Considerations in Calculating Total Transfer Capability

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Abstract

The computation of total transfer capability (TTC) is a significant task in the new power system deregulated environment. In this paper, assumptions and considerations used throughout the study are indicated first, a framework for TTC calculation is then presented. A 4-bus test power system is used to demonstrate TTC calculation followed by further discussion.

1. Introduction

The move towards open electricity markets is gaining a lot of interest in different places around the world. Some of it is motivated by the desire of dedicated governments to deregulate its municipal utilities as a part of the direction towards new privatized economy [1, 2]. While others are seeking competitive prices, improved services, and better utilization of system capabilities [3]. The currently envisioned restructuring policy tends to divide the vertically integrated utilities into generation, transmission and distribution entities which are coordinated by the system operator. This regulated operator body would keep the integrity and reliability of the network by coordinating with the associated entities. However this new environment is likely to bring more problems in terms of operability, security, and stability [4].

The U.S. electricity industry has recently experienced drastic restructuring procedures. The Federal Energy Regulatory Commission (FERC) has mandated, through orders 888/889, the nondiscriminatory access of the transmission facilities to wholesalers. To ensure a level playing field for all, FERC required that all parties have access to the same transmission information provided by the so called Open Access Same Time Information system (OASIS) network. The OASIS should display extensive information about current operating conditions, scheduled transactions, ancillary services, announces, and Available Transfer Capability (ATC) information [5]. ATC information is necessary to all players of the power market. It is defined as the measure of the transfer capability remaining in the physical transmission network for further commercial activity above already committed uses [6,7]. ATC must accurately reflect the physical realities of the transmission network, all system conditions, uses, and limits in a consistent manner while not being complicated that it unduly constrains commerce. ATC determination depends on other parameters namely TTC, TRM, and CBM. Total Transfer Capability (TTC) is defined as the amount of electric power that can be transferred over the interconnected transmission network in a reliable manner while meeting all of a specific set of defined pre-and post-contingency system conditions. Transmission Reliability Margin (TRM) is 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) 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 mathematically is defined as TTC less TRM, less the sum of existing transmission commitments and the CBM.

TTC from a source to a sink represents the maximum transfer power from the source bus to the sink bus with security constraints. It is time variable and dependent upon various conditions such as the corresponding operating conditions, system control capability and the contingencies used for TTC evaluation etc.

Usually TTC will be constrained by the following:

- Thermal limits (branch MVA, loading limits)
- Voltage limits (voltage magnitude limits)
- Stability limits (voltage stability limits, transient angle stability limit and dynamic angle stability limit)

The limiting condition of the transmission network can shift among thermal, voltage, and stability limits as the network operating conditions change over time. Such variations make the determination of TTC a non-trivial task. Moreover the generator real and reactive power limits should be considered in TTC calculation as well.

This paper first outlines considerations, main conditions and assumptions used in TTC calculations. The framework

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for TTC evaluation is then presented. A 4-bus sample system is used to illustrate the overall scenario. Further discussions are made at the end of the paper.

2. Considerations and assumptions in TTC Calculation

- Depending upon the power market requirements, TTC might be calculated hourly, daily, or monthly. An accurate load forecast is very important for correct TTC calculation. Some effects such as unit commitment, maintenance, etc might be necessary to consider. Therefore it is very difficult to calculate TTC far from now in a large scale power system. In this paper, only current system operation condition is used for demonstrating TTC calculation. Here we assume system state estimation result is available and the operation point is stable and secure.

- Some assumptions are made in the paper for simplifying TTC calculation. They are:

  -- The system is properly controlled and can provide enough damping so there is no Hopf bifurcation in system dynamics.

  --The system has sufficiently large transient stability margin; hence it can survive the transient period and shift to a new steady state.

  Then the only stability constraint is voltage collapse at a saddle node bifurcation point that can be solved for via continuation load flow. The TTC calculation will be in the steady state analysis domain.

- System contingency list that represents the most severe disturbances to be considered should be developed for TTC evaluation. Here we assume it is already available and is composed of single line outage contingencies only.

- Based on the assumptions made above, the TTC calculation method in this paper will be the conventional load flow if system is not in ill condition and the continuation load flow if in ill-condition. The TTC limit will be determined by thermal constraints, voltage constraints and voltage stability constraints.

- System control, e.g. the voltage regulation and reactive power control etc., can have strong effects on TTC. Here we assume these effects can be neglected. Otherwise an optimal power flow should be used to evaluate TTC.

3. TTC calculation framework

In order to calculate TTC between a certain source and a certain sink (i. e. point to point TTC) of the system, we do the following calculation:

Step 1 For the base case of current operation point, increase the load on the sink bus gradually with the source bus as swing bus, and calculate corresponding load flow. If there is thermal limit, voltage limit or voltage stability constraint reached, the corresponding power transfer from the source to the sink becomes a TTC candidate.

Step 2 Apply one contingency to the system according to the contingency list and calculate the resultant load flow. Similar to Step 1, we increase the load on the sink bus with source bus as a swing bus till system constraint reached. The corresponding power transfer from the source to the sink becomes a new TTC candidate.

Step 3 After all the contingencies in the list have gone through Step 2, the minimum one of all the TTC candidates is taken as the final TTC for the source-sink pair for the base operation point.

It is not necessary to calculate TTC for all possible pairs of sources and sinks in the system. But it is still a time tedious job. This is extremely true when system transient stability limit should be considered.

4. Study Example

A four-bus power system is used to illustrate total transfer capability calculations. The system is shown in Fig. 1 with the power flow solution for the base case. This system can give insight about TTC calculation implications and we can easily track and interpret factors influencing TTC although it is very simple. EPRI program VSTAB[8] is used in TTC analysis. The computer software of POWERWORLD is used for load flow diagram output. System data including line thermal limits and generator real and reactive power limits are given in the appendix. The system voltage lower and upper limits are taken as 0.95~1.05 p. u. for both contingency and normal operation conditions.

Taking bus 1 as the sink and bus 2 the source, the results of the system transfer capabilities in normal operation (base case) and when experiencing a set of single line outage contingencies are given in table 1. The load level at bus 1 increases until the first violation of system constraint occurs. Bus 2 is taken to be the swing bus. The critical contingency in that case is the loss of line 1-3 as the voltage is fallen rapidly and almost leads to voltage collapse.

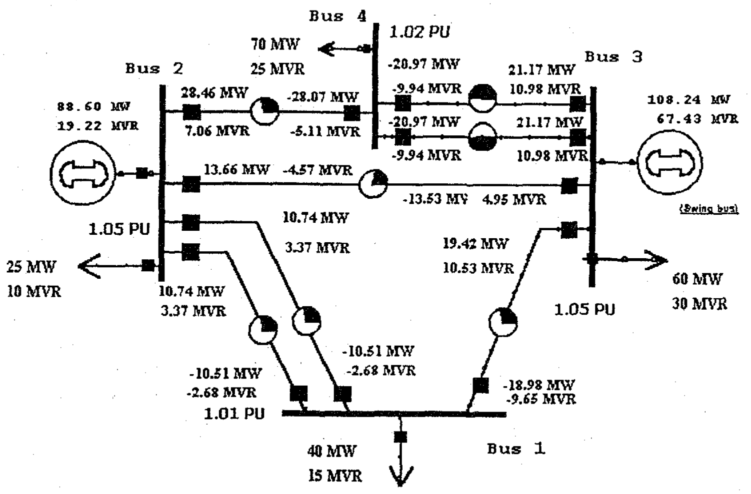

Figure 1. Four bus sample system

The base case and line 2-3 outage corresponds to a load of 100 MW at bus 1. The reactive power losses at these particular cases are significant and equal 9.4 MVAR and 13.6 MVAR, which is even higher than the reactive power transmitted itself, respectively which means that the transmission system is exhausting its reactive reserve and finally prone to voltage instability. It can be also seen that the limiting factor is changed between low voltage and line overload criteria.

Table 1. Transfer limits between points 2-1

Configuration	Power Transfer*	Limiting Condition
Normal	51.4 MW, 13.0 MVAR	V_l
Line 1-3 out.	45.2 MW, 16.8 MVAR	V_l
Line 2-4 out.	53.4 MW, 6.2 MVAR	Overload 2-3
Line 2-3 out.	63.2 MW, 6.6 MVAR	V_l

* The power transfer from source to sink is currently calculated by sum up the load flows on the direct paths between the two buses. A program is under development that can calculate all the power transfer from the source to the sink via both direct or indirect paths.

This confirms that the transfer capability is a nonlinear function of many parameters as indicated in earlier section of the paper. One other supportive clue to this fact is the transfer capability when line 2-3 is outaged. It is higher than the normal system configuration though both of them are obtained at the same load level of 100 MW. However this is interpreted as the changing of the network configuration due to tripping one of the lines which definitely changes the effective impedance of the network that is directly proportional to the transfer capability increase. Anyway the total transfer capability in this case is 45.2 MW as it is the most limiting figure.

Table 2 shows TTC analysis results for the bus pair of 4 (sink) and 2 (source). The load increases at bus 4 where bus 2 is the slack bus under base case and other contingencies. Transmission line limits was basically the limiting condition and no other factor is far concerned. The transfer capability under the outage of line 2-3 is again higher than its counterpart in the base case. The limiting constraint for this contingency was overload of line 2-4 unlike the other cases. One other observation is the dramatic increase in the reactive power losses due to load increase. For instance the losses at the base case is about 12 MVAR. The total transfer capability is taken to be 46.7 MW. Therefore the reactive power compensation and voltage regulation play an important role in accurate TTC evaluation. For later commercial TTC calculation, an optimal power flow is necessary.

Table 2. Transfer limits between points 2-4

Configuration	Power Transfer	Limiting Condition
Normal	67.8 MW, 7.2 MVAR	Overload 3-4
Line 2-3 out.	93.6 MW, 2.3 MVAR	Overload 2-4
Line 3-4 out.	46.7 MW, 12.3 MVAR	Overload 3-4
Line 1-2 out.	74.2 MW, 5.9 MVAR	Overload 3-4

Table 3 shows another transfer capabilities analysis results and the corresponding voltage limit violation where the load at bus 1 is increased gradually at a constant power factor rate with generator bus 3 as swing bus. All possible line outage contingencies were conducted. It appeared that the most critical contingency in that particular case was the outage of one of the parallel lines 1-2 that occurs at a load of 80 MW. The loss of line 3-4 corresponds to the highest MW transfer and least MVAR flow. The base case and most contingencies, rather than line 1-2, occur at a load 100 MW. Tripping line 2-3 is insignificant in this transaction even coupled with other contingencies. So the total transfer capability is considered to be the most conservative figure, i.e. TTC is 54.8 MW. This ensures a considerable margin for voltage stability.

Table 3. Transfer limits between points 3-1

Configuration	Power Transfer	Limiting Condition
Normal	59.8 MW, 18.6 MVAR	V_l
Line 2-4 out.	54.8 MW, 21.3 MVAR	V_l
Line 1-2 out.	57.7 MW, 21.3 MVAR	V_l
Line 3-4 out.	61.8 MW, 17.6 MVAR	V_l

Now the load is increased at bus 4 considering G2 at bus 3 as the slack bus and contingencies are carried out. Results are given in Table 4 that shows the limiting condition is the line 3-4 overload. In case of line 1-3 outage, the flow in line 2-3 will be reduced greatly and all the reactive power will be supplied be G1 while G2 will keep its reactive power unchanged. Loosing line 2-4 here is the critical one and corresponds to a load of 90 MW. TTC is 90 MW flowing from bus 3 to bus 4.

Table 4. Transfer limits between points 3-4

Configuration	Power Transfer	Limiting Condition
Normal	90.2 MW, 34 MVAR	Overload 3-4
Line 1-3 out.	94.6 MW, 30.4 MVAR	Overload 4-3
Line 2-4 out.	90 MW, 32.2 MVAR	Overload 3-4
Line 1-2 out.	92.2 MW, 35.8 MVAR	Overload 3-4

Increasing load level at bus 3 where bus 2 is the swing one, transfer capability figures are tabulated as shown in table 5. The critical condition is line 2-4 in which the thermal limit is hit at a load of 90 MW with generator G1 supplying 4.4 MVAR leading reactive power. However as load is increased gradually the reactive power demand of the system is met from generator 2 connected to bus 3 while the reactive supply from generator 1 at bus 2 is reduced sharply. This can be somehow justified by considering that the original MVAR flow was from bus 3 to bus 2 as shown in Fig. 1. As this transaction is supposed to be supplied from generator 1, as the load continues to increase G1 is likely to reach its MW limits and supply leading MVAR while G2 will reach its ceiling MVAR limit. The base case operation reaches the transmission limit at a load of 145 MW with G1 at (176.8 MW, 0.2 MVAR) and G2 at (108.2 MW, 141.3 MVAR). Voltage deviations in this case are within the acceptable limits but will start to decline if the load is further increased in the contingency case of line 1-3 outage which corresponds to a load of 150 MW. Generally TTC between buses 2 and 3 is taken to be 55.8 MW.

Table 5. Transfer limits between points 2-3

Configuration	Power Transfer	Limiting Condition
Normal	56 MW, 16.7 MVAR	Overload 2-3
Line 1-3 out.	57.4 MW, 17 MVAR	Overload 2-3
Line 1-2 out.	55.8 MW, 16.6 MVAR	Overload 2-3
Line 2-4 out.	55.8 MW, 16.6 MVAR	Overload 2-3

Table 6 shows the results of increasing the load at bus2, as bus 3 is the swing bus. In most of the cases the limiting criterion was the generation limit. Two contingencies are ineffective, that is one of the lines 1-2 and line 2-4. TTC is equal to 18.6 MW in that case.

Table 6. Transfer limits between points 3-2

Configuration	Power Transfer	Limiting Condition
Normal	31.5 MW, 10.1 MVAR	G2 limit
Line 1-3 out.	54.8 MW, 16.4 MVAR	G2 limit
Line 3-4 out.	18.6 MW, 6.2 MVAR	Overload 3-4
Line 1-2 out	30.8 MW, 9.9 MVAR	G2 Limit

So far we have two TTC values for the transmission line 2-3 one is 55.8 MW in the direction 2-3 and the other is 18.6 MW in the direction 3-2. This proves that TTC is not a bi-directional quantity and should announced emphasizing the source and sink points.

4. Summary

Total transfer capability (TTC) calculations based on certain assumptions and considerations were carried out in this paper. A sample power system was used for the purpose of demonstration of the strategy involved. Results show that TTC is influenced by various factors and is very difficult to evaluate. The following comments might be useful for future R&D:

- In certain time frame, TTC calculation should consider unit commitment, maintenance schedule etc. in order to yield correct system transfer limit.

- System transient stability limit should be considered to guarantee the transient security.

- Optimal power flow should be used in TTC calculation that takes voltage and reactive power control into consideration. It should be cooperated with continuation load flow since the latter is more efficient in ill-conditioned systems for searching saddle node bifurcation point.

- Another task is to generate the contingency list similar to power system security analysis. For the different pairs of sources and sinks, the list should be different, and the list should include all the severe contingencies for that specific case but still remains short to save CPU time.

- An even more important factor is that we should know all the possible paths between the studied pair of buses. Sometime the overflow happens on paths outside the studied system, i.e. external system. Neglecting this fact will cause insecure operation in the deregulated environment.

- In order to determine TTC, the sensitivity analysis method, continuation load flow, optimal power flow and direct method (transient energy function method) might be very useful. The future TTC evaluation software package will be an integration of various system analysis methods that have been proved efficient and successfully used in the real power system analysis.

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References

[1] S. Saraf, "Indian Energy Deregulation", http://www.ftenergy.com/general/genrs152.htm.

[2] H. Rudnick, "Latin American Experience in the Restructuring of Electric Power", http://www.ing.puc.cl/~power/deregula.htm, Jan. 1996.

[3] H. B. Püttgen, H. J. haubrich, J. Stotz, D. Winje, G. Klappa and D. H. Denton, "Energy Market Environments in Europe and the United States", IEEE Power Engineering Review, pp. 3-15, November 1997.

[4] W. H. Dunn, M. A. Rossi and B. Avramovic, "Impact of Market Restructuring on Power Systems Operation", IEEE Computer Applications in Power, pp. 42-47, January 1995.

[5] Y. Tian and G. Gross, "OASIS*NET*: an OASIS Network Simulator", IEEE 1998 PES Winter Meeting, PE-139-PWRS-1-10-1997, Tampa, FL., February 1998.

[6] Transmission Transfer Capability Task Force, "Available Transfer Capability Definitions and Determination", North American Electric Reliability Council, Princeton, NJ, June 1996.

[7] M. D. Ilic, et al., "Available transmission capacity (ATC) and its value under open access", IEEE Trans. on PWRS, vol. 12No.2, 1997.

[8] Powertech Labs Inc., " Voltage stability analysis program (VSTAB) user's manual", Prepared for EPRI, USA, 1997.

Appendix

The sample system data are as follows.

Transmission lines (R, X in p.u. on 100 MVA base)

Line	Circuit #	R	X	Limit
1-2	1	0.2	0.6	40 MVA
1-2	2	0.2	0.6	40 MVA
1-3	1	0.1	0.2	80 MVA
2-3	1	0.07	0.2	60 MVA
2-4	1	0.05	0.25	100 MVA
3-4	1	0.04	0.2	50 MVA
3-4	2	0.04	0.2	50 MVA

Loads

Bus	P (MW)	Q (MVAR)
1	40	15
2	25	10
3	60	30
4	70	25

Generators

Gen. #	P_{max} (MW)	P_{min} (MW)	Q_{max} (MVAR)	Q_{min} (MVAR)
G 1	200	50	150	-150
G2	200	50	150	-150