the area-to-area and the point-to-point ATC. The ATC is then determined by referring to the maximum power transfer that cause the limiting levels of MVA power flow or voltage magnitude, respectively. The outage of critical line in the transfer capability analysis is considered because it will give a huge impact to the ATC result. The shaded area in Table 3 (3-1, 3-2, 3-3, 3-4, 3-5), shows this critical tie lines. Using the proposed ATC method, the results of the area-to-area ATC and the point-to-point ATC are obtained as shown in Tables 3 (3-1, 3-3, 3-4, 3-5) and 4, respectively. Results shown in Tables 3 and 4 indicate that the limitation occurs for all the cases of power transfer are due to over voltage limits. For instance, from the area-to-area ATC results shown in Table 3-1, by considering an outage tie line 4-12 as a contingency, the ATC from areas 1 to 2 is 150.88 MW and it is limited by the over voltage on bus 16. Similarly, from the point-to-point ATC results shown in Table 4, by considering an out aged tie line 27–28 as a contingency, the ATC between buses 2 and 23 is 53.019MWand it is limited by over voltage on bus 11. The ATC results shown in Tables 3 and 4 prove that the proposed ATC calculation method indicate the effects of voltage limits as well as the contingency and line outages effects on evaluating ATC. In this paper, ATC evaluated by considering of the critical line outages that adversely affect the transfer capability of a power transmission system.

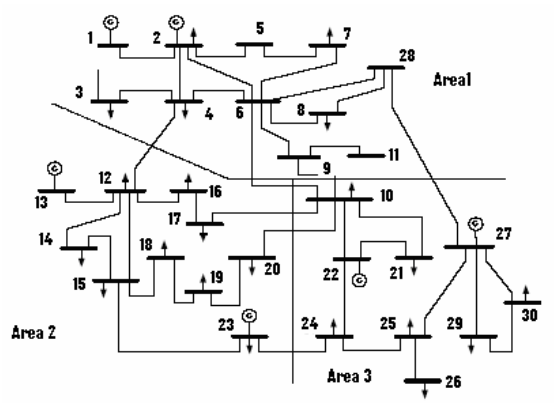

Fig. 1. IEEE 30 bus RTS system.

5. Conclusion

This paper, proposes a new approach for steady-state ATC calculation. This method take into account system limitations such as bus voltage and transmission current limits, for evaluating area-to-area and point-to-point ATC, using the static security constrained optimal power flow method (SSCOPF). In the proposed ATC method, prior to ATC evaluation the critical line outages that adversely affect the transfer capability of a power transmission system are obtained through the process of contingency ranking and selection. The effectiveness of the proposed method is verified by simulation studies on the IEEE 30-bus system.

6 References

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Table 1: Three Areas in RTS

Area	Bus	Gen. Capacity (MW)	Load(MW)	Margin(MW)
1	1,2,3,4,5,6,7,8,9,11,28	500	196.6	303.4
2	12,13,14,15,16,17,18,19,20,23	200	56.2	143.8
3	10,21,22,24,25,26,27,29,30	200	48.5	151.5

Table 2: Tie Lines between Areas

Area	Tie Lines
Area 1 to area 2	Line 2-4
Area 1 to area 3	Line 28-27,9-10,6-10
Area 2 to area 3	Line 10-20,23-24,10-17

Table 3-1: TTC Levels and ATC Values from Area 1 to Area 2

Case	TTC(MW)	Limiting Bus	ATC(MW)
Normal	150.88	16	76.691
Tie Line 4-12 outage	76.691	11	

Table 3-2: TTC Levels and ATC Values from Area 2 to Area 1

Case	TTC(MW)	Limiting Bus	ATC(MW)
Normal	32.82	12	32.82
Tie Line 4-12 outage	32.82	15	

Table 3-3: TTC Levels and ATC Values from Area 1 to Area 3

Case	TTC(MW)	Limiting Bus	ATC(MW)
Normal	104	12	99.5537
Tie Line 28-27 outage	99.5537	11	
Tie Line 9-10 outage	104	13	
Tie Line 6-10 outage	104	13	

Table 3-4: TTC Levels and ATC Values from Area 3 to Area 1

Case	TTC(MW)	Limiting Bus	ATC(MW)
Normal	51.86	12	25.32
Tie Line 28-27 outage	25.32	30	
Tie Line 9-10 outage	51.86	13	
Tie Line 6-10 outage	51.86	12	

Table 3-5: TTC Levels and ATC Values from Area 2 to Area 3

Case	TTC(MW)	Limiting Bus	ATC(MW)
Normal	32.82	12	16.718
Tie Line 10-20 outage	16.718	19	
Tie Line 23-24 outage	32.82	12	
Tie Line 10-17 outage	32.82	17	

Table 3-6: TTC Levels and ATC Values from Area 3 to Area 2

Case	TTC(MW)	Limiting Bus	ATC(MW)
Normal	51.86	12	51.86
Tie Line 10-20 outage	51.86	20	
Tie Line 23-24 outage	51.86	12	
Tie Line 10-17 outage	51.86	16	

Table 4: Results of Point-to-Point ATC

POINT OF TRANSFER		LINE OUTAGES	LIMITATION BUS	ATC(MW)
SELLER BUS	BUYERBUS			
2	23	4-12	20	70
2	27	28-27	11	53.019
22	23	10-17	17	48
22	27	22-21	21	48
13	23	15-23	13	24.56
13	27	23-24	12	24.56

Appendix

The mathematical formulation of TSCOPF can be represented as follows: Maximize

$$f\left(P_{Gi\,(i\in Source)}, P_{Dj\,(j\in Sink)}, Q_{Dj\,(j\in Sink)}\right) = \sum_{i\in Sink} P_{Di} - \sum_{i\in Sink} P_{Di}^{0}$$

Subject to:

$$P_{Gi} - P_{Di} - \sum_{j=1}^{n} |U_i||U_j|\left(G_{ij}\cos\delta_{ij} - B_{ij}\sin\delta_{ij}\right) = 0 \quad (9)$$

$$Q_{Gi} - Q_{Di} - \sum_{j=1}^{n} |U_i||U_j|\left(G_{ij}\sin\delta_{ij} - B_{ij}\cos\delta_{ij}\right) = 0 \quad (10)$$

$$P_{Gi}^{0} \le P_{Gi} \qquad i \in Source \quad (11)$$

$$P_{Di}^{0} \le P_{Di} \;\; Q_{Di}^{0} \le Q_{Di} \qquad i \in Sink \quad (12)$$

$$P_{Di} / P_{Di}^{0} = Q_{Di} / Q_{Di}^{0} \quad (13)$$

$$|U_i|_{\min} \le |U_i| \le |U_i|_{\max} \quad (14)$$

$$S_{ij} \le S_{ij\,\max} \quad (15)$$

The real power output of generators in source area and real/reactive load in sink area can be adjusted in order to get maximum transfer capability. And the complex load is adjusted with constant power factor.