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Mitigating Transmission Congestion and Enhanced ATC Using FACTS Device in the Deregulated Power Systems

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Abstract

Series capacitors have been successfully utilized for many years in electric power networks. With series compensation, it is possible to increase the transfer capability of power transmission systems at a favorable investment cost and with a short installation time compared to the building of additional lines. This is due to the inherent ability of series capacitors to achieve improved voltage regulation and reactive power balance, improved load sharing between parallel lines. The impacts of the FACTS controller and its control setting on power system performance are also presented in the form of practical case studies.

Keywords: SSR, TCSC, FACTS, Transfer capability

Introduction

The electricity supply industry of the world is always changing, causing new opportunities and challenges to the users of high voltage transmission systems. The ratings of the various network components and the operating state determine the maximum power carrying capability of the network elements. However, the configuration of the network can further limit the overall power-transfer capability. These stem mainly from the strong increase in interregional and/or international power transfer, the effects of deregulation, and political, economical, and ecological considerations on the building of new transmission facilities. Technically, limitations on power transmission capability in a grid can always be removed by adding of new transmission and/or generation capacity. This, however, may not be practicable or desirable in the real case, for a variety of reasons. Adding of new lines and/or extending of existing substations may be too costly and time-consuming. Concessions for new right of way may be hard or impossible to come by. And lastly, environmental impact aspects today are much more important than they used to be and need to be addressed in a serious way in conjunction with transmission development procedures. In cases of need to transmit large amounts of power over long distances, for instance in conjunction with establishing of power links between countries or regions of countries, Thyristor-Controlled Series Compensation (TCSC) based on state of the art high power electronics will help to alleviate such constraints and thereby offer a superior option, from technical, economic and environmental points of view. The primary uses of TCSC are to enhance

Constraints of Line Loading

Transfer capability is the measure of the ability of interconnected electric system to reliably move or transfer power from one area to another over all the transmission lines (or paths).

Power flow along a transmission line is a function of the sending end voltage (s V), receiving end voltage (Vr), the angle between them(δ) and the line reactance (X) and is given by

$$P = \frac{V_s V_r}{X_r} \sin \delta \qquad (1)$$

Assuming that bus bar voltage magnitudes are maintained at fixed levels, in order to increase power flow, δ has to be increased (the angle between s V & Vr). However increasing δ , increases the risk of transient stability problems if a fault were to occur along the line. The main factor limiting steady-state power flow is the question of stability. This often has the effect of constraining maximum circuit loading to a level well below the maximum thermal capacity.

In the power flow relation if X is the line reactance and I is the line current then the reactive power absorbed by the line is given by

$$Q_1 = I^2 X, \qquad (2)$$

This equation is load dependent, greater the line loading, greater is the reactive power absorption. If the reactive power is not available locally to offset the reactive power absorbed by the line, and then line loading is constrained. Further, the shunt capacitance will generate reactive power according to the equation

$$Q = V^2 B, \qquad (3)$$

where B is the total line charging suceptance of the line. Thus we see that lightly loaded lines generate reactive power. Under heavy loading condition the reactive power absorbed by line reactance will be greater than the reactive power generated, by the line suceptance and so on. Hence under changing load conditions, there is a variation of reactive power thus some dynamic reactive compensation is needed to ensure that reactive power balance is met and the line loading is not adversely constrained [1]. It is thus clear that a loading condition exists where the shunt reactive power generation of the line is equal to the reactive power absorbed by the line. This is called the natural load of the line and is given by

$$P_o = \frac{V^2}{Z_o} \quad (4)$$

where Z_o = Surge Impedance = $\sqrt{\frac{L}{C}}$

“FACTS” is an acronym for Flexible A.C Transmission system. The philosophy of FACTS is to use power electronic controlled devices to control power flows in a transmission network, thereby allowing transmission line to be loaded to its full capability. Power electronic controlled devices, such as static VAR compensators, have been used in transmission networks for many years; however, Dr N.G.Hingorani introduced the concept of FACTS as a total network control philosophy in 1988 from the Electric Power Research Institute (EPRI) in USA[2].

FACTS devices are based on solid state control and so are capable of control actions at very high speed. The three parameters that control transmission power flow are line impedance, sending and receiving voltage magnitude and phase of sending and receiving end voltages. Conventional control of these parameters, although adequate during steady-state and slowly changing load conditions, cannot in general be achieved quickly enough to handle dynamic system conditions. This can be achieved by the use of FACTS controllers.

Thus FACTS device provide reactive compensation, which allow the line to behave as though it is naturally loaded. The use of reactive compensation is by no means new; however, the advantage that FACTS provide is, firstly that the compensation can be infinitely varied, as opposed to merely switching reactors inand out, and secondly, that the compensation can be varied at high speed thus giving stability advantage. The term “FACTS” covers several power electronics based systems used for AC power transmission. FACTS solutions are justifiable in applications requiring one or more of the following qualities.

- Rapid dynamic response
- Ability for frequent variations in output
- Smoothly adjustable output

FACTS devices are classified under two main headings: Series and Shunt compensated equipment

Series and Shunt Facts Devices

Amongst the available series and shunt FACTS devices TCSC and SVC are more prominent.

Series Facts Device

Thyristor Controlled Series Capacitor (TCSC)

It introduces a number of important new benefits in the application of series capacitors

- Mitigation of sub synchronous resonance risks
- Damping of active power oscillation.
- Post contingency stability improvement
- Dynamic power flow control.

The other benefits are:

- Increases power transfer
- Improves reactive power balance
- Improves voltage regulation
- Economic savings

The benefits of TCSC are also applicable for the modified existing series capacitor system either fully or partially by thyristor control and there by extending their impact and usefulness in the grid.

Shunt Facts Device

Static Var Compensator (SVC)

The SVC is a solid-state reactive power compensation device based on high power thyristor technology. An SVC can improve system transmission and distribution performance in a number of ways. Installing an SVC at one or more suitable points in the network can increase transfer capability and reduce losses while maintaining a smooth voltage profile under different network conditions. The dynamic stability of the grid can also be improved and active power oscillations mitigated. The benefits of SVC to power transmission are:

- Stabilized voltages in weak systems.
- Higher transient stability limit.
- Increased damping of minor disturbances
- Reduced transmission losses.
- Increased transmission capacity.
- Greater voltage control and stability
- Power swing damping.

System inter-connected via a relatively weak link often experience power oscillation problems. Transmission capability is then determined by damping. By increasing the damping factor (typically by 1–2 MW per MVar installed) and SVC can eliminate or postpone the need to install new lines and it has been proved that SVC can boost transmission capacity by 30-50 percent in most cases. Optimum improvement is some times achieved in combination with series compensation.

Thyristor Ontrolled Series Capacitor

A. Basic Circuit

The basic circuit from which TCSC is built is given in Fig. 1[3]. In TCSC the circuit is connected in series to a transmission line. The firing angle α of the thyristor determines the equivalent reactance Xeq of the circuit and is defined as the delay angle measured from the peak of the capacitor voltage to the firing instant. The equivalent reactance Xeq is determined by

$$X_{eq}(\alpha) = \frac{X_C X_L(\alpha)}{X_L(\alpha) + X_C}$$

$$X_C = -\frac{1}{\omega C}; \qquad X_L = \omega L \cdot \frac{\pi}{\pi - 2\alpha - \sin(2\alpha)}$$

(5]

and the characteristic of Xeq versus firing angle α is given in figure 2.

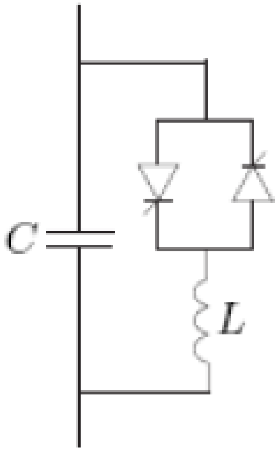

Figure. 1. Basic circuit for TCSC

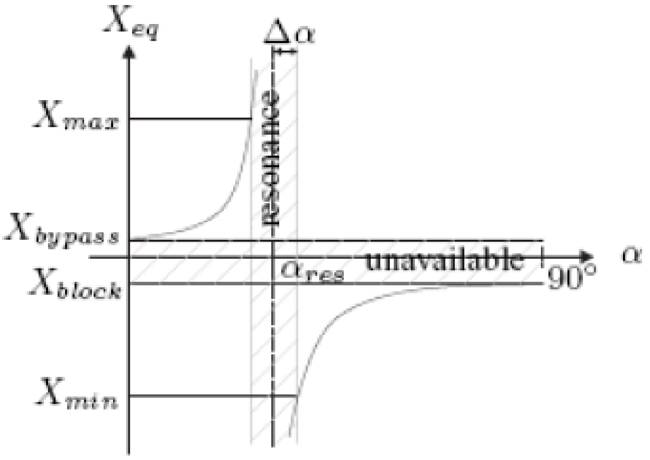

Figure 2. Equivalent reactance Xeq of TCSC

Operating modes

Bypass mode (α=00): The thyristor valve is triggered continuously. The basic circuit behaves like a parallel connection of the series capacitor and the inductor.

Inductive boost mode (00<α<αres): For α below the resonance angle the equivalent reactance Xeq is positive corresponding to an inductance.

Capacitive boost mode (αres<α<900): If the firing angle is larger than the resonance angle, the equivalent reactance is negative resulting in capacitive behavior.

Blocking mode (α=900): The thyristor is not triggered and therefore kept in non conducting state. Simply the fixed capacitor contributes to the reactance.

Limitations

From the characteristics of the basic circuit, some limitations concerning the firing angle α give implicitly rise to constraints on the equivalent reactance Xeq. The minimal and maximal values for the firing angle are 00 and 900, respectively, resulting in an unavailable band between X block and X bypass. As it is not acceptable to introduce an infinite reactance in series to a line, the firing angle in case of the TCSC must be kept at a certain distance $\Delta\alpha$ from the resonance angle α bres. This yields an upper bound Xmax and a lower bound X min for Xeq

Problem Definition

The fast changing electricity supply industry of the world are undergoing continuous changes and restructuring. They are becoming heavily loaded and are being operated in ways not envisioned, due to the effects of deregulation, economical and ecological considerations on building of new transmission facilities. This has necessitated utilizing the existing transmission system to its fullest capacity and improving the transfer capability in the system. Particular cases of uneven loading of the lines result in not utilizing the full capacity of the transmission system resulting in reduced transfer capability. This occurs when different voltage lines runs in parallel with each other. In the instant case, there is a parallel running of 220kV and 400kV which makes the 400kV system to be under utilized and 20kV system to be fully loaded resulting in more losses and reduced power transfer capacity. Further, the loading limits in long transmission lines are often restricted due to oscillation which imposes low stability limits. Hence TCSC compensation is employed in electric power system to raise the power transmission limit of long high voltage lines [4]. Figure 3 shows an 11 bus system (part of a larger existing system) with generations of 1000 and 240 MW feeding to bus 169 and 171 at 220 kV level. There is a long 400 kV double circuit transmission line between buses 54 and 58 with transformers on either side of the buses connected to 220 kV buses. The lines at 220kV level are of drake conductors and that at 400 kV level are of twin moose conductors. Two shunt reactors are connected at buses 54 and 58.There are several loads connected at different buses as shown in the figure.

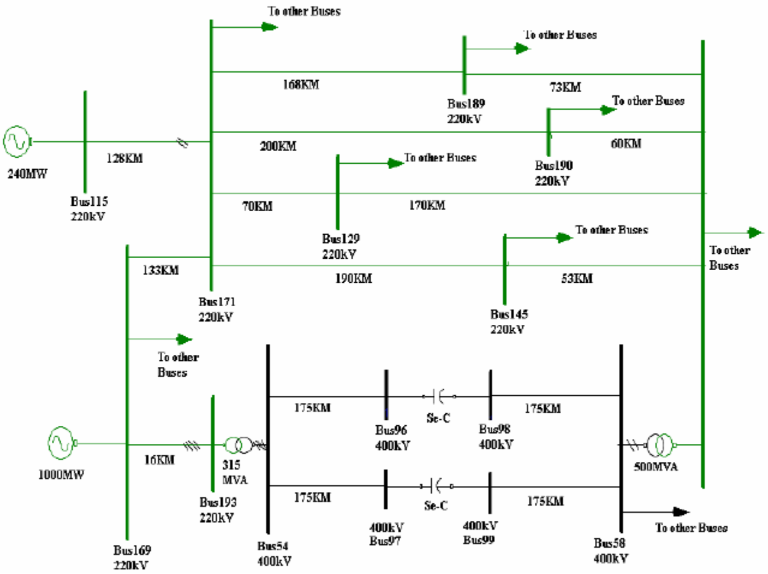

Figure .3 Part of the Large Inter connected System with buses of interest

The problem associated with this large interconnected system is that due to parallel 220 kV paths available, maximum power flow on 400 kV line is not occurring. It is required to investigate the application of series compensation of FACTS devices on the 400 kV line to push the power these lines.

Load Flow Analysis

Load flow is one of the analyses; most commonly used computational procedure in power system. The load problem can be defined as: Given the load, power consumption at all buses, power generation at each generator, power flow in each line and transformer of interconnection network, the voltage magnitude and phase angle at each bus are obtained. Analyzing the solution of the problem for numerous conditions helps to ensure that the power system is designed to satisfy its performance criterion.

The load flow was conducted for the given system and it was observed that 400kV lines were loaded only to 61 %. The low loading is due to the long line length and the line impedance. In order to improve the power flow in 400 kV lines, two fixed capacitors of 500 MVAr's each are connected in series in the lines between the buses 54 and 58 to mitigate the problem of low power flow. In order to analyze the best location for placement of series compensation, the analyses was done with the fixed series capacitor being installed at three different locations. In the first case the compensation was provided at the receiving end of the line. Table 1 gives the fixed capacitor compensation at the receiving end of line54- 58 with power flows in 400 kV bus and some of the major 220 kV buses, the total system generation and the loss. In the second case the compensation was provided at the sending end of the said 400 kV line and table 2 gives the respective readings. In the third case the compensation was provided at the mid point of the 400 kV line as shown in figure 4. Table 3 gives the corresponding readings. Since the compensation is provided at the mid point, the shunt line reactors on either side of the lines are removed as the line length is reduced and table 4 gives the line flows, total power and loss.

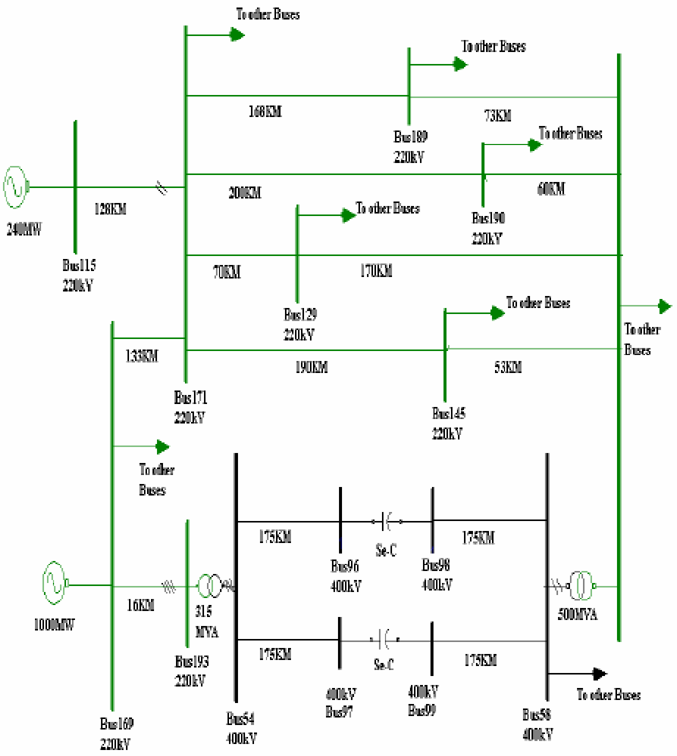

Figure .4 Part of the Large Inter connected System with mid point fixed capacitor compensation

Table- 1; Fixed capacitor compensation at receiving end of line 54-58 with flows, system generation and loss in MW

Compensation	line flow 54-58 per circuit	line flow 171-189	line flow 171-190	line flow 171-19	line flow 171-145	system power gen	system power loss	Loss In % age
Nill	216.226	97.799	83.149	131.088	75.100	28996.259	1176.231	4.056
30%	243.293	94.338	79.925	127.627	71.726	28990.735	1170.406	4.037
35%	248.436	93.677	79.310	126.967	71.082	28989.883	1169.550	4.034
40%	253.796	92.987	78.667	126.277	70.409	28989.056	1168.727	4.032
45%	259.391	92.271	77.999	125.561	69.709	28988.260	1168.091	4.030
50%	265.226	91.512	77.292	124.802	68.970	28987.512	1168.223	4.027
55%	271.325	90.722	76.556	124.012	68.199	28986.850	1166.570	4.0424

Table- 2; Fixed capacitor compensation at sending end of line 54-58 with flows, system generation and loss in MW

Compensation	line flow 54-58 per circuit	line flow 171-189	line flow 171-190	line flow 171-19	line flow 171-145	system power gen	system power loss	Loss In % age
30%	241.737	94.935	80.464	128.202	72.253	28992.722	1172.515	4.044
35%	246.530	94.397	79.959	127.660	71.717	28992.157	1171.949	4.042
40%	251.508	93.837	79.435	127.096	71.161	28991.592	1171.397	4.040
45%	256.681	93.255	78.889	126.510	70.582	28991.064	1170.585	4.039
50%	262.059	92.650	78.321	125.900	69.980	28890.561	1170.350	4.037
55%	267.653	92.020	77.730	125.266	69.353	28990.060	1169.858	4.035

Table- 3; Fixed capacitor compensation at the center of line 54-58 with flows, system generation and loss in MW

Compensation	line flow 54-58 per circuit	line flow 171-189	line flow 171-190	line flow 171-19	line flow 171-145	system power gen	system power loss	Loss In % age
30%	245.458	94.257	79.841	127.535	71.621	28990.448	1170.251	4.037
35%	250.755	93.613	79.240	126.890	70.989	28989.529	1169.342	4.034
40%	256.282	92.935	78.607	126.210	70.324	28988.602	1168.275	4.030
45%	262.046	92.237	77.955	125.510	69.636	28987.729	1167.557	4.028
50%	268.074	91.494	77.262	124.766	68.908	28986.835	1166.522	4.024
55%	274.375	90.722	76.541	123.992	68.149	28985.968	1165.664	4.021

Table- 4; Mid point compensation (line reactors open on either side) with flows, system generation and loss in MW

Compensation	line flow 54-58 per circuit	line flow 171-189	line flow 171-190	line flow 171-19	line flow 171-145	system power gen	system power loss	Loss In % age
Nill	220.018	97.066	82.483	130.373	74.454	28986.057	1165.975	4.023
30%	247.957	93.657	79.301	126.956	71.108	28981.131	1160.858	4.006
35%	253.275	93.005	78.692	126.302	70.467	28980.270	1160.023	4.003
40%	258.818	92.323	78.056	125.619	69.798	28979.471	1159.220	4.000
45%	264.605	91.610	77.390	124.905	69.098	28978.693	1158.437	3.998
50%	270.651	90.864	76.693	124.157	68.365	28977.893	1157.660	3.995
55%	276.972	90.082	75.964	123.374	67.597	28977.179	1156.934	3.993

It is seen from the tabulation, the mid point compensation is more effective and the simulation is done for 40 % compensation which consists of 30 % fixed and 10 % variable capacitor as shown in figure 5.With the advent of thyristor control, dynamic compensation could be provided. It has also been proved that the application of TCSC has positive effect in mitigating SSR consequences. Table 5 gives the dynamic compensation for 400kV and some of the major 220 kV lines and also the total system loss. From the table it is seen that with TCSC, it is possible to have smooth control in the power flow on the 400 kV line.

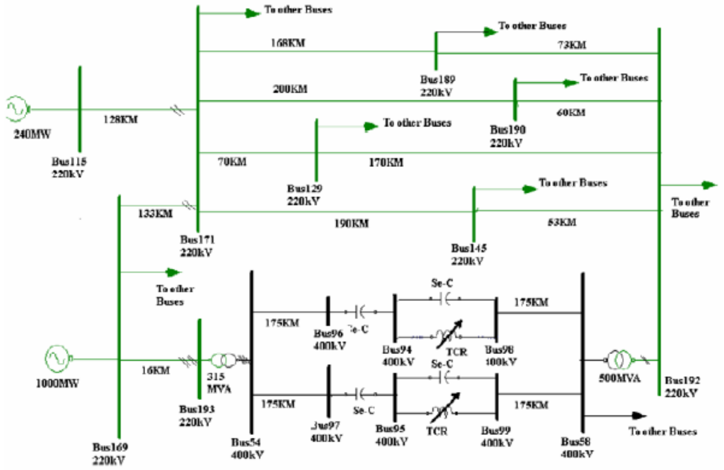

Figure .5 Part of the Large Inter connected System with mid point TCSC

Table-5: TCSC compensation at the center of line 54-58 with flows, system generation and loss in MW.

Reactance X(α) input	Line flow 54-96 per circuit	Line flow 171-189	Line flow 171-190	Line flow 171-129	Line flow 171-145	System Power Gen	System Power Loss	Loss In %age
Nil	220.007	97.067	82.485	130.374	74.456	28985.947	1165.994	4.023
0.0001	247.779	93.681	79.323	126.895	71.130	28980.975	1160.976	4.006
0.001	246.153	93.878	79.507	127.177	71.325	28981.381	1161.140	4.007
0.002	243.634	94.186	79.795	127.486	71.627	28981.802	1161.553	4.008
0.003	239.865	94.647	80.226	127.949	72.080	28982.446	1162.188	4.010
0.004	233.602	95.411	80.939	128.714	72.830	28983.542	1163.278	4.014
0.005	221.163	96.922	82.350	130.229	74.315	28985.880	1165.596	4.021
0.0055	208.837	98.412	83.741	131.723	75.779	28988.425	1168.117	4.030
0.006	184.524	101.338	86.473	134.658	78.651	28994.177	1173.999	4.049
0.00625	160.688	140.176	89.123	137.507	81.440	29000.748	1180.537	4.071
0.0065	114.498	109.605	94.193	142.960	86.774	29046.116	1195.834	4.121
0.0067	28.352	119.519	103.453	152.933	96.510	29055.826	1235.630	4.253

0.007								
0.00725	589.939	48.633	37.311	81.988	26.989	29015.582	1195.487	4.120
0.0075	418.869	71.952	59.049	105.242	49.818	28975.0825	1154.948	3.986
0.008	336.497	82.120	68.548	115.420	59.835	28947.723	1127.558	3.895
0.009	297.453	87.533	73.584	120.821	65.095	28975.110	1154.888	3.986
0.01	284.467	89.154	75.097	122.444	66.685	28976.312	1156.195	3.990
0.025	363.062	91.800	77.567	125.095	69.284	28978.879	1158.635	3.998
0.05	260.593	92.104	77.852	125.400	69.583	28979.196	1158.968	3.999
0.1	259.638	92.222	77.961	125.518	69.699	28979.355	1159.106	4.000
0.5	258.973	92.304	78.038	125.600	69.779	28979.440	1159.195	4.000
1	258.894	92.314	78.047	125.610	69.788	28979.456	1159.207	4.000

The graph of the impedance offered by the parallel combination of the fixed capacitor and the thyristor controlled reactor (variable inductor) between the buses 94-98 (95-99) is shown in figure 6. It is seen from the graph that the equivalent reactance of the TCSC spreads from inductive to the capacitive based on the firing angle of the thyristor. Evidently it is also seen from table 4 that the line flow could be varied to a large extent, much below the value of the uncompensated line and also much beyond the fixed compensation of 40% in the case considered. The precaution the firing angle should be avoided in the resonant range.

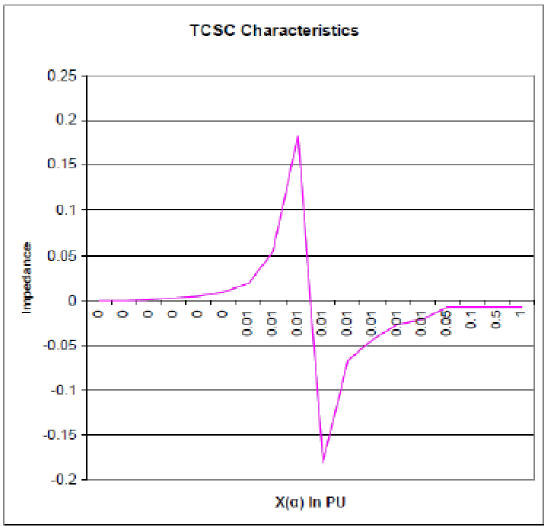

Figure 6 : Impedance versus Xeq in PU

Conclusion

With the installation of fixed series capacitor, it is seen that the loadability of 400 kV lines has increased substantially in all the three cases, however based on the economic factors, midpoint compensation was found to be most suited. As the line length gets reduced for midpoint compensation, the shunt line reactors on either side of the line could be removed. It is also seen that with TCSC, it is possible to have smooth control of active power on 400 kV lines. It could be concluded that with the TCSC compensation, the active power transfer of the transmission lines can be controlled thus improving the transfer capability between the areas.

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