

ATC ENHANCEMENT USING REACTIVE POWER FLOWS AND FACTS DEVICES

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Abstract

In deregulated electric power system, more concern is about customer satisfaction with their benefits. The power demand should be maintained in stability limits. To maintain the stability limits in network Available Transfer Capability (ATC) is needed. Basically in the network, the methodologies for evaluation of Linear ATC will not consider transfer of reactive power effect. But, in Enhancement of Linear ATC (ELATC) method the reactive power flows in the network are considered. This paper also emphasizes on the assessment of effect of TCSC as FACTS device on enhancement of ATC by determining their optimal location through Sensitivity Index method. The main contribution in this paper is assessment of ATC and the FACTS devices optimal location for better reliability in the system. A sample 3 bus system is taken as case study for theoretical evaluation and simulation studies. The MATLAB program has been developed and the simulation results are presented.

Key Words: Linear ATC, Enhanced ATC, Reactive Power Flows, FACTS Devices, Deregulation.

1 INTRODUCTION

In recent years, deregulated power system has made drastic changes in total power industry. Deregulation in electric power industry is reformation of the rules and financial incentives that are set up by government in order to control power industry. ATC in a deregulated power system is transferring of maximum power between one control area to another control area without violating the constraints in their limits. Those constraints mainly thermal, voltage profile and stability are considered [8].

FACTS device makes it possible to use circuit reactance, voltage magnitude, and phase angle as controls to redistribute line flow and regulate voltage profile. With suitable location, the effect of a TCSC on the ATC enhancement is studied and demonstrated through case study. Installing of TCSC in the appropriate location will enhance voltage profile and also recover the ATC [6].

From the literature, it is observed that some research has been carried out for ATC calculation using reactive power flows. But, it is observed that, no work has been carried out for ATC evaluation by including both reactive power flows and FACTS devices. In this paper, the ATC evaluation and analysis is carried out using both reactive power flows and FACTS device placement.

In this section, the role of ATC in the power system is presented. In Section 2, procedure for evaluation of linear ATC is presented. In Section 3, methodology for enhanced ATC is discussed. In Section 4, procedure for placement of FACTS devices is discussed. In Section 5, algorithm for ELATC evaluation is presented. In Section 6, simulation results and analysis are presented. In Section 7, conclusions are presented.

2 LINEAR ATC

In this technique, the DC-OPF is considered as base case solution. This linear methodology of ATC will work with a system without losses. In this type of system, the deviations between the net active injections and branch active power flows are linearly proportional to each other. For this analysis, the power transfer is considered as end to end transfer from bus 's' i.e., slack bus to another bus taken as 'i' in the system, but this transfer can be maximized that not to violate the line limits [1].

A. Power Shift Distribution Factor

The process of power transmission can be achieved by using PSDF [7]. The linear ATC evaluations typically consider a lossless transmission system, where there are changes only in the real powers of line and net power flows.

For illustration, a system is considered in order to maximize the power transfer but not violating the power flow limits in any line by assuming the point-to-point transfer to any bus 'i' from slack bus 's' in the system [4].

$$\rho_{jk,i} = \frac{\partial P_{jk}}{\partial P_s} = -\frac{\partial P_{jk}}{\partial P_i} \quad (1)$$

where, $\rho_{jk,i}$ = PSDF, ∂P_{jk} = Variation of power flow in j – k line,

∂P_s = Additional injected power from 's' bus,

P_i = Additional injected power from 'i' bus

B. LATC Calculation

In this process, the assumed system is lossless system that the power received by any bus 'i' is equal to the power added at bus 's'. Now the amount of power transfer for a specific line is equal to:

$$\Delta P_s^{jk} = \begin{cases} \frac{P_{jk}^{max} - P_{jk}^0}{\rho_{jk,i}}, & \rho_{jk,i} > 0 \\ \frac{-P_{jk}^{max} - P_{jk}^0}{\rho_{jk,i}}, & \rho_{jk,i} < 0 \end{cases} \quad (2)$$

where, P_{jk}^{max} is maximum power transfer of specific positive line and P_{jk}^0 is initial power transfer. Now, the linear ATC in all the lines has been calculated, the linear ATC of the system will be evaluated by smallest value of ΔP_s^{jk} as:

$$(LATC)_{s \rightarrow i} = \min \{ \Delta P_s^{jk} : \text{all lines } jk \} \quad (3)$$

□ j = 1 to n, k = 1 to n but, k ≠ j where n is the number of buses

3 ELATC WITH REACTIVE POWER FLOWS

For evaluating the ATC by considering the flow of reactive power, this ATC method is used i.e. enhanced linear method of ATC. For analyzing this method a discussion on flow of complex power is presented [2].

A. Branch Complex Power Flows

From π model of transmission line, the complex power flows to bus 'k' are formulated from bus 'j' as:

$$\begin{aligned} S_{jk} &= P_{jk} + jQ_{jk} \\ &= V_j^2 G_{jk} - V_j V_k Y_{jk} \cos(\theta_j - \theta_k + \alpha_{jk}) + j[-V_j^2 B_{jj} - V_j^2 B_{jk} - \\ &\quad V_j V_k Y_{jk} \sin(\theta_j - \theta_k + \alpha_{jk})] \end{aligned} \quad (4)$$

Form this, the active and reactive terms in the Eqn. (4) are separated as,

$$\begin{aligned} P_{jk} - V_j^2 G_{jk} &= -V_j V_k Y_{jk} \cos(\theta_j - \theta_k + \alpha_{jk}) \\ Q_{jk} + V_j^2 B_{jj} + V_j^2 B_{jk} &= -V_j V_k Y_{jk} \sin(\theta_j - \theta_k + \alpha_{jk}) \end{aligned} \quad (5)$$

Now, by performing the squaring on both sides of both equations and then by adding these equations turns into,

$$(P_{jk} - V_j^2 G_{jk})^2 + (Q_{jk} + V_j^2 B_{jj} + V_j^2 B_{jk})^2 = (V_j V_k Y_{jk})^2 \quad (6)$$

By considering LATC, above equation i.e. Eqn. (6) illustrated as a circle on $P_{jk} - Q_{jk}$ plane by having a center and radius as:

$$(P_{jk\theta}, Q_{jk\theta}) = (V_j^2 G_{jk}, -V_j^2 B_{jj} - V_j^2 B_{jk}) \quad (7)$$

$$S_{jk\theta} = V_j V_k Y_{jk\theta} \quad (8)$$

where, θ represents constant circle component.

By substituting the above Eqns. (7) & (8) in Eqn. (6),

$$(P_{jk} - P_{jk\theta})^2 + (Q_{jk} - Q_{jk\theta})^2 = S_{jk\theta}^2 \quad (9)$$

The above equation gives the information about the complex power flow at bus 'j'. But, here the complex power transfer is not same at both the ends. So, the flow of complex power at 'k' bus can be expressed as:

$$(P_{jk} - P_{jk\theta})^2 + (Q_{jk} - Q_{jk\theta})^2 = S_{kj\theta}^2 \quad (10)$$

If there is increase in power transfer, then the power flow also changes in the line. But, in the operating circle of the plane $P_{jk} - Q_{jk}$ all the operating points are lying in the circle. In this plane, by assuming the center of the circle at origin and the thermal limit (S_{jk}^{max}) is considered as radius of the circle for MVA rating characterization of each branch and it is represented as limiting circle as shown in the Fig. 2. But, by maintaining the power flow that in order to lie within the limiting circle, the evaluation of ELATC requires obtaining of maximum ΔP_s for the transfer power from 's' bus to any bus 'i' for all lines. i.e., $|S_{jk}| \leq S_{jk}^{max}$

B. Reactive Power Flows

The maximum flow of complex power in branch j-k is associated with (P_{jk}^0 , Q_{jk}^0) as the flow of complex power is controlled by operating points in the limiting circle. According to the sign of PSDF, there are two types of solutions for P_{jk}^0 .

The procedure for evaluation of P_{jk}^0 and Q_{jk}^0 is as:

$$P_{jk}^2 + Q_{jk}^2 = (S_{jk}^{max})^2 \quad (11)$$

By subtracting the Eqn. (11) from Eqn. (9) and after its expansion, it is obtained as:

$$Q_{jk} = \frac{1}{2Q_{jk\theta}} \left(-2(P_{jk}P_{jk\theta} + (S_{jk}^{max})^2 - M^2) \right) \quad (12)$$

where, $M^2 = S_{kj\theta}^2 - P_{jk\theta}^2 - Q_{jk\theta}^2$

By substituting Eqn. (12) in Eqn. (11), in terms of P_{jk}^0 the quadratic equation is obtained as:

$$(P_{jk\theta}^2 + Q_{jk\theta}^2)P_{jk}^{*2} - P_{jk\theta} \left((S_{jk}^{max})^2 - M^2 \right) P_{jk}^* + \frac{1}{4} \left((S_{jk}^{max})^2 - M^2 \right)^2 - Q_{jk\theta}^2 (S_{jk}^{max})^2 = 0 \quad (13)$$

Then, the maximum flow of complex power is acquired as:

$$P_{jk}^0 = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \quad (14)$$

$$Q_{jk}^0 = \sqrt{(S_{jk}^{max})^2 - P_{jk}^{*2}} \quad (15)$$

where, $a = (P_{jk\theta}^2 + Q_{jk\theta}^2)$, $b = -P_{jk\theta} \left((S_{jk}^{max})^2 - M^2 \right)$,

$$c = \frac{1}{4} \left((S_{jk}^{max})^2 - M^2 \right)^2 - Q_{jk\theta}^2 (S_{jk}^{max})^2$$

Now the amount of power transfer for a specific line can be obtained using Eqn.(2) which includes reactive power flows and designated as ΔP_s^{jk*} . Now, the Enhanced Linear ATC in all the lines has been calculated, the Enhanced Linear ATC of the system can be evaluated by smallest value of ΔP_s^{jk} as:

$$(ELATC)_{s \rightarrow i} = \min \{ \Delta P_s^{jk0} : \text{all lines } jk \} \quad (16)$$

□ $j = 1$ to n , $k = 1$ to n but, $k \neq j$ where n is the number of buses

4 PLACEMENT OF FACTS DEVICE

For enhancement of power transfer capability in the lines, the static prototypes of FACTS devices are assumed. As the time constant of these devices is assumed as very small, therefore this estimation is acceptable [3-5].

A. Exploration of transmission lines with power flows and losses

Let the complex voltages of bus 'j' and bus 'k' are considered as $V_j \delta_j$ and $V_k \delta_k$. Now, the complex power flowing from bus 'j' to bus 'k' can be expressed as:

$$\begin{aligned} S_{jk}^* &= P_{jk} - jQ_{jk} = V_j^* I_{jk} = V_j^* (I_R + I_C) \\ &= [V_j^2 G_{jk} - V_j V_k G_{jk} \cos(\delta_j - \delta_k) + V_j V_k G_{jk} \sin(\delta_j - \delta_k)] + \\ &j[V_j^2 (B_{jk} + B_c) - V_j V_k B_{jk} \cos(\delta_j - \delta_k) - V_j V_k B_{jk} \sin(\delta_j - \delta_k)] \\ &= V_j^* [(V_j - V_k)(G_{jk} + B_{jk}) + V_j(jB_c)] \end{aligned} \quad (17)$$

From this the active and reactive power flow from bus 'j' to bus 'k' are,

$$\begin{aligned} P_{jk} &= V_j^2 G_{jk} - V_j V_k G_{jk} \cos(\delta_{jk}) + V_j V_k G_{jk} \sin(\delta_{jk}) \\ Q_{jk} &= V_j^2 (B_{jk} + B_c) - V_j V_k B_{jk} \cos(\delta_{jk}) - V_j V_k B_{jk} \sin(\delta_{jk}) \end{aligned} \quad (18)$$

where, $\delta_{jk} = \delta_j - \delta_k$

Similarly, the active and reactive power flow from bus 'k' to bus 'j' are

$$\begin{aligned} P_{kj} &= V_k^2 G_{jk} - V_j V_k G_{jk} \cos(\delta_{jk}) + V_j V_k G_{jk} \sin(\delta_{jk}) \\ Q_{kj} &= V_k^2 (B_{jk} + B_c) - V_j V_k B_{jk} \cos(\delta_{jk}) - V_j V_k B_{jk} \sin(\delta_{jk}) \end{aligned} \quad (19)$$

Then, the active and reactive power losses are evaluated as:

$$\begin{aligned} P_L &= P_{jk} + P_{kj} = V_j^2 G_{jk} + V_k^2 G_{jk} - 2V_j V_k G_{jk} \cos(\delta_{jk}) \\ Q_L &= Q_{jk} + Q_{kj} = V_k^2 (B_{jk} + B_c) + V_j^2 (B_{jk} + B_c) - 2V_j V_k B_{jk} \cos(\delta_{jk}) \end{aligned} \quad (20)$$

B. Power Projection Model of TCSC

The connection of these devices is series connection with the lines. By using TCSC, its effect on the network is to reduce the transfer reactance between the buses by compensating the inductive reactance of a particular transmission line as a controllable reactance. As a result, this will lead to increase in maximum power transfer in that line, also there will be effective reactive power losses reduction in that line. The series capacitors placed in the line will help in improvement of voltage profiles. During the steady state, TCSC can be assumed as static reactance $-jX_c$. For power flow equations this controllable reactance can be implemented directly as control variable.

Line flows Without TCSC ($-jX_c$)

$$G_{jk} + jB_{jk} = \frac{r_{jk}}{r_{jk}^2 + x_{jk}^2} + j \frac{-(x_{jk})}{r_{jk}^2 + x_{jk}^2} \quad (21)$$

With TCSC ($-jX_c$)

$$G'_{jk} + jB'_{jk} = \frac{1}{r_{jk} + j(x_{jk} - x_c)} * \frac{r_{jk} - j(x_{jk} - x_c)}{r_{jk} - j(x_{jk} - x_c)} \quad (22)$$

Where, $G'_{jk} = \frac{r_{jk}}{r_{jk}^2 - j(x_{jk} - x_c)^2}$ and $B'_{jk} = \frac{-(x_{jk} - x_c)}{r_{jk}^2 - j(x_{jk} - x_c)^2}$

By using these equations modelling of TCSC for enhancing the capability of power transfer can be carried out.

C. Optimal Placement using sensitivity method for TCSC

i) Reduction of VAR power loss

For a TCSC placed between bus 'j' and bus 'k', a method for each device is assumed according to the sensitivity of system VAR loss (Q_L) with respect to its control variable (X_{jk}). This can be represented as loss sensitivity index

$$a_{jk}, \quad a_{jk} = \frac{\partial Q_L}{\partial X_{jk}} = [V_j^2 + V_k^2 - 2V_j V_k \cos(\delta_{jk})] \frac{R_{jk}^2 - X_{jk}^2}{(R_{jk}^2 + X_{jk}^2)^2} \quad (23)$$

By using the loss sensitivity indexes, the decision of optimal location of devices can be stated as it must be placed in a particular line which is having most positive value of loss sensitivity index ' a_{jk} '.

5 ALGORITHM FOR CALCULATING ELATC

The steps involved in evaluation of ELATC are organized as:

- Read input data $V_j, V_k, Y_{jk}, B_{jj}, G_{jk}, B_{jk}$
- Compute PSDF ($\rho_{jk,i}$) from Eq. (1)
- Compute P_{jk}^0 from Eq. (14)
- Calculate ΔP_s^{jk0} from Eq. (2)
- Evaluate ELATC from Eq. (16)
- Stop

6 SIMULATION RESULTS AND ANALYSIS

In this paper, for explanation of various methods to evaluate LATC and ELATC a sample three bus system was considered as one of the case studies.

A. LATC and ELATC

Now, the simulation results and analysis of these results are presented here. By considering bus 1 and bus 3 as seller bus and buyer bus respectively, the values of PSDF, LATC without reactive power and with reactive power are represented in Table 1 and Table 2 respectively.

In both results, the limiting line is line 2 and LATC and ELATC are 172.77 MW and 166.23 MW.

Line No.	Line Limit (MW)	PSDF	LATC (MW)
1	101.00	0.2360	427.97
2	131.00	0.7640	172.77
3	141.00	0.2360	597.77

Table 1 LATC values without reactive power

Line No.	Line Limit (MW)	PSDF	LATC (MW)
1	101.00	0.2360	427.97
2	127.00	0.7640	166.23
3	141.00	0.2360	597.77

Table 2 ELATC values with reactive power

The actual ATC value is 168 MW for AC power flows. But from simulation results it is clear that the error between original ATC and ELATC very less i.e., -1%, while the error is 4% in case of LATC.

This less error implies that there is more benefit from ELATC. Hence, it is concluded that at line 2 the independent system operator can obtain ATC because of limiting line. Now, by considering bus 2 and bus 3 as seller bus and buyer bus respectively, the values of PSDF, LATC without reactive power and with reactive power are represented in Tables 3 and 4 respectively. In both results, the limiting line is line 3 and LATC and ELATC are 171.66 MW and 166.73 MW.

Line No	Line Limit (MW)	PSDF	LATC (MW)
1	-101.00	-0.1785	565.54
2	132.00	0.1785	739.12
3	141.00	0.8214	171.66

Table 3 LATC values without reactive power

Line No	Line Limit (MW)	PSDF	LATC (MW)
1	-101.00	-0.1785	565.54
2	132.00	0.1785	739.12
3	136.96	0.8214	166.73

Table 4 ELATC values with reactive power

The actual ATC value is 168 MW for AC power flows. But from the simulation values it is clear that the error between original ATC and ELATC very less i.e., -0.7%, while the error is 2% in case of LATC. This less error implies that there is more benefit from ELATC. Hence, it is concluded that at line 3 the independent system operator can obtain ATC because of limiting line.

B. Optimal location of FACTS device

The placement of FACTS device is obtained by sensitivity index. The sensitivity index is calculated in each line using the static VAR losses with respect to controllable reactance.

Line No.	From – To Bus	a_{jk}
1	1 – 2	0
2	1 – 3	-0.0029
3	2 – 3	-0.0051

Table 5 Sensitivity Index values

The values of sensitivity index of line 2 is most positive than the remaining lines i.e., -0.0029 between the buses 1 and 3.

7 CONCLUSION

In this paper, the evaluation of Linear and Enhanced Linear ATC and sensitivity index for placement of FACTS devices for enhancement of ATC are presented. The allocation of ELATC for all transactions and optimal location of device placement provides the maximum information for future transaction in the system for the independent system operator. While comparing ELATC with LATC, the value of ELATC is having very less error i.e., the limiting line and the utmost positive value of sensitivity index will provide more benefits for system operator for enhancement of ATC in the system.

References

- [1] Santiago Grijalva, Peter W., Sauer, & James D, Weber, "Enhancement of Linear ATC Calculations by the Incorporation of Reactive Power Flows", IEEE Trans. on Power Systems, Vol. 18, No. 12, pp. 619-624, 2003.
- [2] Azhar B, Khairuddin, S, Shahnawaz Ahmed, M, Wazir Mustafa, Abdullah, A., Mahad., Zin & Hussein Ahmad, "A Novel Method for ATC Computations in a Large- Scale Power System", IEEE Trans. On Power Systems, Vol. 19, No. 2, pp. 1150-1158, pp.1150-1158, 2004.
- [3] Rajabi Ghahnavieh, Fotuhi-Firuzabad M, Mohammad Shahidehpour & Feullet, "Optimal Allocation of Available Transfer Capability in Operating Horizon", IEEE Trans. on Power Systems, Vol 24, No. 2, pp. 967-975, 2009.
- [4] Srinu Naik R, Vaisakh K., Anand K, "Determination of ATC with PTDF using Linear Methods in Presence of TCSC", IEEE Conf., Vol. 5, pp. 146-151, 2010.
- [5] Nagalakshmi S, Kalyani S, Alamelu Sobhana V, Naga Ranjeni R, & Deepamangal P, "Estimations of Available Transfer Capability under normal and contingency conditions in Deregulated Electricity Market", IEEE International Conference on Advances in Engineering, Science and Management, pp. 453-459, 2012.
- [6] Sambasivarao N, Amaranth J, Purnachandra rao V, "Enhancement of Available Transfer Capability in Deregulated Power system Using Series Facts Devices", IJERT, Vol. 2, 2013.
- [7] James A, Momoh and Surender Reddy S, "Optimal Location of Facts for ATC Enhancement", IEEE Conference, pp.1-5, 2014.
- [8] Srinivasa Varma P and Sankar V, "Available Transfer Capability Cost Analysis in Electricity Market", I-manager's Journal on Electrical Engineering, Vol. 8, No. 3, pp. 31-39, 2015.

