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TCSC – Modeling and Operation

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Abstract - *For practical system operation, for the satisfactory operation of the system at a particular operating condition, it is important to make sure that the system operates with adequate level of security. Security defines as the ability of the system to operate within system constraints (on bus voltage magnitudes, current and power flow over the lines) in the event of outage (contingency) of any component (generator or transmission line). The goal of this power system analysis function is to give the information about the static security to operator. Contingency analysis is the study of outage in the system. Whenever the maximum violation occurs in power system, that line and generator are outage elements. For the generation, transmission, and distribution system, security can be assessed using contingency analysis. For the corrective actions, FACTS devices like TCSC is installed on line by finding proper location by sensitivity analysis method based on performance index by AC load flow. After installed TCSC device, GSF and LODF sensitivity factors are calculated and compared for with and without TCSC. This paper presents the modeling of TCSC as an application of FACTS devices for the power system security. It also describes the operating modes of TCSC, which one is safer mode, calculation of the TCSC reactance.*

Key Words – *Power system security, Contingency analysis, FACTS, TCSC, Power system security.*

I. INTRODUCTION

A. FACTS devices

Contingencies results into voltage limit violations and leads to overloading of lines. The system overloading can be recovered by restructuring the power system or by controlling the line parameters. The Power system restructuring requires expanding unused potentials of transmission systems but environmental, right-of-way, and cost problems are major hurdles for power transmission network expansion. Nowadays, FACTS devices are used as an alternative to reduce the flows in heavily loaded lines. [1]

FACTS are the alternating current transmission system incorporating power electronics based and other static controllers to enhance the controllability and available power transfer capacity. [2]

The FACTS controllers are classified into thyristor controlled based controllers like TSC, TCR, FC-TCR, SVC, TCSC, TCPAR, etc. and VSI based FACTS controllers like STATCOM, UPFC, GUPFC, IPFC, GIPFC, etc. Resonance phenomena occurs in the thyristor based FACTS controllers, where as VSI based controllers are free from this phenomena. FACTS devices are divided into four categories named series connected FACTS devices, i.e. TCSC, shunt connected FACTS devices, i.e. SVC, STATCOM, combined series-series connected FACTS devices, i.e. IPFC, combined series-shunt connected FACTS devices i.e. UPFC. [2]

In power system without violating specified power dispatch addition of controllable components such as controllable series FACTS devices can changed line flows in such a way that, losses minimized, thermal limits are not violated ,stability margin increased, contractual requirement fulfilled etc. [1]

B. Advantages and drawback of FACTS devices

FACTS devices has the following advantages: [1], [2], [3]

- Increase the loading of lines to their thermal limits.
- Control the power flow in heavily loaded lines.
- Improve the stability, reliability, quality of supply, availability, line loadability of the power system.
- Reduce the reactive power flows and the loop flows.
- Limits the short circuit currents and the overloads.
- Low system losses.
- Reduce cost of production.
- Added flexibility in siting new generation and provide secure tie-line connections to neighbouring utilities.

Main drawback of FACTS devices is that they have considerable high cost. [1]

II. Thyristor Controlled Series Capacitor (TCSC)

Thyristor Controlled Series Capacitor (TCSC) is connected in series with transmission lines, which provide not interrupted and changeable control of line impedance with much faster response compared to conventional control devices. TCSCs are connected in series with the lines, so it injects voltage in series. By inserting the series capacitance the voltage profile is improved in the line. The net reactance is to make smaller and control to increase in power transfer ability. A basic set up of a TCSC is shown in figure 1. [3]

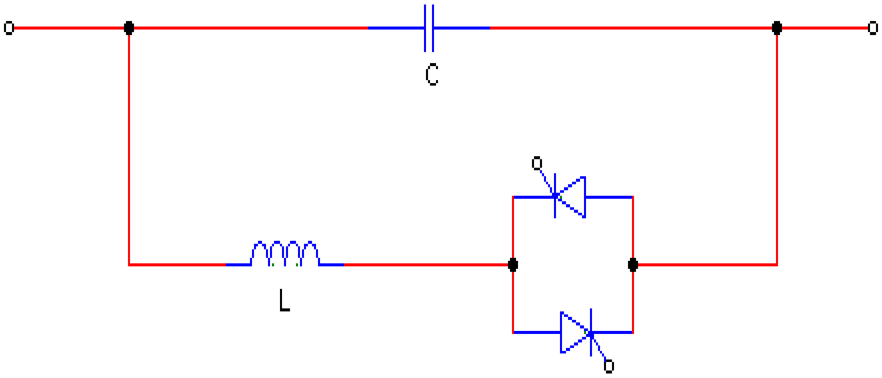

Figure 1. TCSC

In this circuit, the parallel LC circuit is given. So the impedance of the TCSC is given by the following formula:

$$X_{TCSC} = \frac{X_C X_L(\alpha)}{X_L(\alpha) - X_C} \tag{1}$$

Where,

$X_L(\alpha)$ = Variable Inductive Impedance

$$X_L(\alpha) = X_L \frac{\pi}{\pi - 2\alpha - \sin\alpha}, \quad X_L \leq X_L(\alpha) \leq \infty \tag{2}$$

X_C is the fixed capacitive reactance $= \frac{1}{\omega C} = \frac{1}{2\pi f C}$

X_L is the inductive impedance $= \omega L = 2\pi f L$

α is the delay angle, measured from the crest of the capacitor voltage (zero crossing of the line current)

Percentage compensation of the line is given by, $\frac{X_C}{x_l} \times 100$ (3)

Where, x_l is the reactance of the line, on which TCSC is being placed.

The TCSC thus presents a tunable parallel LC circuit to the line current that is substantially a constant alternating current source. As the impedance of the controlled reactor, $X_L(\alpha)$, is varied from its maximum (infinity) toward its minimum (ωL), the TCSC increases its minimum capacitive impedance, $X_{TCSC.min} = X_c = \frac{1}{\omega C}$, (and thereby the degree of series capacitive compensation) until parallel resonance at $X_c = X_L(\alpha)$ is established and $X_{TCSC.max}$ theoretically becomes infinite. Decreasing $X_L(\alpha)$ further, the impedance of the TCSC, $X_{TCSC}(\alpha)$ becomes inductive, reaching its minimum value of $X_L X_c/(X_L - X_c)$ at $\alpha = 0$, where the capacitor is in effect bypassed by the TCR. Therefore, with the usual TCSC arrangement in which the impedance of the TCR reactor, X_L, is smaller than that of the capacitor, X_c.

A. Operating Modes of TCSC

TCSC has four operating modes. Among of them, there are two operating ranges of TCSC around its internal circuit resonance: one is the $\alpha_{Clim} \leq \alpha \leq \pi/2$ range, where $X_{TCSC}(\alpha)$ is capacitive, and the other is the $0 \leq \alpha \leq \alpha_{Llim}$ range, where $X_{TCSC}(\alpha)$is inductive, as illustrated in Figure 2. In the inductive mode, TCSC can control the power flow and can increase the impedance where as in the capacitive mode, the power flow rises and the impedance falls.[4] Another two operating modes are bypassed mode and blocking mode. In the bypassed mode the value of the firing angle α is taken as 0 degree, so the series capacitor bypassed and the whole TCSC works as a pure inductor. In the blocking mode of operation, the value of the firing angle α is chosen π/2 degree, so that the anti parallel combination of the thyristor are in blocking mode and the whole circuit works as a fixed capacitor.

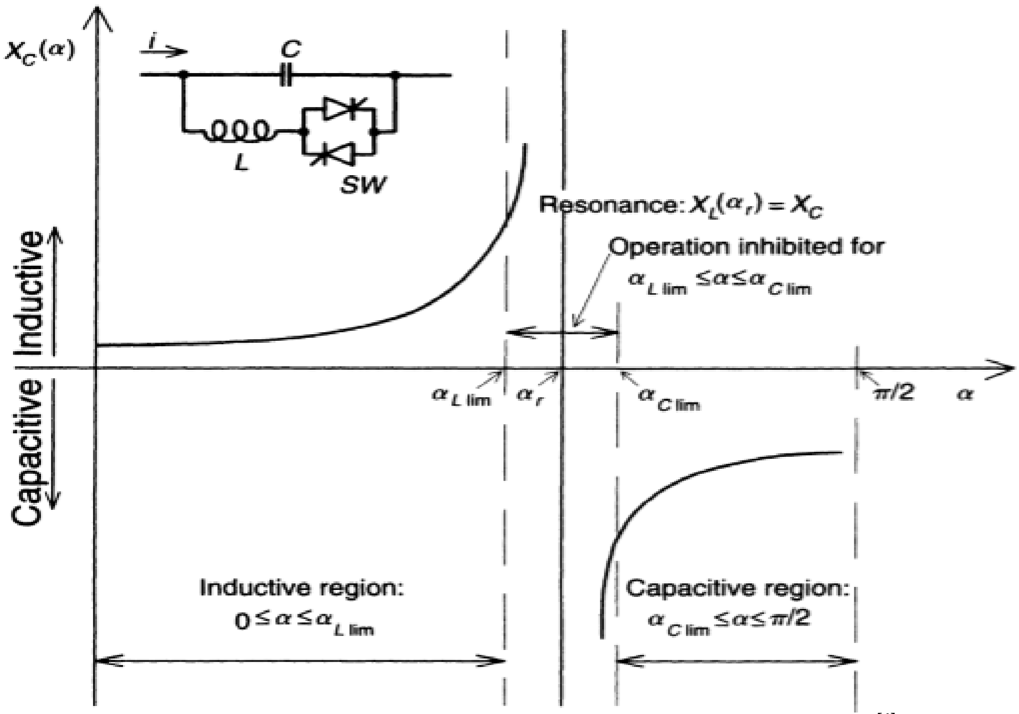

Figure 2. The impedance vs. delay angle characteristic of the TCSC [4]

B. Purpose of TCSC

Main purpose of TCSC is to minimize the total power losses, to minimize the generation cost, to minimize the reactive power generation limits.[3] TCSC can provide current control, power oscillation damping control, voltage and transient stability control, fault current control attributes.[2]

C. Advantages and Disadvantages of TCSC

TCSC can improve dynamic stability of the power system, improve voltage regulations and reactive power balance, improve load sharing between parallel lines, dynamic power flow control, minimizing system losses, elimination of line overloads, these are the advantages of TCSC.[5] The main drawback in TCSC is resonance phenomena occurs, because it is a thyristor controlled FACTS device.[3]

D. Applications of TCSC

TCSC uses for the control of active power flow, and to increase the line capacity. If there is a low voltage at heavy load, then TCSC can supply reactive power by series capacitors and for high voltage at light load, TCSC can remove reactive power supply by switch EHV line. If there is a low voltage and over load in the system, then TCSC can supply reactive power limit and prevent over load by switching series capacitor.[2]

III. TCSC Modeling

For a finite, but still relatively small X_L, the time duration of the charge reversal is not instantaneous but is quite well defined by the natural resonant frequency, $f = 1/2\pi\sqrt{LC}$, of the TCSC circuit, since the TCR conduction time is approximately equal to the half-period corresponding to this frequency: $T/2 = 1/2\,f = \pi\sqrt{LC}$. However, as X_L is increased relative to X_c, the conduction period of the TCR increases and the zero crossings of the capacitor voltage become increasingly dependent on the prevailing line current. However, the design of the reactor for an actual compensator requires careful considerations to reconcile contradictory requirements. Small X_L is advantageous in providing well-defined charge reversal and control of the period time of the compensating voltage.

In present installations the X_L/X_C ratio used is 0.1343, and thus the natural resonant frequency of the TCSC circuit is 2.73 times the 50 Hz fundamental frequency. Generally, the X_L/X_C ratio for practical TCSCs would likely be in 0.1 to 0.3 range, depending on the application requirements and constraints. It is important that the natural resonance frequency of the TCSC does not coincide with, or is close to, two and three times the fundamental.[4]

Considering the above conditions, in my work TCSC parameters are designed as follows:[6]

L = 6.71 mH so that $X_L = 2.108\ \Omega$; $X_L \le X_L(\alpha) \le \infty$
C = 203 µF so that $X_C = 15.68\ \Omega$; $X_C \le X_{TCSC} \le X_{TCSC,max}$
X_L/X_C ratio = 0.1343, which is between the range of 0.1 to 0.3
Capacitive range is $79° \le \alpha \le \pi/2$ and Inductive range is $0 \le \alpha \le 75°$,
Resonance occurs at 77.42°
Take the delay angle $\alpha = 82°$ for the capacitive operation.
So the value of the $X_L(\alpha) = 25.280\ \Omega$ as per the equation no. (2)
So, from the equation no. (1) and above parameters $X_{TCSC} = 41.290\ \Omega$

Table 1. TCSC operating regions with respect to change in firing angle 'α'

α	**$X_L(\alpha)$**	**$X_L(\alpha)-X_C$**	**$X_L(\alpha)*X_C$**	**$X_{TCSC} = X_L(\alpha)*X_C/(X_L(\alpha)-X_C)$**	**Remarks**
0	2.108	-13.572	33.05344	-2.435414088	
2	2.156337	-13.5237	33.811357	-2.500162579	
5	2.233145	-13.4469	35.015711	-2.604007422	
8	2.315623	-13.3644	36.308962	-2.716846503	
10	2.374076	-13.3059	37.22551	-2.797664358	
12	2.435554	-13.2444	38.189479	-2.883433411	
15	2.533972	-13.146	39.73268	-3.022409503	
17	2.604118	-13.0759	40.832565	-3.122738835	
20	2.716923	-12.9631	42.601349	-3.286360811	
22	2.797706	-12.8823	43.868031	-3.405296505	
25	2.928288	-12.7517	45.915562	-3.600737215	
27	3.022316	-12.6577	47.389917	-3.743964293	
30	3.17523	-12.5048	49.787608	-3.981489373	
32	3.286045	-12.394	51.525193	-4.157284345	
35	3.467533	-12.2125	54.370917	-4.452083062	
37	3.600061	-12.0799	56.448964	-4.672951268	
40	3.818944	-11.8611	59.881047	-5.048542835	
42	3.980241	-11.6998	62.410186	-5.334314016	
45	4.249381	-11.4306	66.630298	-5.829106846	
47	4.449933	-11.2301	69.774949	-6.213226415	
50	4.788853	-10.8911	75.089219	-6.894519111	
52	5.04494	-10.6351	79.104654	-7.438101037	
55	5.491101	-10.1889	86.100459	-8.450418079	
57	5.823079	-9.85692	91.305884	-9.263124498	
58	6.008361	-9.67164	94.211097	-9.740964783	
59	6.20579	-9.47421	97.306788	-10.27070208	
60	6.416613	-9.26339	100.61249	-10.86130752	
62	6.884252	-8.79575	107.94507	-12.27241485	
65	7.728894	-7.95111	121.18906	-15.24178596	
67	8.41713	-7.26287	131.98059	-18.17196088	
70	9.714186	-5.96581	152.31844	-25.53187983	
72	10.82599	-4.85401	169.75147	-34.97136279	
75	**13.06877**	**-2.61123**	**204.91833**	**-78.47581197**	**Near to Resonance**
76	**14.03784**	**-1.64216**	**220.11333**	**-134.0388811**	**Near to Resonance**
77	**15.16201**	**-0.51799**	**237.74037**	**-458.9701624**	**Near to Resonance**
77.4	**15.66374**	**-0.01626**	**245.60744**	**-15104.85011**	**Near to Resonance**
77.41	**15.67672**	**-0.00328**	**245.8109**	**-74834.21212**	**Near to Resonance**
77.42	**15.68971**	**0.009706**	**246.01459**	**25347.38449**	**Resonance**
77.43	**15.7027**	**0.022698**	**246.21831**	**10847.46791**	**Near to Resonance**
77.44	**15.71575**	**0.03575**	**246.42296**	**6892.944584**	**Near to Resonance**

77.45	**15.7288**	**0.0488**	**246.62759**	**5053.836745**	**Near to Resonance**
77.5	**15.79434**	**0.114337**	**247.65521**	**2166.005732**	**Near to Resonance**
78	**16.4817**	**0.801698**	**258.43302**	**322.3571308**	**Near to Resonance**
79	**18.05275**	**2.372754**	**283.06718**	**119.2990111**	**Near to Resonance**
80	19.95456	4.274563	312.88754	73.19755659	
81	22.30373	6.623731	349.72251	52.79841337	
82	**25.28016**	**9.600158**	**396.39287**	**41.29024578**	**Capacitive Region**
83	29.17086	13.49086	457.39913	33.9043642	
85	42.14174	26.46174	660.78246	24.97124136	
88	126.4505	110.7705	1982.7438	17.89956578	
88.5	189.6821	174.0021	2974.2148	17.09298554	
89	379.3641	363.6841	5948.4295	16.3560328	
89.1	474.1815	458.5015	7435.1652	16.21623036	
89.2	632.2946	616.6146	9914.3796	16.07872944	
89.3	948.3629	932.6829	14870.33	15.9436077	
89.4	1896.252	1880.572	29733.229	15.8107381	
89.5	**3794400**	**3794384**	**59496192**	**15.6800648**	**Fixed Capacitor**
89.6	-1898.149	-1913.83	-29762.98	15.55153377	
89.7	-948.8372	-964.517	-14877.77	15.42509278	
89.8	-632.5054	-648.185	-9917.685	15.30069125	
89.9	-474.3593	-490.039	-7437.954	15.17828023	
89.91	-462.7881	-478.468	-7256.518	15.16614677	
89.92	-451.7681	-467.448	-7083.723	15.1540327	
89.93	-441.2606	-456.941	-6918.966	15.14193795	
89.94	-431.2308	-446.911	-6761.699	15.1298625	
89.95	-421.6468	-437.327	-6611.423	15.1178063	
89.96	-412.4796	-428.16	-6467.68	15.10576929	
89.97	-403.7025	-419.383	-6330.056	15.09375144	
89.98	-395.2912	-410.971	-6198.166	15.08175269	
89.99	-387.2232	-402.903	-6071.66	15.06977301	
90	-379.44	-395.12	-5949.619	15.05775258	
95	-34.50678	-50.1868	-541.0663	10.78105248	
100	-18.08166	-33.7617	-283.5204	8.397703854	
105	-12.25348	-27.9335	-192.1345	6.878289281	
110	-9.268288	-24.9483	-145.3268	5.825119344	
115	-7.453694	-23.1337	-116.8739	5.052108215	
120	-6.234022	-21.914	-97.74947	4.460590032	
125	-5.357877	-21.0379	-84.01151	3.993345284	
130	-4.698016	-20.378	-73.6649	3.614919962	
135	-4.183135	-19.8631	-65.59155	3.302175145	
140	-3.770169	-19.4502	-59.11625	3.039369554	
145	-3.431564	-19.1116	-53.80692	2.815411582	

150	-3.14888	-18.8289	-49.37443	2.622271429	
155	-2.909312	-18.5893	-45.61801	2.453991228	
160	-2.703681	-18.3837	-42.39372	2.306051665	
165	-2.525243	-18.2052	-39.59581	2.174967496	
170	-2.36893	-18.0489	-37.14482	2.058006678	
175	-2.230857	-17.9109	-34.97984	1.952996328	
180	-2.108	-17.788	-33.05344	1.858187542	

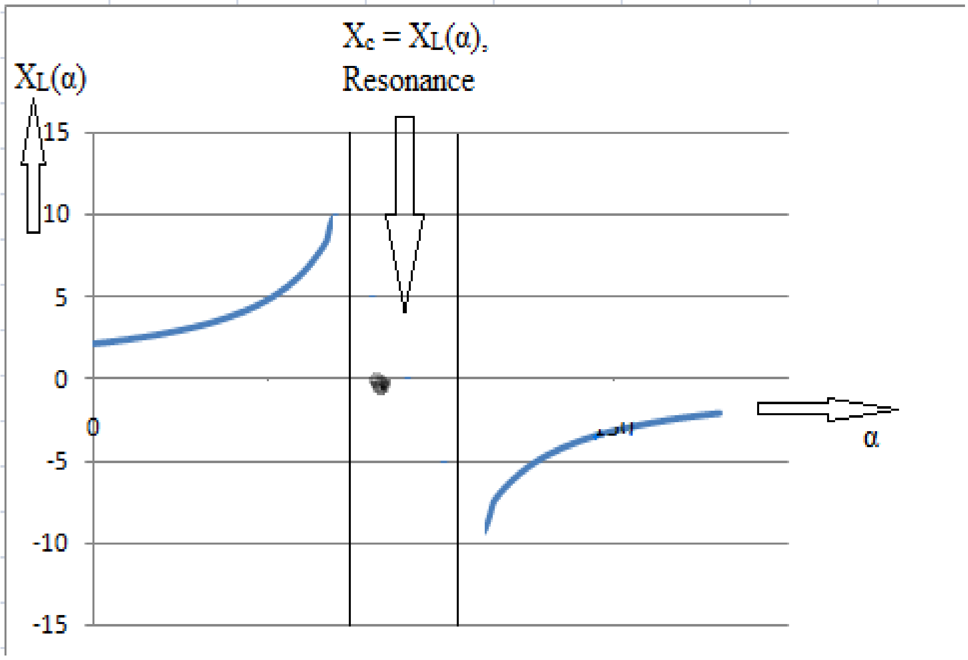

Figure 3. Impedance vs. delay angle characteristic of the TCSC for modeling value

A. Operational Feasibility of TCSC in Inductive Region [7]

During normal operation, the TCSC generally operates in the capacitive region. In this region, it can be controlled easily. TCSC operating as a varying series capacitance can effectively alleviate load voltage sags due to load fluctuations. During system faults, it is desirable to operate in the inductive region to lower the fault current contribution, When fault has been cleared, TCSC returns to the capacitive region. TCSC can operate in the inductive region to reduce short-circuit currents, contributes to fault current limitation and maintenance of voltage at sensitive loads in neighboring feeders close to its nominal value. When TCSC operates in the inductive region, it represents a varying inductance, which can reach values much higher than the nominal inductor value, as the control angle increases towards the resonance value. In cases of excessive currents flowing, damping can be effected by regulating accordingly the TCSC angle. Thus, although operation near the resonance area should be avoided, such operation of TCSC during a short circuit, lasting essentially no longer than a few periods, is very beneficial.

CONCLUSION

Hence from the above characteristics, it can be conclude that TCSC can be operated in both inductive region and capacitive region. From the result table, when we consider zero crossing of line current of TCSC, the inductive region starts from the 0 degree of firing angle α and then resonance condition occurs and then it starts to operate in capacitive region. TCSC can operated only in capacitive region only in the healthy condition, but in the fault condition only TCSC is operated in inductive region. For the selected values for the security purpose TCSC operated long time in inductive region to convert the system in healthy condition.

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