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

M.M. OTHMAN*,c, N. MAT*, I. MUSIRIN*, A. MOHAMED** and A. HUSSAIN**
*Faculty of Electrical Engineering
Universiti Teknologi MARA
40450 Shah Alam, Selangor
MALAYSIA

**Department of Electrical, Electronic
and Systems Engineering
Faculty of Engineering
Universiti Kebangsaan Malaysia
43600 UKM, Bangi, Selangor
MALAYSIA
[c]email: mamat505my@yahoo.com

Abstract: - One of the concepts in restructuring the electric power industry is the ability to accurately and rapidly quantify the power transfer so-called as the available transfer capability (ATC). Accurate identification of ATC provides vital information for both planning and operation of the bulk power market in reserving transmission services. There are various methods used to determine ATC such as the DC power flow, AC power flow, optimal power flow and sensitivity techniques. These methods considered the transmission line and voltage limits as the constraints for ATC computation. 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 multi-machine integral square generator angle (ISGA) index is used to measure the severity of stable and unstable transient events during the occurrence of line outage and it is considered as the dynamic security constraint of the ATC assessment. The determination of ATC considering dynamic security constraint has been performed on the 6 bus and 11 bus systems. Comparative study has been made between the cubic-spline interpolation technique and recursive AC power flow method in determining the value of ATC.

Key-Words: - Cubic-spline interpolation technique, recursive AC power flow method, 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 [1,2].

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 [3]. 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 [4]. 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.

Posting the transfer capability signal incurred within a limited time requires a fast computational method in estimating the ATC. Presently, there are not many fast ATC calculation methods available and therefore there is a need for a fast ATC calculation method. However, various approaches have been proposed to determine ATC such as using the methods of DC power flow [5], AC power flow [6], optimal power flow [7,8] and sensitivity [9]. The earliest application of NN in ATC assessment was proposed by X. Luo *et al.* [10] in which real power transfer capability is calculated based on the optimal power flow formulation of the problem and considering generator status, line status and load status as the NN inputs. The method based on linear DC power flow considering distribution factors is considered fast but less accurate for transfer capability analysis because the DC network model does not require the voltage magnitude and reactive power component in the power flow calculation. Therefore, the linear DC power flow may result in optimistic ATC value especially for the heavily stressed system that caused by critical contingency. The AC power flow method gives an accurate solution in determining the ATC because it considers the effects of reactive power flows and voltage limits. However, transfer capability evaluation using repetitive AC power flows is time-consuming because it requires a load flow solution at every transfer step size.

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 that violates the dynamic security limit [11]. 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 [12]. 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 [12].

Rossales *et al.* [13] 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.* [11] 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.* [14] 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.* [15] 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.* [16] 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 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.* [17] 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 [18]. 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 [18]. 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 ISGA limit. Comparison has been made between the cubic-spline interpolation technique and repetitive AC power flow method in estimating the ATC that takes into account the impact of transmission line outage. The 6 bus and 11 bus systems are used as a case study in the determination of ATC which considers the dynamic security constraint of angle stability.

2 Problem Formulation of Integral Square Generator Angle (ISGA)

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) [18].

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

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. In order avoid excessive changes of the index therefore, the ISGA could also be determined by considering each generator's equilibrium condition that refers to *δi(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 value of ISGA becomes more significant in which it is independent from the time interval in situations where the index is calculated during equilibrium conditions [18]. Normalization by M_{total} makes the index less sensitive to disconnected generators, unless the generators are losing synchronism [18].

3 ATC Determination Using Cubic-Spline Interpolation Technique

In this section, determination of *P-ISGA* curve using the cubic-spline interpolation technique is first described and then followed by the procedure of ATC estimation using cubic-spline interpolation technique.

3.1 Formulation of Cubic-Spline Interpolation Technique

The ATC is estimated based on the cubic-spline interpolation technique that used to trace the curve of *P-ISGA*. The *P-ISGA* curve is obtained due to the amount of ISGA that is varied by the increase of MW power transfer (*P*). The basic idea of this method is to determine four known points on the curve and then fit appropriate curves to the four points. In the cubic-spline interpolation technique [19], tracing the curves of $f(k_1)$, $f(k_2)$ and $f(k_3)$ begins with finding the value for parameters $f''(x_2)$, $f''(x_3)$ and $f''(x_4)$ which are given by,

$$\begin{aligned} f''(x_2) = \Bigg\{ & 2\left(\frac{x_4 - x_2}{x_3 - x_2}\right)\left[\frac{6}{x_3 - x_2}\left[f(x_3) - f(x_2)\right] \right. \\ & \left. + \frac{6}{x_2 - x_1}\left[f(x_1) + f(x_2)\right]\right] \\ & - \frac{6}{x_4 - x_3}\left[f(x_4) - f(x_3)\right] \\ & + \frac{6}{x_3 - x_2}\left[f(x_2) + f(x_3)\right] \Bigg\} \\ & \div \left\{ 2(x_3 - x_1) * 2\left(\frac{x_4 - x_2}{x_3 - x_2}\right) - (x_3 - x_2) \right\} \end{aligned} \qquad (5)$$

$$
\begin{aligned}
f''(x_3) = \Bigg\{ & \frac{6}{x_4 - x_3}\left[f(x_4) - f(x_3)\right] \\
& + \frac{6}{x_3 - x_2}\left[f(x_2) - f(x_3)\right] \\
& - \left[(x_3 - x_2) * f''(x_2)\right]\Bigg\} \div 2(x_4 - x_2)
\end{aligned} \tag{6}
$$

$$
\begin{aligned}
f''(x_4) = \Bigg\{ & \frac{6}{x_4 - x_3}\left[f(x_4) - f(x_3)\right] \\
& + \frac{6}{x_3 - x_2}\left[f(x_2) - f(x_3)\right] \\
& - \left[(x_3 - x_2) * f''(x_2)\right] \\
& - \left[2(x_4 - x_2) * f''(x_3)\right]\Bigg\} \div (x_4 - x_2)
\end{aligned} \tag{7}
$$

The values of $f''(x_2)$, $f''(x_3)$ and $f''(x_4)$ are then used to obtain the curve functions of $f(k_1)$, $f(k_2)$ and $f(k_3)$, which are given by,

$$
\begin{aligned}
f(k_1) = & \frac{f''(x_2)}{6(x_2 - x_1)}(k_1 - x_1)^3 + \frac{f(x_1)}{x_2 - x_1}(x_2 - k_1) \\
& + \frac{f(x_2)}{x_2 - x_1}(k_1 - x_1)
\end{aligned} \tag{8}
$$

$$
\begin{aligned}
f(k_2) = & \frac{f''(x_2)}{6(x_3 - x_2)}(x_3 - k_2)^3 + \frac{f''(x_3)}{6(x_3 - x_2)}(k_2 - x_2)^3 \\
& + \left[\frac{f(x_2)}{x_3 - x_2} - \frac{f''(x_2)(x_3 - x_2)}{6}\right](x_3 - k_2) \\
& + \left[\frac{f(x_3)}{x_3 - x_2} - \frac{f''(x_2)(x_3 - x_2)}{6}\right](k_2 - x_2)
\end{aligned} \tag{9}
$$

$$
\begin{aligned}
f(k_3) = & \frac{f''(x_3)}{6(x_4 - x_3)}(x_4 - k_3)^3 + \frac{f''(x_4)}{6(x_4 - x_3)}(k_3 - x_3)^3 \\
& + \left[\frac{f(x_3)}{x_4 - x_3} - \frac{f''(x_3)(x_4 - x_3)}{6}\right](x_4 - k_3) \\
& + \left[\frac{f(x_4)}{x_4 - x_3} - \frac{f''(x_3)(x_4 - x_3)}{6}\right](k_3 - x_3)
\end{aligned} \tag{10}
$$

In the *P-ISGA* curve fitting, the parameters parameters $f''(x_2)$, $f''(x_3)$ and $f''(x_4)$ can be described as $ISGA''(P_2)$, $ISGA''(P_3)$ and $ISGA''(P_4)$, respectively. $f(k_l)$ is the cubic-spline function that is used for tracing the curves of ISGA, $ISGA_i$ (k_l). Where, i is the number of generator bus. k_l is the increase of power transfer by 1 MW between x_l and x_{l+1}. l is the number of three incremental steps, that is, 1, 2 and 3. Specifically, $f(k_l)$ is used for tracing the curves between the four points of $f(x_n)$ with respect to the increase of k_l by 1 MW from x_l to x_{l+1}. Whereby, $f(x_n)$ represents as the four points of ISGA, $ISGA_i(P_n)$ which are obtained from the AC power flow solution. The four points of real power transfer, x_n can also be described as P_n, where n= 1, 2, 3 and 4. For an example, the curve from point $f(x_1)$ to point $f(x_2)$ is traced by using $f(k_1)$ with the increase of k_1 by 1 MW from x_1 = 1MW to x_2 = 100MW.

3.2 Procedure of ATC Estimation Using Cubic-Spline Interpolation Technique

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. Determination of power transfer or ATC between buses that uses the cubic-spline interpolation technique are described as follows:

a) Establish a solved base case power flow solution.
b) Perform line outage simulation.
c) Specify the point of transfer. The point-to-point transfer case involves the participation of a generator in the specified selling bus and a load in the specified buying bus.
d) Simultaneously, increase the power generation $\left(P_{G_n}\right)$ and load $\left(P_{D_n}\right)$ at the selected buses at, n, incremental steps. Four incremental steps of P_{G_n} are chosen because it is sufficient to provide an accurate fitting of the curve. The amount of power transfer, P_n, is referring to the amount of power generation, P_{G_n}. The sensitivity method is used to predict the maximum power transfer for P_4 and then it is used to specify the MW step length between each point of P_n. The sensitivity method that used to predict the P_4 [20,21,22,23,24] and it is given by,

$$
PT_{i,\max\delta} = \left| \frac{\partial \lambda}{\partial \max \delta_i} * \left(180^o - \max \delta_i^o\right) \right| \tag{11}
$$

where, $PT_{i,\max\delta}$ is the linear estimation of power transfers based on the 180^o difference of generator rotor angle. The max δ_i^o is referred to as the maximum difference of generator rotor angle. The $\frac{\partial \lambda}{\partial \max \delta_i}$ is the sensitivity method which represents as the increase of power transfer with respect to the changes of maximum generator rotor angle difference. All the sensitivities can be calculated directly by solving two AC power solutions. The first AC power flow solution is performed in order to determine the base case values of maximum generator rotor angle difference. By slightly increasing the power transfer between the two buses, then the second AC power flow solution is performed that vary the maximum difference of generator rotor angle. Then, the sensitivity can be calculated based on the increase of power transfer with respect to the changes of maximum generator rotor angle difference. Simultaneously, the minimum value of $PT_{i,\max\delta}$ gives the value of P_4 [22]. Mathematically, P_4 is given by,

$$P_4 = \min\left\{ PT_{i,\max\delta} \right\} \qquad (12)$$

The specified value for P_1 is 1 MW that is the initial value of power transfer. Equations (13) and (14) are used to specify the amount of P_2 and P_3, respectively.

$$P_2 = P_4/3 \qquad (13)$$

$$P_3 = P_2 * 2 \qquad (14)$$

e) At each incremental step of P_n, solve the AC power flow solution and determine the ISGA, $ISGA_i(P_n)$ for all the generator buses.
f) Obtain the *P-ISGA* curve for all the generator buses by fitting the $ISGA_i\,(k_l)$ curve between the four selected points of $ISGA_i(P_n)$. Therefore, the cubic-spline interpolation technique is used in fitting the $ISGA_i\,(k_l)$ curve.
g) Determine point-to-point ATC in which it is referring to the maximum power transfer that causes the ISGA limit intersects the *P-ISGA* curve. The ISGA limit is referred to as the ISGA value that is obtained when the maximum difference of generator angle reaches to 180°. The

The above procedures are summarized in terms of flowchart as shown in Figure 1.

4 ATC Determination Using Recursive AC Power Flow Method

The other approach that used to determine the ATC is 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. The determination of ATC using the repetitive AC power flow method is described in the following procedures [25,26,27,28].

a) Establish a solved base case power flow solution.
b) Perform line outage simulation.
c) Specify the points of transfer. The point-to-point transfer case involves the 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 ISGA limit 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 2.

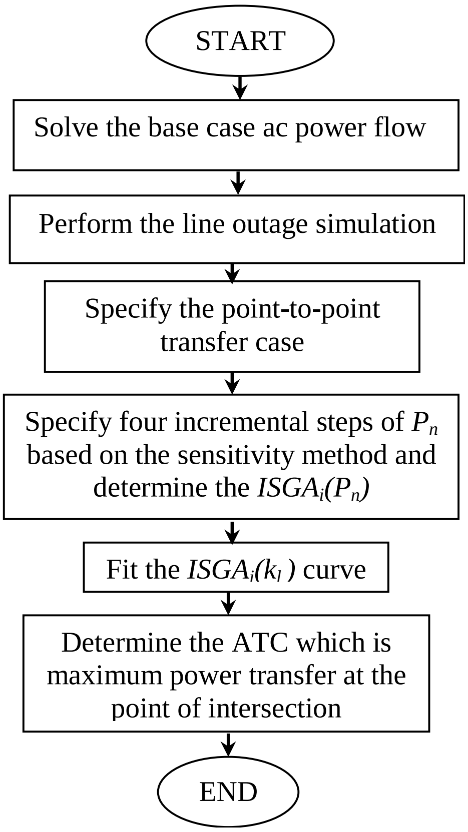

Fig. 1 Flow chart of ATC evaluation using the cubic-spline interpolation technique

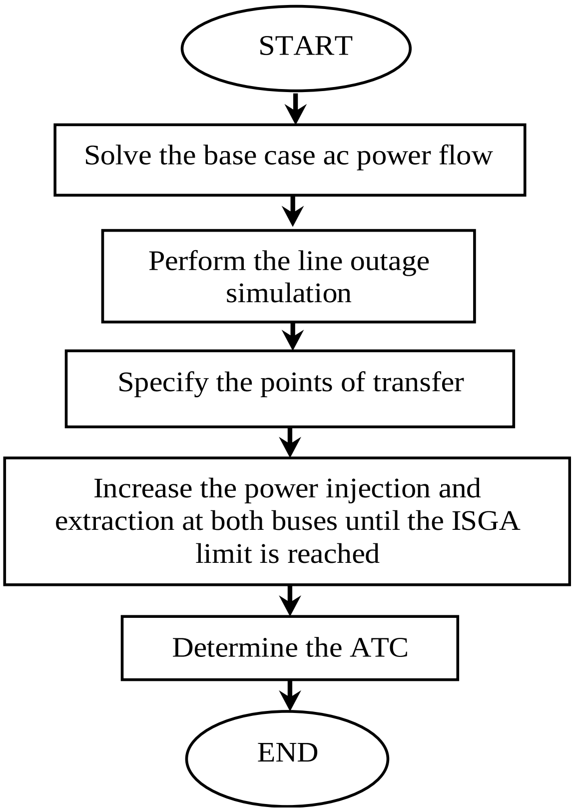

Fig. 2 Flowchart of ATC estimation using the recursive AC power flow method

5 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 3.

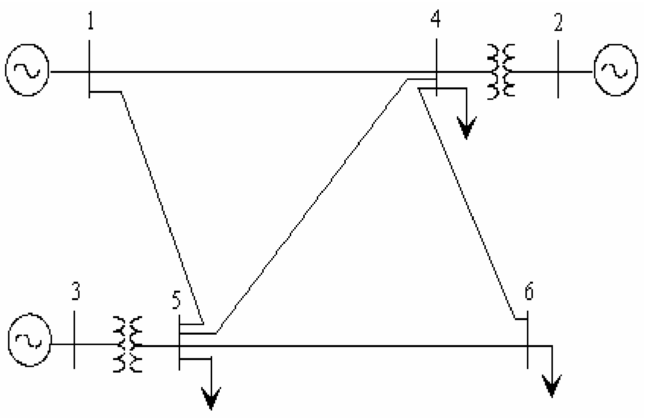

Fig. 3 A 6 bus system

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 4 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 5. Therefore, this causes the instability of the system.

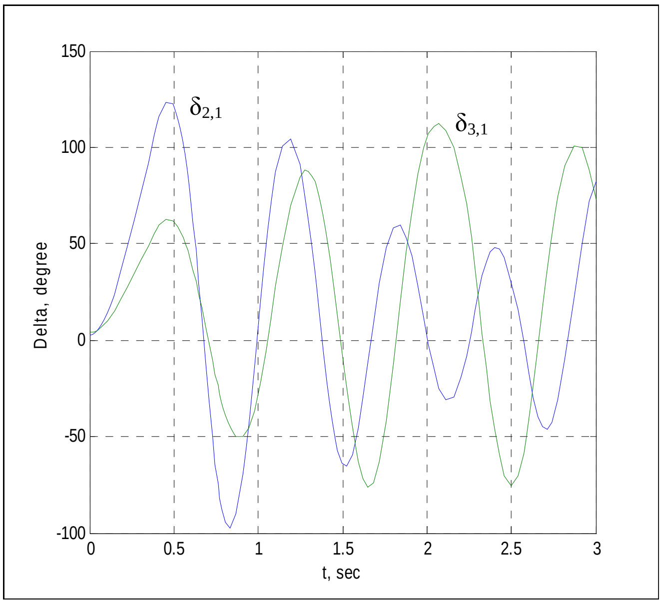

Fig. 4 Differences of rotor angle for generators 2 and 3 corresponds to generator 1.

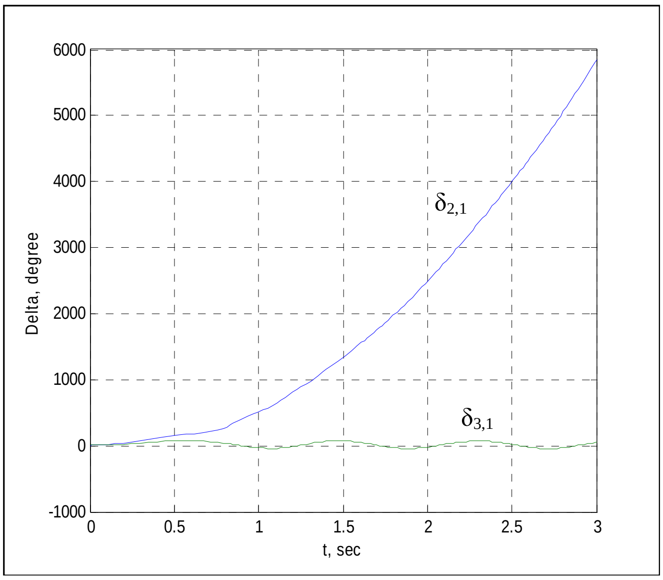

Fig. 5 Differences of rotor angle during unstable condition

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. The results of ATC for different transfer cases are shown in Tables 2-7 and it is obtained by considering the line outages and the dynamic security constraint of ISGA limit. Comparative study in determining the ATCs has been made between the cubic-spline interpolation technique and the recursive AC power flow method and it is shown in Tables 2-7. The results shown in Tables 2-7 prove that the cubic-spline interpolation technique and the recursive AC power flow method give similar results of ATC. In terms of computational time, it is noted that the cubic-spline interpolation technique provides less computational time in estimating the ATC as compared to the time taken to compute the ATC by using the recursive AC power flow method.

In Tables 2 and 3, line outage 4-6 gives the minimum ATC value for both transfer cases, respectively. The maximum ATC value of 490 MW is obtained by referring to the transfer case from selling bus 2 to a buying bus 5 that takes into account 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 value of 839 MW.

Tables 4 and 5 illustrates that the outage of line 5-6 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.

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

Line outage	ISGA limit	ATC (MW)		CPU time (second)	
	T=8sec	Cubic-spline	Recursive AC power flow	Cubic-spline	Recursive AC power flow
1-6	1465.6	490	490	1.79	110.03
1-5	2050.7	481	481	1.76	108.01
5-6	2024.1	455	455	1.66	102.17
1-4	1089.6	351	351	1.28	78.82
4-6	1784.6	331	331	1.21	74.32

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

Line outage	ISGA limit	ATC (MW)		CPU time (second)	
	T=8sec	Cubic-spline	Recursive AC power flow	Cubic-spline	Recursive AC power flow
5-6	464.8	839	839	3.07	188.39
1-6	1465.5	490	490	1.79	110.03
1-5	2050.5	481	481	1.76	108.01
1-4	1089.4	351	351	1.28	78.82
4-6	1783.0	331	331	1.21	74.33

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

Line outage	ISGA limit	ATC (MW)		CPU time (second)	
	T=8sec	Cubic-spline	Recursive AC power flow	Cubic-spline	Recursive AC power flow
1-5	704.6	656	656	2.39	147.3
1-6	756	629	629	2.29	141.24
1-4	779.6	606	606	2.22	136.08
4-6	535.5	592	592	2.16	132.93
5-6	943.2	512	512	1.87	114.97

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

Line outage	ISGA limit	ATC (MW)		CPU time (second)	
	T=8sec	Cubic-spline	Recursive AC power flow	Cubic-spline	Recursive AC power flow
1-5	704.7	656	656	2.39	147.3
1-6	756.2	629	629	2.29	141.24
1-4	779.3	606	606	2.22	136.08
4-6	535.6	592	592	2.16	132.93
5-6	3610.4	496	496	1.81	111.38

The robustness of cubic-spline interpolation technique in the determination of ATC is also analyzed on a case study of 11 bus system. The 11 bus system consists of 3 generating units, 8 load buses and 14 transmission lines and it is shown in Figure 6.

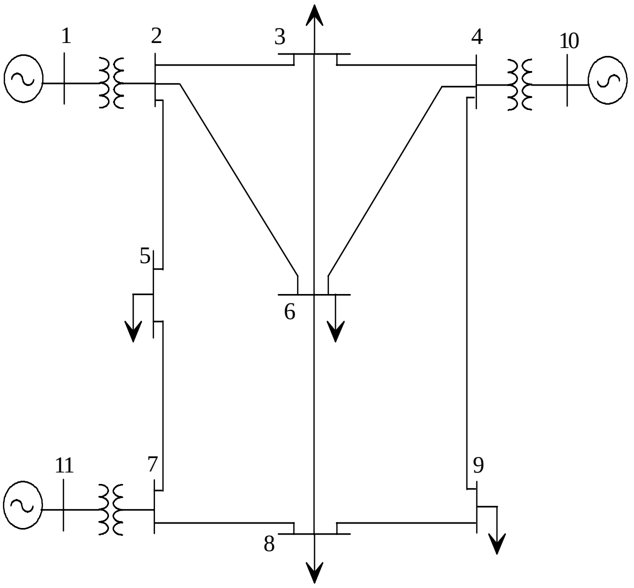

Fig. 6 11 bus system

The results of the point-to-point ATC are obtained by using the proposed method as shown in Table 6 and Table 7, respectively. The ATCs obtained from the cubic-spline interpolation technique are compared with the ATCs obtained from the recursive AC power flow method in terms of accuracy and computational time. Results shown in Tables 6 and 7 indicate that dynamic security constraint of the generators are considered only as the limit for both cases of power transfer. The generator's dynamic security constraint is referred to as the ISGA value that is obtained when the maximum difference of generator angle reaches to 180^o. In Table 6, by considering the outage of line 1-2 as a contingency, this may yields to a minimum amount of ATC that is 6 MW for the transfer case from selling bus 10 to buying bus 9 and it is obtained by the ISGA limit of 15.726. The outage of line 1-2 may also causes the minimum amount of ATC that is 1 MW for the transfer case from selling bus 11 to buying bus 3 and it is obtained by the ISGA limit of 2.77. On the other hand, the maximum ATC value of 1464 MW is obtained for the transfer case from selling bus 10 to buying bus 9. This is due to the outage of line 8-9 with the ISGA limit of 401.33. Furthermore, the outage of line 4-9 contributes to a maximum ATC value of 1721 MW for the transfer case from selling bus 11 to buying bus 3 and this is due to the ISGA limit of 1510.6 that

Table 6 ATC for the transfer case from selling bus 10 to buying bus 9 with line outage

Line outage	ISGA limit	ATC (MW)		CPU time (second)	
	T=8sec	Cubic-spline	Recursive AC power flow	Cubic-spline	Recursive AC power flow
1-2	15.726	6	6	2.67	0.75
2-3	603.18	1373	1373	3.65	282.16
2-5	1131.9	1078	1078	3.06	272.76
2-6	493.23	1349	1349	3.56	278.46
3-4	771.17	1310	1310	3.14	277.24
3-6	681.2	1394	1394	3.75	281.72
4-6	863.27	1329	1329	3.15	278.3
4-9	627.82	1053	1053	3.02	261.23
5-7	786.94	1191	1191	3.09	274.67
6-8	784.83	1010	1010	3.01	263.28
7-8	94.357	740	740	3.12	307.96
8-9	401.33	1464	1464	3.95	288.24

Table 7 ATC for the transfer case from selling bus 11 to buying bus 3 with line outage

Line outage	ISGA limit	ATC (MW)		CPU time (second)	
	T=8sec	Cubic-spline	Recursive AC power flow	Cubic-spline	Recursive AC power flow
1-2	2.77	1	1	2.14	0.23
2-3	1736.5	722	722	3.17	250.66
2-5	1258.6	543	543	3.05	239.97
2-6	1365.4	800	800	3.19	253.02
3-4	1227.8	830	830	3.20	257.92
3-6	1448.2	763	763	3.14	253.19
4-6	1390.4	769	769	3.12	256.36
4-9	1510.6	1721	1721	4.05	298.78
5-7	1324.4	483	483	3.03	231.66
6-8	1451.8	646	646	3.08	242.86
7-8	1743.1	613	613	3.07	233.23
8-9	1422.1	659	659	3.09	243.99

has been reached.

The ATC results shown in Tables 6 and 7 prove that the cubic-spline interpolation technique and the recursive AC power flow method give similar results of ATC. In terms of computational times, it is noted that the ATC computations using the proposed cubic-spline interpolation technique is much faster as compared to the time taken to compute ATC by using the recursive AC power flow method. By referring to the results shown in Tables 2-7, the power transfer that exceeds the specified value of ATC may agitate to a 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. On the other hand, the merit of using the cubic-spline interpolation technique method is that it does not require many recursive load flow solutions in the determining the ATC. Hence, this may yield to a fairly short computational time in estimating accurate value of ATC.

6 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. Comparison has been made in terms of accuracy and computational time in estimating the ATC that uses the cubic spline-interpolation technique and recursive AC power flow method. The simulation results prove that the proposed cubic-spline interpolation technique is a fast and accurate method for ATC evaluation as compared to the ATC method using recursive AC power flow solutions. On the other hand, power transfer that violates the ISGA limit may yield to a system collapse due to rotor angle instability. Nevertheless, the ATC computation using cubic-spline interpolation technique is suggested to be improved by considering the limitations of transmission line, voltage magnitude and ISGA.

Acknowledgements
This work was done under the auspices of the Ministry of Science, Technology and Innovation (MOSTI), Malaysia (EScience fund code 03-01-01-SF0160) and the Institute of Research, Development and Commercialization (IRDC), Universiti Teknologi MARA, Malaysia.

References:

[1] A.A.A El-Ela and R.A.A. El-Sehiemy, Transmission Cost Allocation Schemes in Competitive Power Systems, *WSEAS Transactions on Power Systems*, Vol. 3, No. 1, 2008, pp. 6-13.

[2] M.W. Mustafa, S.N. Khalid, H. Shareef and A. Khairuddin, Transmission Usage Allocation in Pool and Bilateral Trades Using Artificial Neural Networks, *WSEAS Transactions on Power Systems*, Vol. 2, No. 9, 2007, pp. 215-224.

[3] H. Sawhney and B. Jeyasurya, Application of Unified Power Flow Controller for Available Transfer Capability Enhancement, *International Journal of Electrical Power Systems Research*, Vol. 69, 2004, pp. 155-160.

[4] M.M. Othman, A. Mohamed and A. Hussain, Fast Evaluation of Available Transfer Capability Using Cubic-Spline Interpolation Technique, *International Journal of Electric Power Systems Research*, Vol. 73, 2005, pp. 335-342.

[5] G. Hamoud, Assessment of Available Transfer Capability of Transmission Systems, *IEEE Transactions on Power Systems*, Vol. 15, No. 1, 2000, pp. 27-32.

[6] M. Shaaban, Y. Ni, H. Dai and F.F. Wu, Considerations in Calculating Total Transfer Capability, *International Conference on Power System Technology, POWERCON*. Vol. 2, 1998, pp. 1356-1360.

[7] M. Shaaban, Y. Ni and F.F. Wu, Transfer Capability Computations in Deregulated Power Systems, *Proceedings of the 33rd Hawaii International Conference on System Sciences*, 2000, pp. 1-5.

[8] I. Musirin, M.R. Kalil and M.M. Othman, Optimal Reactive Power Dispatch Using Ant Colony Optimization Technique, *WSEAS Transactions on Power Systems*, Vol. 1, No. 8, 2006, pp. 1423-1430.

[9] R.D. Christie, B.F. Wollenberg and I. Wangensteen, Transmission Management in the Deregulated Environment, *Proceedings of the IEEE*, Vol. 8, No. 2, 2000, pp. 170-195.

[10] X. Luo, A.D. Patton and C. Singh, Real Power Transfer Capability Calculations Using Multi-Layer Fed-Forward Neural Networks, *IEEE Transactions on Power Systems*, Vol. 15, No.2, 2000, pp. 903-908.

[11] E.D. Tuglie, M. Dicorato, M.L. Scala and P. Scarpellini, A Static Optimization Approach to Assess Dynamic Available Transfer Capability, *Proceedings of the 21st IEEE International Conference of Power Industry Computer Applications*, 1999, pp.269-277.

[12] V. Vittal, Consequence and Impact of Electric Utility Industry Restructuring on Transient Stability and Small-Signal Stability Analysis, *Proceedings of the IEEE*, Vol. 88, No. 2, 2000, pp. 196-207.

[13] R.A. Rosales, D.R. Vega, D. Ernst, M. Pavella and J. Giri, On-Line Transient Stability Constrained ATC Calculations, *IEEE Power Engineering Society Summer Meeting*, Vol. 2, 2000, pp. 1291-1296.

[14] K. Cui, D.Z. Fang and C.Y. Chung, Analysis of Power Transfer Limit Under Dynamic Security Constraints, *International Conference on Power System Technology*, Vol. 1, 2004, pp. 496-501.

[15] J.A. Momoh and C.B. Effiong, Generation Rescheduling for Dynamic Security Enhancement for Multi-Area Power System, Vol. 4, 1997, pp. 3437- 3442.

[16] A.L. Bettiol, L. Wehenkel and M. Pavella, Transient Stability-Constrained Maximum Allowable Transfer, *IEEE Transactions on Power Systems*, Vol. 14, No. 2, 1999, pp. 654-659.

[17] Y. Yuan, J. Kubokawa, T. Nagata and H. Sasaki, A Solution of Dynamic Available

Transfer Capability by means of Stability Constrained Optimal Power Flow, *IEEE Bologna Power Tech Conference*, Vol. 2, 2003.

[18] G. Li and S.M. Rovnyak, Integral Square Generator Angle Index for Stability Ranking and Conttrol, *IEEE Transactions on Power Systems*, Vol. 20, No. 2, 2005, pp. 926-934.

[19] S.C. Chapra and R.P. Canale, Numerical Methods for Engineers: with Software and Programming Applications, McGraw-Hill 2003, 4th Edition.

[20] G.C. Ejebe, G.D. Irisarri, S. Mokhtari, O. Obadina, P. Ristanovic and J. Tong, Methods for Contingency Screening and Ranking for Voltage Stability Analysis of Power Systems, *IEEE Transactions on Power Systems*, Vol. 11, No. 1, 1996, pp. 350-356.

[21] R.H. Lasseter and R. Wang, The Impact of Generation Mix on Placement of Static Var Compensators, *IEEE Transactions on Power Delivery*, Vol. 14, No. 3, 1999, pp. 1018-1023.

[22] R. Wang, R.H. Lasseter, J. Meng and F.L. Alvarado, Fast Determination of Simultaneous Available Transfer Capability (ATC), Power System Energy Research Centre, Vol. 9, 1999, http://www.pserc.wisc.edu/ecow/get/publicatio/1999public

[23] P.R. Bijwe, R.S. Tare and S.M. Kelapure, Anticipatory Load Shedding Scheme for Loadability Enhancement, *IEE Proceedings of Generation, Transmission and* Distribution, Vol. 146, No. 3, 1999, pp. 483-490.

[24] S. Greene, I. Dobson and F.L. Alvarado, Sensitivity of Transfer Capability Margins with a Fast Formula, *IEEE Transactions on Power Systems*, Vol. 17, No. 1, 2002, pp. 34-40.

[25] M.M. Othman, A. Mohamed and A. Hussain, Available Transfer Capability Assessment Using Evolutionary Programming Based Capacity Benefit Margin, *International Journal of Electrical Power and Energy Systems*, Vol. 28, 2006, pp. 166-176.

[26] M.M. Othman, A. Mohamed and A. Hussain, Performance Comparison of Transfer Capability Computations in Deregulated Power Systems, *Proceedings of the Regional Symposium and Exhibition on Electricity Distribution*, August 2002.

[27] M.M. Othman, A. Mohamed and A. Hussain, Transmission Reliability Margin Assessment of the Malaysian Power System, *National Power Engineering Conference (PECon)*, December 2003.

[28] M.M. Othman, Sarizan Bin Ilias, Ismail Bin Musirin, Azah Mohamed and Aini Hussain, Determination of Available Transfer Capability Using Pareto Based Evolutionary Programming Technique, *First International Conference of Power Engineering and Optimization (PEOCO 2007)*, Shah Alam, Malaysia, 6 June 2007.

Norizan Mat received his B.Eng. (Hons) of Electrical Engineering from Universiti Teknologi MARA in 2007. He is currently working in a prestigious private company that is the Tenaga Nasional Berhad, Malaysia. His research interest is in the area of power system.

Muhammad Murtadha bin Othman received his B.Eng. (Hons) from Staffordshire University, England in 1998; M.Sc. from Universiti Putra Malaysia in 2000 and Ph.D. from Universiti Kebangsaan Malaysia in 2006. He received the award of best Ph.D. thesis 2005/2006 conferred by the Universiti Kebangsaan Malaysia. He currently lectures at the Universiti Teknologi MARA, Malaysia. His area of research interests are artificial intelligence, transfer capability assessment and reliability studies in a deregulated power system.

Ismail bin Musirin obtained his Diploma of Electrical Power Engineering in 1987, Bachelor of Electrical Engineering (Hons) in 1990; both from Universiti Teknologi Malaysia, MSc in Pulsed Power Technology in 1992 from University of Strathclyde, United Kingdom and PhD in Electrical Engineering from Universiti Teknologi MARA, Malaysia in 2005. He is currently The Head of Department in Electrical Power Engineering, Faculty of Electrical Engineering, Universiti Teknologi MARA, Shah Alam, Selangor. His area of research interests are artificial intelligence, voltage stability studies, and application of microgrid and distributed generation in power system.

Azah Mohamed obtained her B.Sc. (Eng.) degree from University of London in 1978. She joined Universiti Kebangsaan Malaysia in 1985 and obtained her M.Sc. and PhD. degrees from University of Malaya, Malaysia in 1988 and 1995, respectively. She is currently a professor at the Universiti Kebangsaan Malaysia. At present, she is the Deputy Dean of the Faculty of Engineering at the Universiti Kebangsaan Malaysia. Her research interests are in the areas related to transmission pricing, power quality and power system security.

Aini Hussain obtained her B.Sc. Electrical Engineering degree form Louisiana University, USA; M.Sc. degree in System and Control from

UMIST, England and PhD. degree from Universiti Kebangsaan Malaysia. She is currently a professor at the Universiti Kebangsaan Malaysia. At present, she is the Head of Department of Electrical, Electronics and Systems Engineering at the Universiti Kebangsaan Malaysia. Her area of research interests includes signal processing and application of artificial intelligence in power system. She is also a member of Tau Beta Pi.