Determination of Available Transfer Capability (ATC) Considering Integral Square Generator Angle (ISGA)

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Abstract: - This paper presents the determination of power transfer between two buses that takes into account the dynamic security constraint. The dynamic security constraint based transient stability has been found to be one of the limiting factors in determining the power transfer so-called as the available transfer capability (ATC). The multimachine integral square generator angle (ISGA) index is used to measure the severity of stable and unstable transient events during the occurrence of line outage that is considered in the ATC assessment. The determination of ATC considering dynamic security constraint has been performed on a case study of 6 bus system.

Key-Words: - Integral square generator angle, available transfer capability and line outage.

1 Introduction

In the transition to a more competitive electric power market, transmission providers are required to produce commercially viable information of available transfer capability (ATC) so that such information can help power marketers, sellers, and buyers in planning, operation and reserving transmission services. A predetermined set of ATC values are usually accessed by electricity market participants and system operators through an open access same-time information system.

Available transfer capability (ATC) is the measure of the ability of interconnected electric power systems to reliably move or transfer the additional amount of power from one bus to another over all the transmission lines [1]. Mathematically, ATC is the total transfer capability (TTC) less the transmission reliability margin (TRM), less the capacity benefit margin (CBM) and less the base case power transfer [2]. By definition, TTC represents the maximum amount of power transfer that can be transferred over the transmission network while meeting all of a specific set of defined pre- and post-contingency systems condition. CBM is defined as the amount of transmission transfer capability reserved by load serving entities to meet the generation system reliability requirements. However, TRM is the amount of transmission capability necessary to ensure that the transmission network is secure under a reasonable range of uncertainties in systems conditions.

At present, there are many papers discussed on the determination of ATC that takes into account the steady-state security constraints such as the voltage and transmission line limits. Nevertheless, dynamic security constraint should be considered in the ATC assessment. This is due to the fact that a large amount of power transfer may sometime causes instability in a system subjected to the occurrence of a disturbance [3]. The dynamic security constraints are often referring to the assessment of voltage and transient stabilities. Transient stability is the ability of the power system to maintain synchronism when subjected to large disturbances [4]. On the other hand, voltage stability is the ability of the power system to maintain acceptable voltages at all buses in the system under normal operating conditions and after being subjected to disturbances [4].

Rossales *et al.* [5] uses the optimal power flow (OPF) solution to compute the ATC that takes into account the dynamic security constraint which is based on the on-line transient stability assessment (TSA). Tuglie *et al*. [3] proposed an approach to determine the ATC that uses the optimization technique incorporating with the Lagrange multipliers. The steady-state voltage and thermal limits and, rotor angle stability limit are taken into account as the constraints of the optimization technique. Cui *et al*. [6] presents an approach using generation reallocation to maximize the ATC under dynamic security constraints. The tool for dynamic security assessment is a normalized transient energy function (TEF). The power reallocated to each generator is determined by the sensitivity of transient stability margin and linear programming. The TEF has also been used by Momoh *et al*. [7] to determine the amount of ATC that flows through the interconnected lines. Specifically, the sensitivities of TEF with respect to the changes in generation and also the generation shift distribution factor (GSDF) are used to estimate the change in power generation whilst concerning on the transient stability and transmission line limits, respectively. Therefore, reallocating the power generation may increase the amount of ATC which flows through the interconnected lines. Bettiol *et al*. [8] utilizes an approach for reallocating the power generation in order to alleviate the ATC via the tie-lines. The transient stability constraint is considered in the computation of ATC. The power generation is decreased for the critical machines that that are identified by a set of contingencies. This is performed in order to satisfy the transient stability constraint based rotor angle of a generator. On the other hand, the power generation is increased for the non-critical machines so that the ATC that flows through the tie-lines is maximized whilst complying with the transient stability constraint. Yuan *et al*. [9] implement the optimization methodology based on primal-dual Newton interior point method (IPM) for nonlinear programming (NLP) problems that used to compute the ATC. The power generation, voltage magnitude, transmission line, voltage stability and angle stability limits are considered as the constraint in the transfer capability computation.

The integral square generator angle (ISGA) index is considered as one of the methods that used to estimates the severity of stable and unstable transient events [10]. This paper presents a new approach which computes the ATC by considering the ISGA as the dynamic security constraint. The ISGA measures the total differences of generator angles during both transient and equilibrium conditions [10]. The ATC is referred to as the largest amount of power transfer that causes the generator to experience the commencement of angle instability which is indicated by the maximum value of ISGA. The repetitive AC power flow method is used to determine the ATC that takes into account the impact of transmission line outage. A 6 bus system is used as a case study in the determination of ATC which considers the dynamic security constraint of angle stability.

2 Problem Formulation

The multi-machine integral square generator angle (ISGA) index is used to verify the severity of stable and unstable transient events that occur in the ATC assessment during the incidence of transmission line outage. The ISGA is given by equation (1) [10].

$$ISGA = \int_0^T \sum_i M_i \left[\delta_i(t) - \delta_{coa}(t)\right]^2 dt \qquad (1)$$

where,

$\delta_i(t)$: generator rotor angle as a function of time
M_i : machine inertia
i : number of generator
T : simulation time

and

$$\delta_{coa}(t) = \frac{\sum_i M_i\ \delta_i(t)}{\sum M_i} \qquad (2)$$

The ISGA measures the total differences of generator angles during both of the transient and equilibrium conditions. The transient events that adversely affect on the generator angle divergence may yield to the largest value of ISGA.

During the non-occurrence of outage events in a power system, any changes in system topology, generation, load and ATC which results to a large steady-state angle differences will increase the value of ISGA. Hence, the ISGA could also be determined by considering each generator's equilibrium condition that refers to $\delta i(t)$ instead of $\delta_{coa}(t)$ and it is given by equation (3).

$$ISGA = \lim_{T \to \infty} \int_0^T \sum_i M_i \left[\delta_i(t) - \delta_i(T)\right]^2 \qquad (3)$$

The ISGA index is normalized by T and the sum of generator inertias (M_{total}) which is used in this paper.

$$ISGA = \int_0^T \frac{1}{M_{total}\,T} \sum_i M_i \left[\delta_i(t) - \delta_{coa}(t)\right]^2 dt \qquad (4)$$

Normalization by T causes the ISGA to be independent from the time interval in situations where the index is calculated during equilibrium conditions [10]. Normalization by M_{total} makes the index less sensitive to disconnected generators, unless the generators are losing synchronism [10].

3 Methodology

The ATC is obtained by performing the recursive AC power flow method under a specific set of operating conditions. Among the operating conditions that are usually considered are the projected customer demand, generation dispatch, system configurations and based scheduled transfers. In general, the procedure in determining the ATC involves the definition of a base case, determination of network response and finding the maximum transfer or ATC. The determination of ATC using the repetitive AC power flow method is described in the following procedures [11].

a) Establish a solved base case power flow solution.
b) Perform line outage simulation of one of the specified critical lines.
c) Specify the points of transfer. The point-to-point transfer considers participation of a generator in the specified selling bus and a load in the specified buying bus.
d) Simultaneously, increase the power injection and extraction at both sides of the selected buses until the maximum ISGA is reached which gives the commencement of angle instability. The angle instability is referred to as the difference of generator rotor angle that exceeds the angle stability limit of 180°. The simulation time (T) considered in the ISGA calculation is 3 and 8 seconds. At every power injection and extraction, equal power increments of generation and demand are considered and simultaneously, the AC power flow solution is calculated.
e) Calculate the ATC that is given by the difference between the maximum power transfer at the limiting case and the transfer at the base case.

The procedure of recursive AC power flow method that used to determine the ATC is summarized in terms of flowchart as shown in Figure 1.

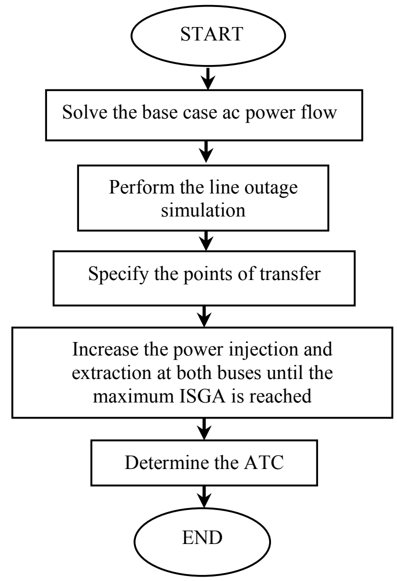

Fig. 1 Flowchart of ATC determination using recursive AC power flow method

4 Results and Discussion

A 6 bus system is used as a case study to demonstrate the determination of ATC considering the dynamic security constraint of ISGA. The 6 bus system consists of 3 generator buses, 3 load buses and 5 transmission lines as shown in Figure 2.

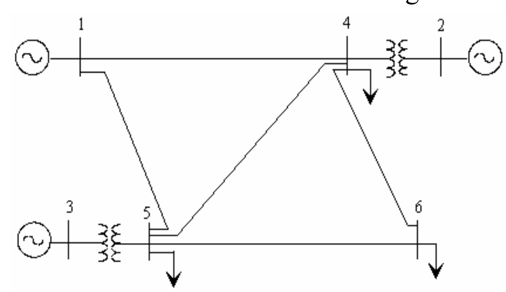

Fig. 2 A 6 bus system

In the ATC determination, the impact of line outage to the rotor angle stability is analyzed by referring to the ISGA index estimated at T = 3 seconds and T = 8 seconds and it is shown in Table 1. Table 1 shows that the outage at line 4-6 causes severity to the rotor angle stability that refers to the highest ISGA of 35.3080 and 35.2981 at T = 3 seconds and T = 8 seconds, respectively. The minimum ISGA value is 2.7838 and 2.7840 at T = 3 seconds and T = 8 seconds, respectively in which it is obtained due to the occurrence of line outage at 1-4. This shows that the outage of line 1-4 is less sensitive to initiate the violation of rotor angle stability.

Table 1 ISGA index considering single line outage

Line outage	ISGA	
	T = 3 sec	T = 8 sec
1 – 4	2.7838	2.7840
1 – 5	4.5274	4.5207
1 – 6	3.6523	3.6531
5 – 6	21.6450	21.6473
4 – 6	35.3080	35.2981

Figure 3 illustrates the differences of rotor angle at PV buses 2 and 3 which respect to the slack generator. From the plotted graph, the differences of rotor angle is said to be stable since it does not exceeds 180^o. Hence a stable system is obtained. Otherwise, the difference of rotor angle is said to be unstable when it exceeds 180^o as shown in Figure 4. Therefore, this causes the instability of the system.

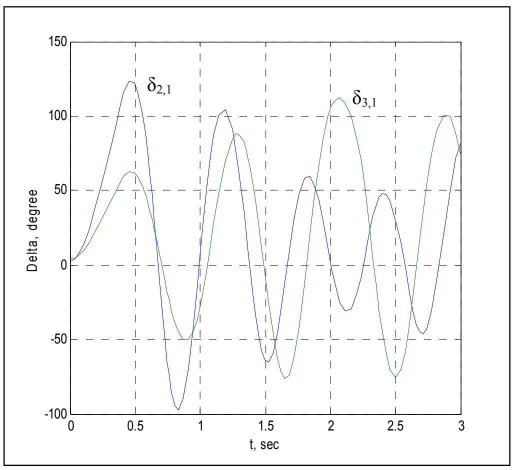

Fig. 3 Differences of rotor angle for generators 2 and 3 corresponds to generator 1.

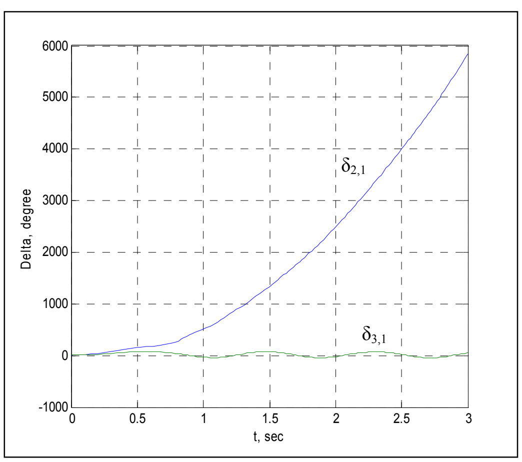

Fig. 4. Differences of rotor angle during unstable condition

ATC can also be used to measure the ability of interconnected systems to reliably move or transfer the power from one selling bus to the other buying bus. In this case study, the ATC is determined by considering the line outage and dynamic security constraint of ISGA. Tables 2 to 7 shows the results of ATC for different transfer case which are obtained by considering the line outages. The ATC is obtained based on the dynamic security constraint of maximum ISGA. In Tables 2 and 3, line outage 4-6 gives the minimum ATC value for both transfer cases, respectively. The maximum ATC value is 490 MW for the transfer case from selling bus 2 to a buying bus 5 with the outage of line 1-6. For the transfer case from selling bus 2 to a buying bus 6, the outage of line 5-6 gives the maximum ATC of 839 MW.

Tables 4 and 5 illustrates that the outage of line 5-6 that yields to a minimum ATC value of 512 MW and 496 MW for both transfer cases, respectively. Subsequently, the maximum ATC value of 656 MW is obtained for both transfer cases whilst considering the outage of line 1-5.

By referring to Table 2 until 5, the power transfer that exceeds the specified value of ATC may agitate to system collapse due to the occurrence of instable rotor angle. Hence, the utility should consider a safety measure by not to transfer the power that causes the violation of ISGA limit.

Table 2 ATC for transfer case from selling bus 2 to buying bus 5 with line outage

Line outage	Maximum ISGA		ATC (MW)
	T=3sec	T=8sec	
1-6	1460.4	1465.6	490
1-5	2050.6	2050.7	481
5-6	2030.9	2024.1	455
1-4	1083.0	1089.6	351
4-6	2031.0	1784.6	331

Table 3 ATC for transfer case from selling bus 2 to buying bus 6 with line outage

Line outage	Maximum ISGA		ATC (MW)
	T=3sec	T=8sec	
5-6	473	464.8	839
1-6	1460.4	1465.5	490
1-5	2050.4	2050.5	481
1-4	1083.0	1089.4	351
4-6	2030.0	1783.0	331

Table 4 ATC for transfer case from selling bus 3 to buying bus 5 with line outage

Line outage	Maximum ISGA		ATC (MW)
	T=3sec	T=8sec	
1-5	699.9	704.6	656
1-6	752.2	756	629
1-4	799.9	779.6	606
4-6	533.3	535.5	592
5-6	944.1	943.2	512

Table 5 ATC for transfer case from selling bus 3 to buying bus 6 with line outage

Line outage	Maximum ISGA		ATC (MW)
	T=3sec	T=8sec	
1-5	700	704.7	656
1-6	751.9	756.2	629
1-4	799.4	779.3	606
4-6	533	535.6	592
5-6	4222	3610.4	496

5 Conclusion

This paper has presented the assessment of ATC that takes into account the dynamic security constraint of ISGA. The ISGA is considered in the ATC computation in order to ensure that the machine's rotor angle is stable during the occurrence of transient phenomena due to the line outage. On the other hand, power transfer that violates the ISGA limit may yield to a system collapse due to rotor angle instability. The future development for improving the approach is that the ATC should be computed based on the estimated maximum ISGA. Hence, this will improve the computational time in determining the ATC.

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