Linear ATC Enhancement with FACTS Devices Considering Reactive Power Flows using PTDF

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ABSTRACT

In the present day world power system deregulation is at its full stretch. In this deregulated environment there is a clear need for adequate computation of ATC which is currently being given at most importance. The insertion of FACTS devices in electrical systems seems to be a promising strategy to enhance ATC. In this paper, the viability and technical merits of boosting ATC using TCSC are analyzed. The methods used for determining ATC are linear methods, which are based on MVA loading of the system considering system thermal limit constraints, neglecting bus voltages and static collapse. Power Transfer Distribution Factors, commonly referred to as PTDFs, express the percentage of a power transfer that flows on a transmission facility. They are used to determine the maximum ATC that may be available across the system without violating line thermal limits. The effect of reactive power flows in line loading is not considered in linear ATC which is a major limitation. This paper describes a fast algorithm to incorporate this effect. In this paper the line post transfer complex flow is estimated based on exact circle equation and then ATC is evaluated using active power distribution factors. The effectiveness of the proposed method is successfully demonstrated on IEEE 30-Bus system.

Keywords

Linear ATC, ACPTDF, DCPTDF, TCSC, Reactive Power.

1. INTRODUCTION

The electricity market, trade and operation, in the deregulated environment requires ample transmission capability to satisfy the demand of increasing power transactions. The conflict of this requirement and the restrictions on the transmission expansion in the restructured electricity market has motivated the development of methodologies to enhance the available transfer capability (ATC) of the existing transmission grids [4]. Transfer capability is the measure of the ability of interconnected electric systems to reliably move or transfer electric power from one area to another area, by way of all transmission lines or paths between those areas, under specified system conditions. The units of transfer capability are in terms of electric power, generally expressed in MWs. According to the North American Electric Reliability Council (NERC) definition, ATC is “a measure of the transfer capability remaining in the physical transmission network for further commercial activities over and above already committed uses”.

The ATC value is given as: ATC=TTC-TRM-{ETC+CBM} Where TTC is total transfer capability, TRM is transmission reliability margin, CBM is capacity benefit margin and ETC is existing transmission commitment including customer services [2,3].

The available transfer capability indicates the amount by which interarea bulk power transfers can be increased without compromising system security. The value used for available transfer capability affects both system security and the profits made in bulk power transactions. The transfer direction is a real power transaction which takes place between bus s (slack bus) and bus i while holding all other power flow injections fixed at their base case levels. Although the maximum secure transfer should be determined using full nonlinear computations (considering both static and dynamic constraints), ATC studies often involve contingencies and multipattern scenarios, making this an alarming task for most real systems [1]. The linear methods used for determining ATC introduce a number of potential errors. One of the limitations is ignoring reactive power flows [6]. This paper proposes an improved fast method to compute ATC incorporating reactive power flows. Also AC Power Transfer Distribution Factors (ACPTDFs) and DC Power Transfer Distribution Factors (DCPTDFs), for the fast determination of ATC using thermal limits and voltage limits, are proposed in this paper.

Flexible AC transmission systems (FACTS) controllers have been mainly used for solving various power system steady state control problems. They are power electronic based compensating devices and are known for their ability to enhance power transfer capability [8-11].

2. ATC ASSESSMENT

2.1 Linear Method For Determining ATC:

The ATC between two areas provides an indication of the amount of additional electric power that can be transferred from one area to another for a specific time frame for a specific set of conditions. ATC can be a very dynamic quantity because it is a function of variable and interdependent parameters. These parameters are highly dependent upon the conditions of the network. Consequently, ATC calculations may need to be periodically updated. Because of the influence of conditions throughout the network, the accuracy of the ATC calculation is highly dependent on the completeness and accuracy of available network data [4-6].Linear ATC typically assumes a lossless system, where changes in real power flow is linearly related to changes in power injections. For illustration, let us assume a transfer from the slack bus l, to any bus m, and maximize this transfer without exceeding any line or transformer. The key to the linear power solution is the use of Power Transfer Distribution Factors (PTDF) expressed here as sensitivities of line real power injections [1,2]. These PTDFs are essentially current dividers in linear circuit theory. As such, they are large-change sensitivities and can be used to predict the change in the line flow (line p-n) due to a transfer bus (l) to bus (j) as

$$\rho_{pn,m} = \frac{\partial P_{pn}}{\partial P_l} = -\frac{\partial P_{pn}}{\partial P_m} \qquad (1)$$

$$\Delta P_{pn} = \rho_{pn,m} = -\rho_{pn,m}\Delta P_m \quad (2)$$

Note that $\Delta P_l = \Delta P_m$ is the amount of transferred power from slack to any other bus. For a given positive line P_{pn}^{max}, flow limit, assumed equal to the line MVA rating, and an initial positive line flow P_{pn}^{0}, the size of the transfer that drives the line to its limit is equal to

$$\Delta P_l^{pn} = \begin{cases} \dfrac{P_{pn}^{max} - P_{pn}^{0}}{\rho_{pn,m\to j}} & \rho_{pn,m} > 0 \\ \dfrac{-P_{pn}^{max} - P_{pn}^{0}}{\rho_{pn,m\to j}} & \rho_{pn,m} < 0 \end{cases} \qquad (3)$$

In order to determine ATC, the minimum value of ΔP_l^{pn} among all lines in the system is determined [1].

$$ATC_{l\to j} = min\{\Delta P_l^{pn} : all\ lines\ (p-n)\} \qquad (4)$$

Note that it is the linear relation between the transfer and the line flows that makes linear ATC the fastest algorithm for transfer studies [1].

2.2 Reactive Power Consideration In Linear ATC:

The transmission line complex flow is constrained to be on the operating circle and inside the limiting circle, as such, the maximum complex flow of the line *p-n* corresponds to point (P_{pn}^*, Q_{pn}^*). Two different solutions for P_{pn}^* can be obtained depending on the sign of the distribution factor. In order to compute P_{pn}^* and Q_{pn}^* the following system of equations must be solved;

$$P_{pn}^2 + Q_{pn}^2 = \left(S_{pn}^{max}\right)^2 \qquad (5)$$

The following operating circle equation is obtained after incorporating various equations:-

$$\left(P_{pn} - P_{ij\Theta}\right)^2 + \left(Q_{pn} - Q_{ij\Theta}\right)^2 = S_{pn\Theta}^2 \qquad (6)$$

Expanding Eqn. (5) and then subtracting it from Eqn. (6), gives

$$Q_{pn} = \left(\frac{1}{2}Q_{pn\Theta}\right)\left(-2P_{ij}P_{pn\Theta} + \left(S_{pn}^{max}\right)^2 - \left(S_{pn\Theta}^2 - P_{pn\Theta}^2 - Q_{pn\Theta}^2\right)\right) \quad (7)$$

Let us assume $S_{pn\Theta}^2 - P_{pn\Theta}^2 - Q_{pn\Theta}^2$ as T and now the above Eqn. (7) becomes

$$Q_{pn} = \left(\frac{1}{2}Q_{pne}\right)\left(-2P_{pn}P_{pne} + \left(S_{pn}^{max}\right)^2 - (T^2)\right) \qquad (8)$$

The quadratic expression in P_{pn}^* is obtained on substituting Eqn. (8) in Eqn. (5) and then replacing P_{pn} by P_{pn}^*, as:-

$$P_{pn}^{*2}\left(P_{pn\Theta}^2 + Q_{pn\Theta}^2\right) - P_{pn}^*\left[\left(\left(S_{pn}^{max}\right)^2 - T^2\right)P_{pn\Theta}\right] + \frac{1}{4}\left(\left(S_{pn}^{max}\right)^2 - T^2\right)^2 - Q_{pn\Theta}^2\left(S_{pn}^{max}\right)^2 = 0 \qquad (9)$$

Defining the corresponding constant coefficients:-

$$a = P_{pnb\Theta}^2 + Q_{pn\Theta}^2 \quad (10a)$$

$$b = -P_{pn}^*\left(\left(S_{pn}^{max}\right)^2 - T^2\right) \qquad (10b)$$

$$c = \frac{1}{4}\left(\left(S_{pn}^{max}\right)^2 - M^2\right)^2 - Q_{pn\Theta}^2\left(S_{pn}^{max}\right)^2 \qquad (10c)$$

Then the solution for the maximum complex flow is obtained as:-

$$P_{pn}^* = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \qquad (11a)$$

$$Q_{pn}^* = \sqrt{\left(S_{pn}^{max}\right)^2 + P_{pn}^{*2}} \qquad (11b)$$

The sign in the previous equation is chosen to be positive if the PTDF of line *p-n* is positive and negative otherwise [1].

$$\Delta P_l^{pn} = \begin{cases} \dfrac{P_{pn}^{max} - P_{pn}^{0}}{\rho_{pn,m\to j}} & \rho_{pn,m\to j} > 0 \quad (12) \\ \dfrac{-P_{pn}^{max} - P_{pn}^{0}}{\rho_{pn,m\to j}} & \rho_{pn,m\to j} < 0 \quad (13) \end{cases}$$

The process of computing linear ATC including the effect of reactive flows is summarized as follows:

Firstly compute the distribution factors $\rho_{pn,m}$ and then P_{pn}^* using Eqn. (10) and Eqn. (11a). Secondly compute the necessary transfer ΔP_l^{pn} using Eqn. (12) or (13) then the minimum ΔP_l^{pn} among all line ends is obtained.

Since the incorporation of reactive flows into the algorithm resides in computing a new line flow limit, all of the advantages of the linear ATC method are preserved [1]. Therefore, the basic ATC problem regarding thermal security limits is given by an initial operating state of the power system, determine the maximum amount ΔP for a transaction between seller (*s*) and buyer (*b*) such that $|S_{pn}| < |S_{pn}^{max}|$ for all *p-n* lines in the system [5].

It should be remarked that the value of the ATC with the Reactive Linear method is always smaller than that value of the ATC with the Linear method, which can be considered as a conservative characteristic of the method [6].

2.3 Computation Of PTDFs:

PTDFs determine the linear impact of a transfer on the elements of the power system. These values provide a linearized approximation of how the flow on the transmission lines and interfaces change in response to transactions between the seller and buyer [2].

2.3.1 DCPTDF Formulation:

The linear DCPTDFs, based on DC power-flow equations, are used to allocate MW flows on the lines for a transaction in the system. These equations are simply the real part of decoupled power-flow equations. So only angle and real powers are solved by iterating

$$[\Delta\delta] = [B]^{-1}\Delta P \qquad (14)$$

The net change in angle is

$$\Delta\delta = \Delta\delta^0 - \Delta\delta_{mn} \qquad (15)$$

Where $\Delta\delta^0$ is the base-case angle.

The power flow on lines i and j is given by

$$P_{ij,mn} = \left(\frac{1}{x_{ij}}\right)\left(\Delta\delta_i - \Delta\delta_j\right)m \qquad (16)$$

Where x_{ij} denotes the reactance of the line *i-j*. However, this has a poor accuracy due to the assumption involved in the DC power flow model [8].

2.3.2 ACPTDF Formulation:

The ACPTDFs proposed for the calculation of ATC were used to find various transmission system quantities for a change in MW transaction at different operating conditions. Consider a bilateral transaction t_k between a seller bus m and buyer bus n . Line 1 carries the part of the transacted power and is connected between buses i and j. PTDFs can be defined as

$$PTDF_{ij,mn} = \frac{\Delta q_1}{\Delta t_k} \qquad (17)$$

The transmission quantity q_1 can be either real power flow from bus i to j or j to i (P_{ji}). The above factors have been proposed to compute at a base-case load flow results using the sensitivity properties of NRLF Jacobian. Consider full Jacobian in polar coordinates [J_T], defined to include all the buses except slack.

$$\begin{bmatrix}\Delta\delta \\ \Delta V\end{bmatrix} = \begin{bmatrix}\frac{\partial P}{\partial \delta} & \frac{\partial P}{\partial V} \\ \frac{\partial Q}{\partial \delta} & \frac{\partial Q}{\partial V}\end{bmatrix}^{-1} \begin{bmatrix}\Delta P \\ \Delta Q\end{bmatrix} = [J_T]^{-1} \begin{bmatrix}\Delta P \\ \Delta Q\end{bmatrix} \quad (18)$$

In the above equation the change in active power flow of line i-j with respect to changes in state variables is determined as

$$\frac{\partial P_{ij}}{\partial \delta_e} = \begin{cases} 0 & for\ e \neq i,j \\ -V_iV_jY_{ij}\sin(\delta_i - \delta_j - \theta_{ij}) & for\ e = i \\ -V_iV_jY_{ij}\,sin(\delta_i - \delta_j - \theta_{ij}) & for\ e = j \end{cases} \quad (19)$$

$$\frac{\partial P_{ij}}{\partial V_e} = \begin{cases} 0 & for\ e \neq i,j \\ 2V_iY_{ij} + V_jY_{ij}\cos(\delta_i - \delta_j - \theta_{ij}) & for\ e = i \\ V_jY_{ij}\cos(\delta_i - \delta_j - \theta_{ij}) & for\ e = j \end{cases} \quad (20)$$

In a base-case load flow, if only one of the kth bilateral transactions is changed by $\Delta\ t_k$ MW, only the following two entries in the mismatch vector on right-hand side of Eqn. (18) will be non zero:

$$\Delta\ P_i = \Delta\ t_k\,, \quad \Delta P_j = -\Delta\ t_k \qquad (21)$$

The new voltage profile can be calculated from Eqns. (18) and (21). These can be utilized to compute all of the transmission quantities q_1 and hence corresponding quantities $\Delta\ q_1$ from the base case. Once the $\Delta\ q_1$ for all lines corresponding to a change in the transaction $\Delta\ t_k$ is known, the PTDFs can be obtained from Eqn. (17) [7].

3. TCSC MODEL

FACTS devices such as thyristor controlled series compensators controls the power flow in the network, and helps to reduce the flows in heavily loaded lines. The thyristor-controlled group employs capacitor and reactor banks with fast solid-state switches in traditional shunt or series circuit arrangements. The thyristor switches control the on and off periods of the fixed capacitor and reactor banks and thereby realize a variable reactive impedance. Figure 1 shows a model of a transmission line with a TCSC connected between buses *i* and *j*. The transmission line is represented by its lumped Π equivalent parameters connected between the two buses. During the steady state, the TCSC can be considered as a static reactance $-jX_c$. This controllable reactance, X_c, is directly used as the control variable to be implemented in the power flow equation [2,9,10].

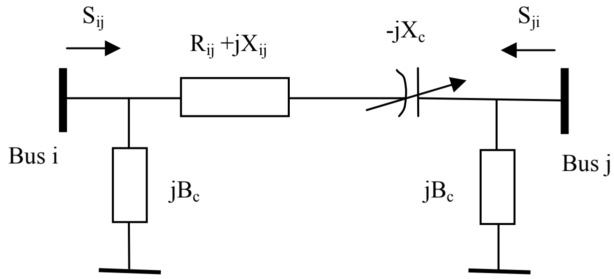

Fig. 1: Model Of TCSC

The following equations are used to model TCSC. The complex power from bus *i* to *j* is

$$S_{ij}^* = P_{ij} - Q_{ij} = V_i^* I_{ij} = V_i^* \left[[G_{ij} + j(B_{ij} + B_c)] - V_i^* V_j (G_{ij} + jB_{ij}) \right] \qquad (22)$$

From the above equations the real and reactive power equations can be written as

$$P_{ij} = V_i^2 G_{ij} - V_iV_jG_{ij}\cos(\delta_i - \delta_j) - V_iV_jB_{ij}\sin(\delta_i - \delta_j) \quad (23)$$

$$Q_{ij} = -V_i^2(B_{ij} + B_c) - V_iV_jG_{ij}\sin(\delta_i - \delta_j) + V_iV_jB_{ij}\cos(\delta_i - \delta_j) \qquad (24)$$

4. SENSITIVITY APPROACH FOR OPTIMAL PLACEMENT OF TCSC

Generally, the location of FACTS devices depends on the objective of the installation. In this paper the main objective considered is to enhance ATC. Consider a line connected between buses *m* and *n* and having a net series impedance of *Xmn*, that includes the reactance of a TCSC, if present, in that line[9]. The loss sensitivities with respect to *Xmn* can be computed as**:**

$$a_{mn} = \frac{\partial Q_L}{\partial X_{mn}} = [V_m^2 + V_n^2 - 2V_mV_n\cos(\delta_m - \delta_n)]\frac{R_{mn}^2 - X_{mn}^2}{(R_{mn}^2 + X_{mn}^2)} \qquad (25)$$

Where, V_m is the voltage at bus m,
V_n is the voltage at bus n,
R_{mn} is resistance of line between bus m and n,
X_{mn} is the reactance connected between bus m and n.
With the sensitive indices computed for FACTS device, TCSC, should be placed in the most positive line [11].

5. SIMULATION AND RESULTS

A sample 30-bus system is considered to illustrate the implementation of TCSC for ATC enhancement. The simulation has been carried out for the IEEE 30 bus system, by incorporating FACTS device (i.e. TCSC), using Power World Simulator Software.

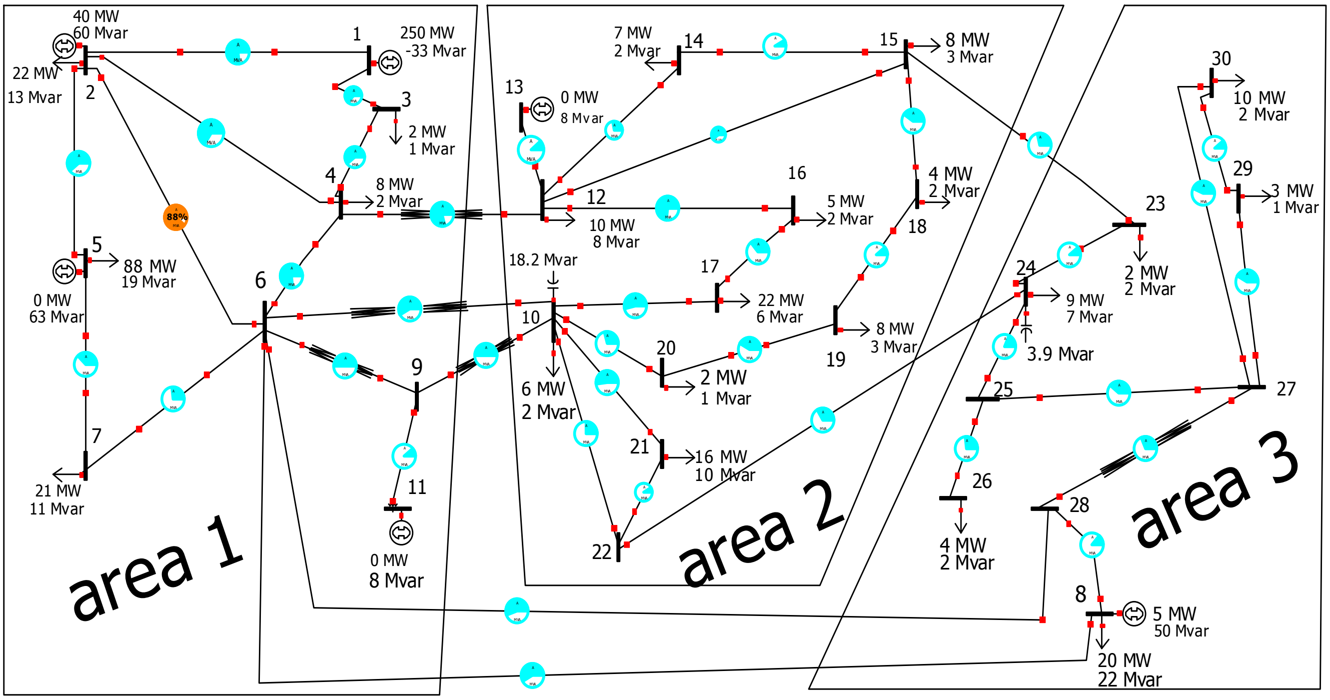

Fig 2: Modified IEEE 30 bus system

The single line diagram of the modified IEEE-30 bus system is shown in figure 2. The system is divided in to three areas. The ATC is calculated between all the areas. Base values are assumed to be 100 MVA .The ATC enhancement results for the 30 bus system, ignoring and considering reactive power flows can be observed from the below graph:

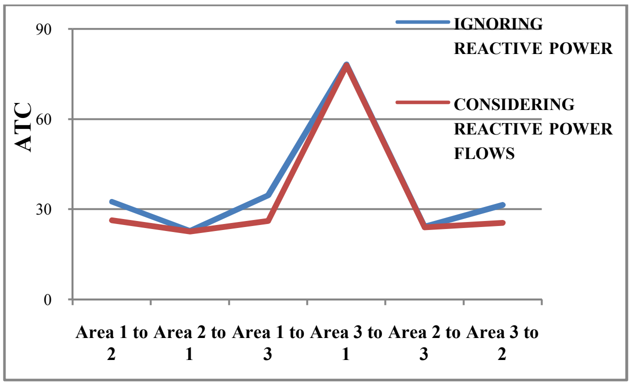

Fig 3 : Available Transfer Capability (ATC)

The proposed PTDFs can be computed quite quickly at base case load flow results and can be utilized for changes in system operating conditions. Use of these factors offer an approximate but extremely fast model for the static ATC determination. However DCPTDFs are derived based on DC load flow assumptions and hence provide less accurate results when compared to ACPTDFs. The ATC using ACPTDF and DCPTDF methods for ignoring and considering reactive power flows is plotted below.

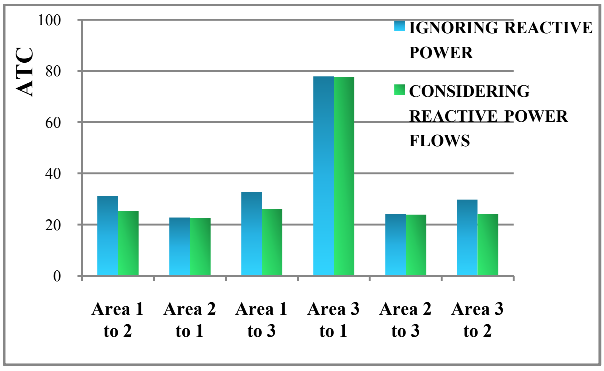

Fig 4: ATC using ACPTDF

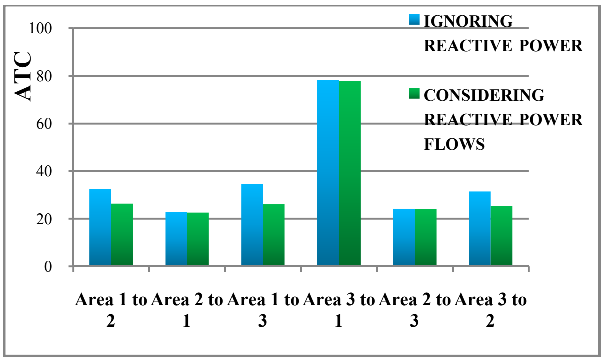

Fig 5: ATC using DCPTDF

The FACTS device considered here is Thyristor Controlled Series Capacitor (TCSC). By using sensitivity approach analysis, the optimal placement of TCSC is determined. The most positive sensitivity in case of TCSC is highlighted in the tabular form. The TCSC is located in the line connected between buses 14 and 15. The sensitivity indices for TCSC at different compensation levels is tabulated in the table 1.

Table 1: Sensitivity Factors For TCSC

Line	From Bus	To Bus	Sensitivity Index		
			TCSC(20%) (a_{ij})	TCSC(40%) (a_{ij})	TCSC(60%) (a_{ij})
1	1	2	-2.9812	-3.5610	-2.0961
2	1	3	-0.8416	-1.1476	-1.1747
3	2	4	-0.1973	-0.2390	-0.1513
4	2	5	-0.8124	-1.1811	-1.4882
5	2	6	-0.3506	-0.4234	-0.2634
6	3	4	-0.6649	-0.7656	-0.3633
7	4	6	-0.6010	-0.7972	-0.7401
8	4	12	-0.3431	-0.61004	-1.3726
9	5	7	-0.0653	-0.0652	-0.0023
10	6	7	-0.1458	-0.1777	-0.1159
11	6	8	-0.1062	-0.1414	-0.1330
12	6	9	-0.1777	-0.3160	-0.7110
13	6	10	-0.0536	-0.0953	-0.2144
14	6	28	-0.0393	-0.0527	-0.0508
15	8	28	-0.0033	-0.0042	-0.0029
16	9	10	-0.1708	-0.3037	-0.6832
17	9	11	-0.0091	-0.0162	-0.0364
18	10	17	-0.0287	-0.0299	-0.0049
19	10	20	-0.0063	-0.0051	0.0032
20	10	21	-0.0196	-0.0147	0.0134
21	10	22	-0.0041	-0.0027	0.0037
22	12	13	-0.0091	-0.0161	-0.0362
23	12	14	-0.0051	-0.0035	-0.0044
24	12	15	-0.0214	-0.0121	0.0253
25	12	16	-0.0094	-0.0066	0.0076
26	**14**	**15**	**0.000059**	**0.00012**	**0.00019**
27	15	18	-0.0028	-0.0018	0.0028
28	15	23	-0.0014	-0.0009	0.0015
29	16	17	-0.0040	-0.0055	-0.0057
30	**18**	**19**	**-0.00024**	**-0.00015**	**0.00024**
31	19	20	-0.0028	-0.0017	0.0031
32	21	22	-0.0004	-0.00023	0.00036
33	22	24	-0.00087	0.00037	0.0033
34	23	24	-0.00025	-0.00016	0.00024
35	24	25	-0.00039	-0.00008	0.00083
36	25	26	-0.00047	0.00039	0.0022
37	25	27	-0.0025	-0.0012	0.0034
38	28	27	-0.0613	-0.1090	-0.2453
39	27	29	-0.0026	-0.0012	0.0038
40	27	30	-0.0028	-0.0012	0.0042
41	29	30	-0.00057	-0.00026	0.00083

The ATC results of the system without and with TCSC, at different compensation levels, for a modified IEEE-30 bus system can be observed from the tables below. Table 2 represents ATC results for ignoring reactive power and Table 3 for considering reactive power. The value of the ATC is enhanced considerably by placing TCSC in the system.

Table 2: ATC Ignoring Reactive Power

From Area To Area	ATC Without FACTS	ATC With TCSC(20%)	ATC With TCSC(40%)	ATC With TCSC(60%)
1-2	32.56	32.57	32.58	32.6
2-1	22.86	22.94	23.03	23.12
1-3	34.63	34.64	34.64	34.64
3-1	78.23	78.23	78.23	78.23
2-3	24.27	24.36	24.45	24.56
3-2	31.48	31.49	31.5	31.51

Table 3: ATC Considering Reactive Power Flows

From Area To Area	ATC Without FACTS	ATC With TCSC(20%)	ATC With TCSC(40%)	ATC With TCSC(60%)
1-2	26.36	26.37	26.37	26.38
2-1	22.65	22.72	22.81	22.91
1-3	26.12	26.12	26.12	26.12
3-1	77.87	77.87	77.87	77.87
2-3	24.05	24.13	24.22	24.33
3-2	25.49	25.49	25.5	25.51

The plots which represent the lodabilty of transmission lines at different compensation levels were shown in figures 6 and 7. From the plots below it can be clearly observed that by placing TCSC in the most positive lines, the power carrying capability of most of the transmission lines increases.

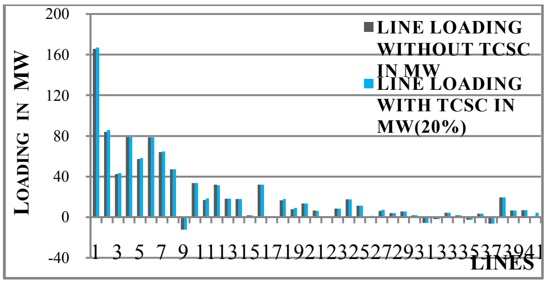

Fig 6: Loadability Of Lines At 20% Compensation

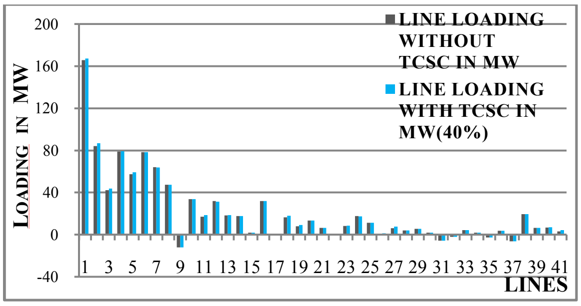

Fig 7: Loadability Of Lines At 40% Compensation

6. CONCLUSION

An accurate ATC computation is also very important to the transmission system. If the computed ATC is less than the ATC of the system, the transmission of power will not be efficient economically, if the computed ATC is more than the ATC of the system, the transmission will be operating in a dangerous state and any power increased will stand a chance to collapse the whole system and the result of that is disastrous. The results obtained in this paper by incorporating the effect of reactive power flows in transmission elements show a significant error reduction in linear ATC. The method is based on a megavar-corrected megawatt limit, which captures the change in reactive power flow as the active power flow in the line increases due to large transfers. This method can be easily incorporated into existing linear ATC software. Also ATC is calculated using AC and DC power transfer distribution factors. The inclusion of reactive power and FACTs device in a linear ATC can enhance the maximum transaction over a transmission system.

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