Scientific Journal of Impact Factor(SJIF): 3.134
e-ISSN(O): 2348-4470
p-ISSN(P): 2348-6406

International Journal of Advance Engineering and Research Development

Volume 2,Issue 5, May -2015

THYRISTOR CONTROLLED SERIES CAPACITOR: SIMULATION AND ANALYSIS

Chauhan Chandkuwarbaa Hitendrasinh[1], Dr. Vijay Makwana[2]

[1]ME Student, [2]Professor
Electrical Department, GCET, V.V. Nagar, Gujarat, India,

Abstract — *As power system interconnections become more prevalent, there has been an increase in use of series connected controllers for dynamic power compensation and enhancement of active power transmission capacity. A thyristor controlled series capacitor (TCSC) is one of the series FACTS devices which can be employed to enhance power transfer capability of transmission line. It can govern the power either in inductive or capacitive operating region appropriately by selecting proper L-C parameters and conduction angle. Mismatch in selection of parameters cause multi-resonance condition. This paper represents various steps to be followed in selection of TCSC parameters. The selected parameters are implemented in MATLAB software and satisfactory results are obtained. Also results are carried out for various modes of operation of TCSC.*

Keywords- TCSC , operating modes, Power control, TCSC Characteristics, Transmission line, Matlab Simulink .

I. INTRODUCTION

Thyristor controlled series capacitor are used to compensate inherent inductive reactance of EHV/UHV transmission lines to increase the power transfer capability . Also, it can be employed to play various roles in the operation and control of power system such as providing voltage support, enhancing transient stability, damping power oscillations, power flow control, sub synchronous resonance (SSR) mitigation, etc. In general, compensation limit of the line lies in the range of 25%-75%. By selecting appropriate degree of compensation and TCSC parameters, the risk of multi-resonance problems can be eliminated.

Fig 1 shows basic TCSC module. It consists of parallel combination of capacitor and a TCR branch. TCR branch consist of thyristor valve in series with an inductor. The thyristor valve in consists of anti-parallel connected thyristor in order to provide bi-directional functionality. The TCSC module is connected in series with a transmission line [7].

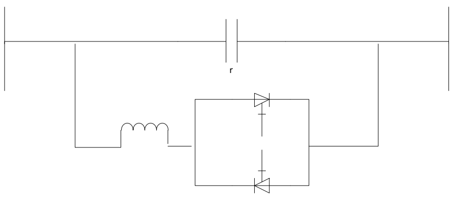

Figure 1: Basic Module of TCSC

The practical module of TCSC consists of protective equipment connected in series with capacitor as shown in Fig 2. It consists of metal-oxide varistor (MOV), a non-linear resistor, connected across the capacitor to provide protection against high capacitor voltage. Circuit breaker is also connected across the capacitor for controlling its insertion in the line. Also in case of severe fault circuit breaker bypasses the TCSC. Ultra high speed contacts are used across the valves for minimizing the conduction losses when TCSC valves are required to operate for prolonged duration in the fully 'ON' mode.

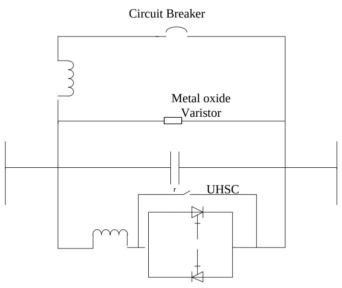

Figure 2: Implemented Module of TCSC

II. REACTANCE CHARACTERISTIC OF TCSC

The TCR at the fundamental system frequency is continuously variable reactive impedance, controllable by firing angle α. Thus, the total impedance of TCSC can be changed by changing the firing angle of TCR branch, in which the current through the reactor $i_L(\alpha)$ can be continuously controlled from maximum to 0. Considering voltage on reactor as $v(t) = V_m \cos \omega t$, value of current though the reactor is [1]:

$$i_L(t) = \frac{1}{L}\int v(t)dt = \frac{V_m}{\omega L}\sin\omega t$$

Using Fourier analysis the magnitude of the fundamental frequency current can be obtained as [1]:

$$I_{L1}(\alpha) = \frac{V_m}{\omega L}\left(1 - \frac{2}{\pi}\alpha - \frac{1}{\pi}\sin 2\alpha\right)$$

Where,

V_m is the magnitude of voltage of reactor,
L is inductance of reactor and
ω is circular frequency of voltage.

Thus, it is possible to control the current flowing through the reactor

By use of formula $I_{L1} = V\, B_{TCR}$; $B_L = 1/(\omega L)$ and from above equation it is possible to calculate inductive susceptance of TCR which is the function of the firing angle α [1]:

$$B_{TCR}(\alpha) = \frac{1}{\omega L}\left(1 - \frac{2}{\pi}\alpha - \frac{1}{\pi}\sin 2\alpha\right) = B_L\left(\frac{\pi - 2\alpha - \sin 2\alpha}{\pi}\right)$$

Thus as current can be varied from the maximum value to 0 by controlling the firing angle the inductive susceptance of TCR branch $B_{TCR}(\alpha)$ can also be changed from the maximum value ($\alpha=0$, $B_{TCR}=B_L$) upto zero ($\alpha=\pi/2$, $B_{TCR}=0$). Thus from the above equation the TCR reactance can be obtained as [1]:

$$X_{TCR}(\alpha) = \frac{1}{B_{TCR}(\alpha)} = X_L\left(\frac{\pi}{\pi - 2\alpha - \sin 2\alpha}\right)$$

$$X_L(=\omega L) \le X_{TCR}(\alpha) \le \infty$$

Now, as TCSC is the parallel combination of the fixed capacitive reactance, X_C, and the varying inductive reactance $X_L(\alpha)$, that is [1],

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

$$\text{where } X_L \le X_L(\alpha) \le \infty$$

Where $X_L = \omega L$ and α is the delay angle measured from the crest of the capacitor voltage or equivalent zero crossing of the line current

As the impedance of the TCR branch, X_L (α), is varied from its maximum (infinity) toward its minimum (ωL), the TCSC reactance increases from its minimum capacitive impedance, X_{TCSC}.min = X_C = 1/ωC, until parallel resonance at $X_C = X_L(\alpha)$ is reached and X_{TCSC}.max theoretically becomes infinite.

Decreasing X_L (α) further, the impedance of the TCSC, becomes inductive, reaching its minimum value of $X_L X_C/(X_L-X_C)$ at α = 0, where the capacitor is in effect bypassed by the TCR. Therefore, with TCSC has two regions for the operation around the resonance of TCSC as follows:

- $\alpha_{Clim} < \alpha < \pi/2$ range, where $X_{TCSC}(\alpha)$ is capacitive,
- $0 < \alpha < \alpha_{Lmax}$ range, where $X_{TCSC}(\alpha)$ is inductive[1].

The above analysis results in the impedance vs firing angle characteristics of the TCSC as follows:

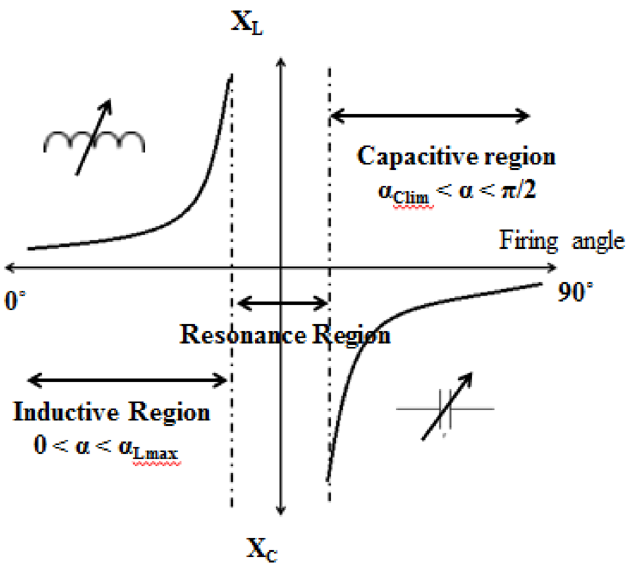

Figure 3: Reactance Characteristic of TCSC

III. OPERATING MODES OF TCSC:

TCSC consist of three modes of operation which is explained in detail as follows:

3.1 BYPASS THYRISTOR MODE:

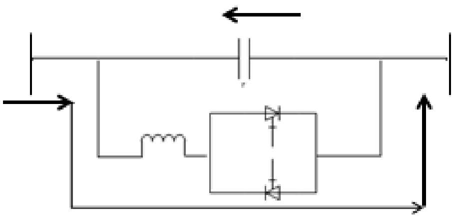

Figure 4: Bypass thyristor mode

Fig 4 is the thyristor bypass mode, in which the thyristors are gated for full conduction i.e. 180˚ and the TCSC module is slightly inductive because of the TCR inductor in series with the thyristor valve. In this mode, most of the line current is flowing through the reactor and the thyristor valve with some current flowing through the capacitor. This mode is also called as thyristor switched reactor mode (TSR) [7].

3.2 BLOCKED THYRISTOR MODE:

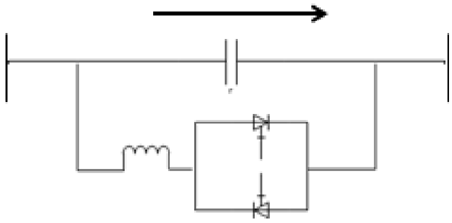

Figure 5: Blocked Thyristor mode

Fig 5 is blocked thyristor mode in which capacitor is inserted by turning off the thyristor valves, i.e. all the gating signals to the thyristor are blocked and no current flows through the thyristor valves. In this mode TCSC reactance is same as that of fixed series capacitance [7].

3.3 PARTIALLY CONDUCTING THYRISTOR OR VERNIER CONTROL MODE:

In this mode TCSC behaves as a continuously controlled capacitive reactance or as a continuously controlled inductive reactance by varying the firing angle of thyristor in an appropriate range. In this mode firing pulses to the thyristor are given in the range from $0^\circ - \alpha_{Llim}$ in the inductive region and from $\alpha_{Clim} - 90^\circ$ in the capacitive region. α_{Llim} and α_{Clim} are below and above the value of α corresponding to the resonance region of TCSC.

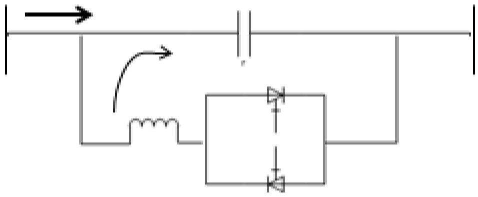

Figure 6: Capacitive vernier mode

In capacitive Vernier mode the effective value of TCSC reactance increases beyond the fixed value of capacitor as the firing angle is decreased from 90° to α_{Clim}. In this mode capacitor is fired when the capacitor voltage and current are of opposite polarity, thus TCR current is in the direction opposite to the capacitor current resulting in the loop current which increases the voltage across the FC and enhances the equivalent capacitive reactance and series compensation level for the same level of the line current.

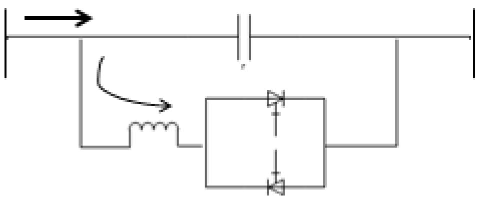

Figure 7: Inductive vernier mode

In inductive Vernier mode thyristor are fired with greater level of conduction period and the inductive reactance increases above the fixed values of TCR reactance as the firing angle is varied from 0° to α_{Llim} [7].

IV. SELECTION OF TCSC PARAMETERS

For the desired operation of TCSC proper selection of capacitor and reactor is required. Capacitor is selected based on the degree of series compensation required and it is the ration of the effective reactance of thyristor controlled series capacitor to the net reactance of transmission line [2].

$$K = \frac{X_{TCSC}(\alpha)}{X_{TL}} \qquad (0<k<1)$$

The value of the TCR reactor depends on the requirement of the operating range of TCSC. Normally Xr/Xc for practical purpose should be in the range of 0.1 to 0.3. Thus the inductive reactance is sufficiently smaller than the capacitive reactance. Also the effect of multi-resonance should be considered which can otherwise lead to reduced operating range of TCSC. Thus one important factor for that is the resonant factor (ω) which is defined as the ratio of the resonant frequency of TCSC to the power system frequency [2].

$$\omega = \frac{\omega_0}{\omega_N} = \sqrt{\frac{X_C}{X_L}}$$

Thus if resonant factor is less than one it is not possible to obtain both capacitive and inductive region and if it is greater than three then multi-resonance occurs. Thus proper selection of TCSC is required for the desired operation.

V. SIMULATION PARAMETERS SELECTION:

To survey the performance of Thyristor controlled series capacitor, a transmission system is developed in MATLAB/SIMULINK platform for 400 kV, 400km long. The parameters used are obtained from the Kanpur Ballabhgarh 400KV line on which for the first time series controlled compensation project was commissioned in India [6].

Technical Data of the transmission line:

- Inductance / km L = 1.044 mH,
- Length of transmission Line = 400 km,
- Total inductance of the line = 0.4176H
- Total line reactance of the line X_{TL} = 131.1929 Ω.

Selection of TCSC parameters:

- For 75% compensation

$$X_C = 0.75 X_{TL}$$

$$\therefore \quad X_C = 98.394675\ \Omega$$

$$C = \frac{1}{2\pi f X_C} = 32.3503 \mu F$$

- As Xr/Xc should be maintained in the range (0.1, 0.3) Xr = 24.59866 Ω for Xr/Xc = 0.25.
- Thus TCR reactor L_{tcr} = 0.07829 H.
- Resonance Factor λ should be less than 3 to avoid multi resonance situation. In this paper the value of resonant factor λ is selected as 2.

Multi-resonance can be avoided by the proper selection of the resonant factor in the range 0< β< 90˚, one of the which can be specified as [7]

$$\beta_{res} = (2m-1)\frac{\pi\omega}{2\omega_r} \qquad m=1,2$$

By using this resonance range in the system is found to be 35˚ to 55˚. Considering the above parameters and the constraints the TCSC setup on the transmission system is modelled in the MATLAB Simulink.

VI. SIMULATION CIRCUIT:

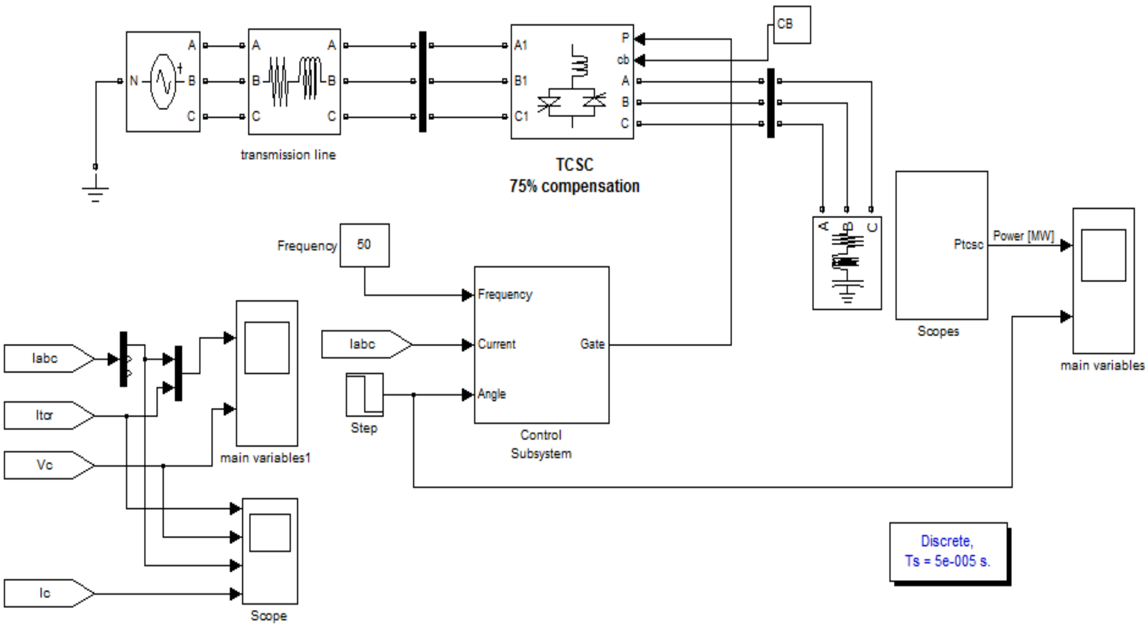

Figure 8: MATLAB circuit of Thyristor controlled series capacitor implemented system

Here for the generation of the trigger pulse for the thyristor line current is taken as the reference since it is not affected by the thyristor switching and remains sinusoidal and constant over the fundamental cycle. Load is 710 MW. There is a circuit breaker connected across the thyristor controlled series capacitor which is closed initially and thus bypasses the TCSC and after 0.5 second it is opened injecting the TCSC in the line. Here in the simulation the resistance of the transmission line is assumed to be 9Ω.

VII. CONTROL CIRCUITRY:

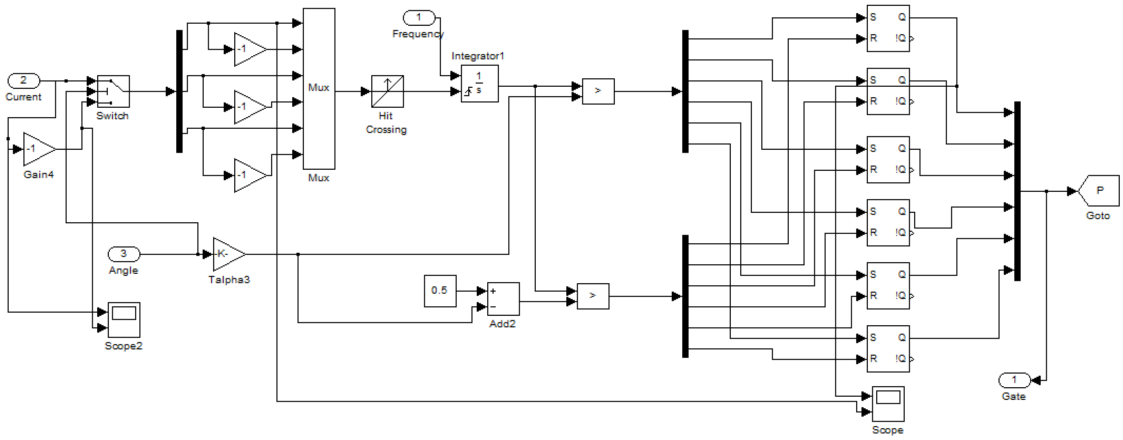

Figure 9: Firing circuit of TCSC

As shown in fig 9, for generating the firing pulses of appropriate conduction angle SR flip-flop is used. In the inductive mode line current is inverted for the synchronization with firing pulse generation. Here in the control circuit initially ramp signal is generated by detecting the zero crossing of line current. That ramp signal is compared with the firing angle. The resultant pulse generated together with the other pulse generated by the ADD operator is given to the SR flip-flop to get proper width of the firing pulse.

SR flip-flop, is one of the most common sequential logic circuit possible. This simple flip-flop is one bit memory bistable device which has two inputs, one which will "SET" the device leading to output 1 and another which will "RESET" the device, leading to output 0. Following is the truth table for the SR Flip-flop:

S	R	Q	$\overline{Q}$
0	0	0	1
0	1	0	1
1	0	1	0
1	1	0	1

VIII. SIMULATION RESULTS:

1 For 75 ° firing angle:

Here are the waveforms for the TCR branch current, capacitor voltage, line current and capacitor current.

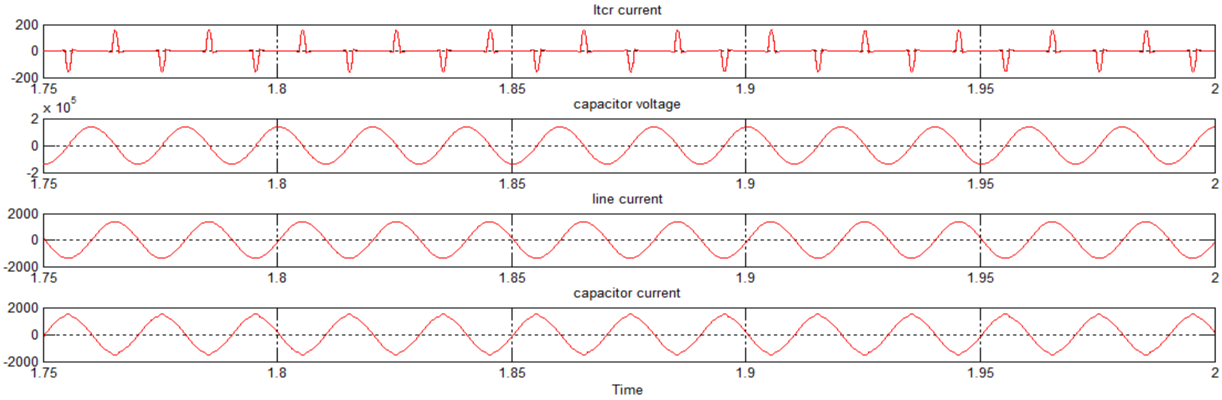

Figure 10: TCR current, capacitor voltage , line current and capacitor current

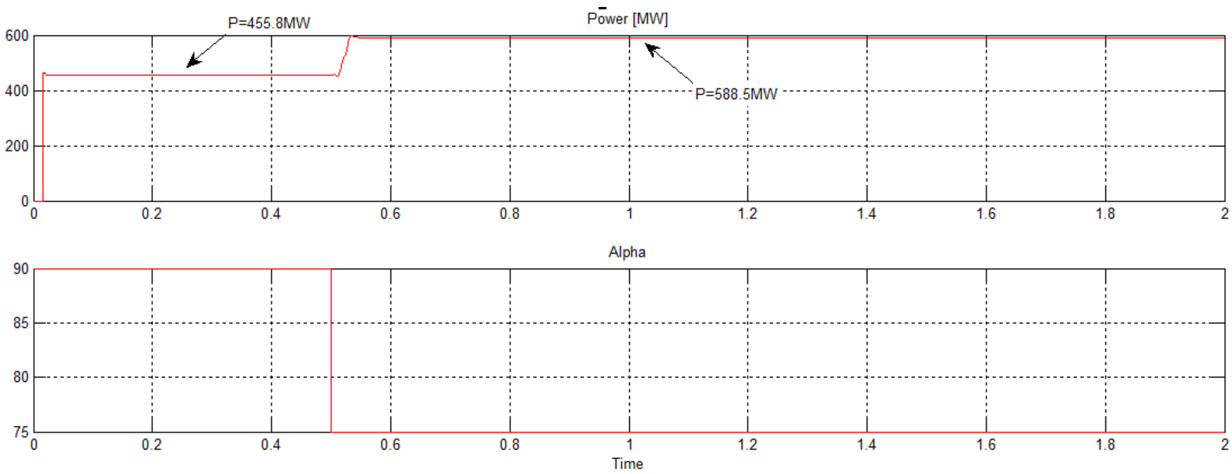

Figure 11: power flow for 75° firing angle

As shown in fig 11, the power flow through the line without TCSC is about 455.8 MW and with TCSC it is increased to 588.5 MW.

2 For 90 ° firing angle: (Blocked Thyristor mode)

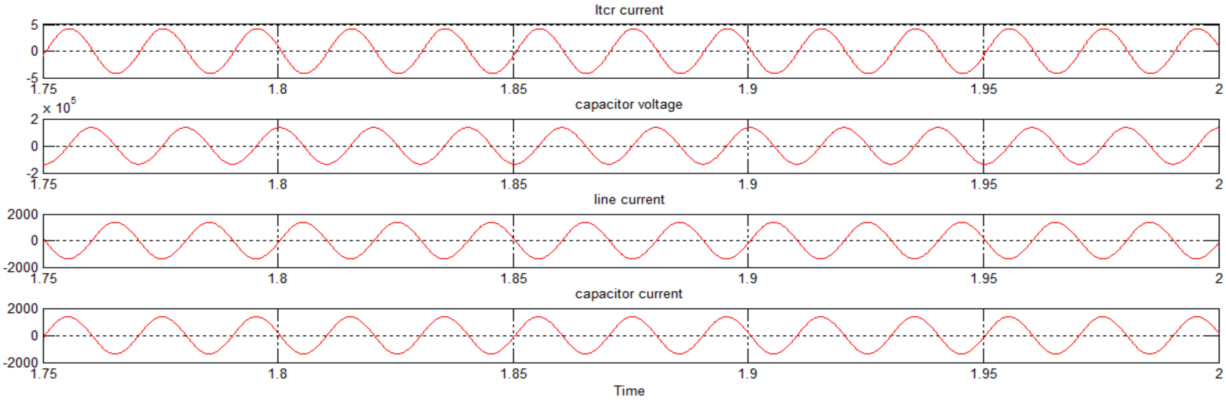

Figure 12: TCR current, capacitor voltage, capacitor current, line current

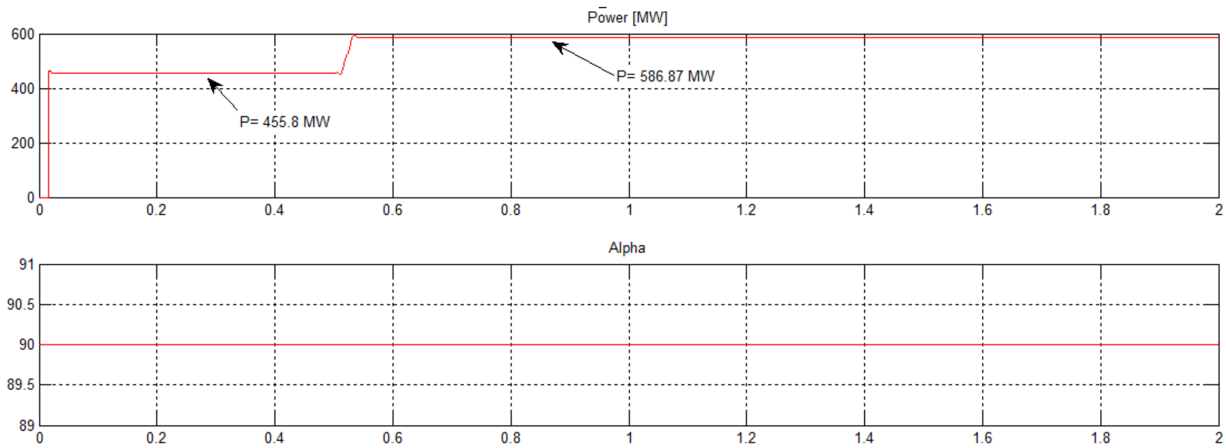

Figure 13: Power flow for Blocked thyristor mode

Reffering to figures 12 and 13 it is observed that as the firing angle is varied from 90˚ towards the resonance region the power flow is increased and again decreasing further the firing angle in the inductive region power flow increases.

3 <u>For 20˚ Firing angle:</u>

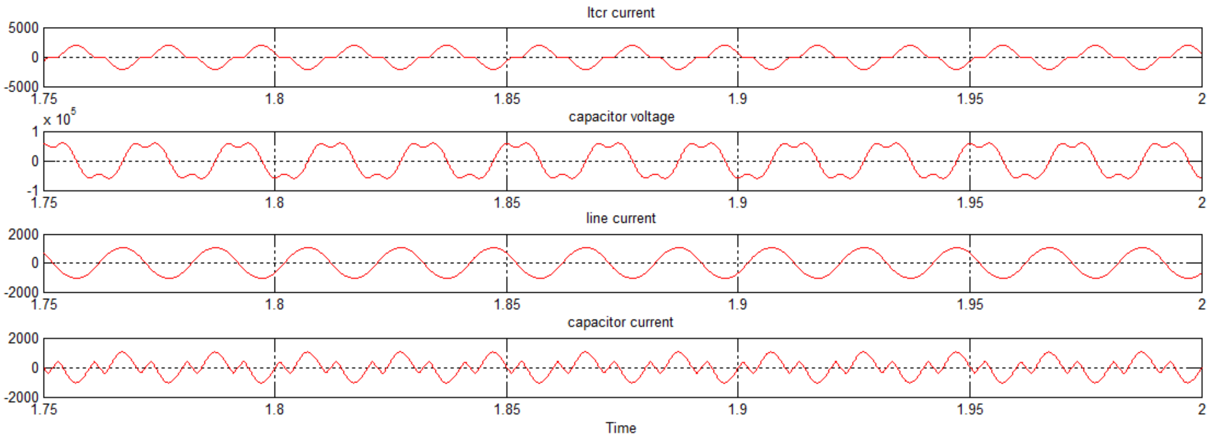

Figure 14: Current through TCR and capacitor and capacitor voltage

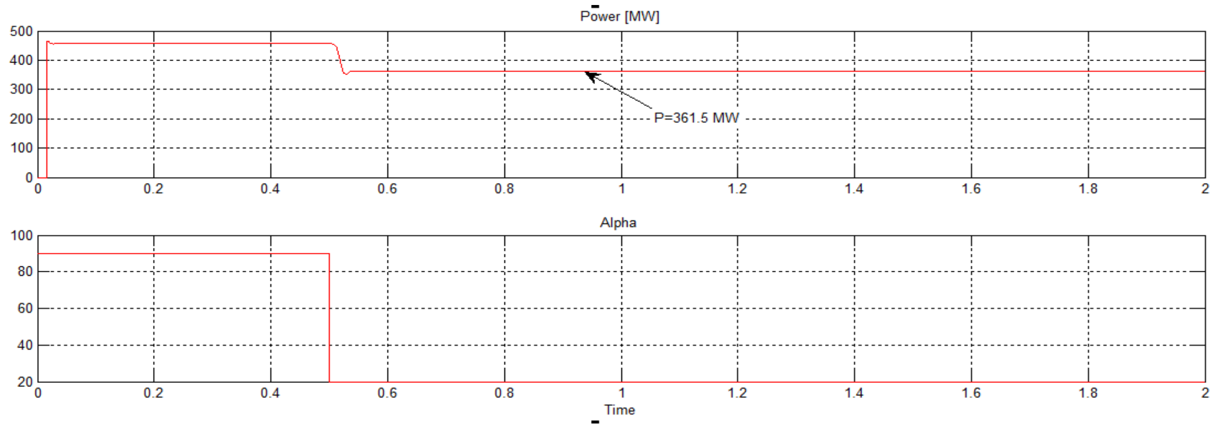

Figure 15: Power flow for inductive mode

Referring to the Fig 15 it is observed that the power flow decreases in the inductive mode as firing angle is increased from 0° towards the resonance region because TCSC in the inductive mode acts as a variable inductance and Fig 14 refers to the current through the TCR branch and capacitor, also the voltage across the capacitor in the inductive mode. Tables 1 and 2 show the variation of the TCSC reactance and the power flow at the varying firing angle.

Table 1 Variation of the power flow and the TCSC reactance in the capacitive mode

CAPACITIVE REGION		
ALPHA	**X_{TCSC}**	**POWER (MW)**
60°	380	598
65°	292.96	594.5
70°	194.220	591
75°	193.82	588.5
80°	158.88	587.3
85°	127.799	586.9
90°	98.3946	586.87

Table 2 Variation of power flow and TCSC reactance in the inductive mode

INDUCTIVE REGION		
ALPHA	**X_{TCSC}**	**POWER (MW)**
0°	32.79495	399.5
5°	43.48257	392.8
10°	64.72401	384.2
15°	86.48892	375
20°	116.958	361.6
25°	163.400	345.1
30°	242.16307	317
33°	312.70728	298

Using the above data the reactance characteristics is plotted as given in fig 16:

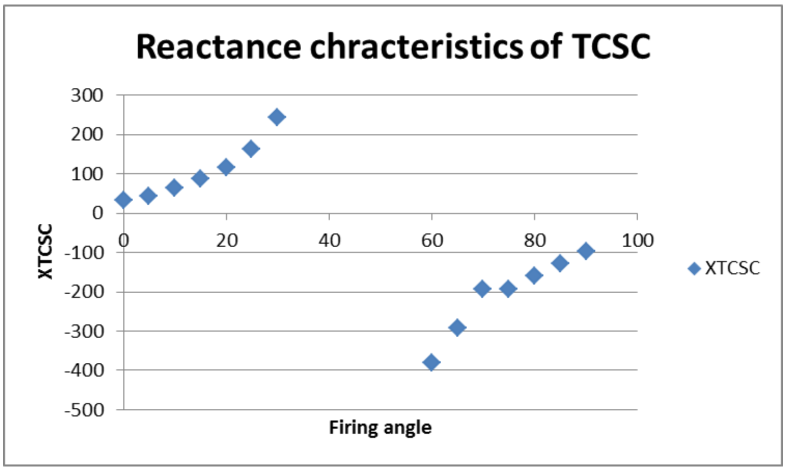

Figure 16: Reactance vs firing angle characteristics of TCSC

IX. CONCLUSION:

Thus the paper discusses the operation of TCSC at the varying firing angle and thus concludes that TCSC improves the power transfer capability of system, if used with proper control techniques to fire the SCRs in proper region with proper conduction angle. It has been referred that in the inductive mode TCSC acts as a variable inductor leading to the increase in the overall inductance of the transmission line and thus decreasing the power flow. Whereas in the capacitive mode the TCSC acts as a variable capacitance decreasing the reactance of the transmission line depending on the firing angle and thus increasing the power flow.

Also in the inductive region the voltage across the capacitor becomes more distorted which is the reason because of which the line current is taken as the reference for triggering the thyristors. Parameter selection is also one of the important things for TCSC as it can avoid the condition that can result into reduced operating range of TCSC. Thus resonance factor is an important factor to be considered for the same.

REFERENCES

[1] N. G. Hingorani and L. Gyugyi, "Understanding FACTS Concepts and Technology of Flexible AC Transmission Systems", IEEE Press.
[2] S. Meinkandasivam, Rajesh Kumar Nema, Shailendra Kumar Jain, "Selection of TCSC parameters: Capacitor and Inductor.", IEEE India International Conference on Power Electronics (IICPE), 978-1-4244-7882-8, pp 1-5, 28-30 Jan 2011.
[3] Scott G. Helbing, G.G. Karady, "Investigation of Advanced form of series compensation", IEEE Transaction on power Delivery, Vol 9, No.2, pp. 939-947,April 1994.
[4] Guowen H U, Ming CHENG, and Guilong CAI, "Relation between Fundamental Frequency Equivalent Impedance and Resonant Point for thyristor controlled series compensation", 30th Annual Conference of the IEEE Industrial Electronics Society, vol. 2, pp. 1128- 1132, November 2004.
[5] Dragan Jovcic, G. N. Pillai, "Analytical Modelling of TCSC Dynamics", IEEE Transactions on Power Delivery, Vol. 20, No. 2, pp. 1097-1104, APRIL 2005.
[6] S. Meikandasivam, D. Vijayakumar, Rajesh Kumar Nema, Shailendra Kumar Jain, "Investigation of split TCSC on Kanpur- Ballabhgarh transmission system" World academy of science, engineering and technology, International journal of Electrical, Robotics, Electronics and communication Engineering Vol:8 No:1,pp. 76- 83, 2014
[7] R. Mohan Mathur, Rajiv K. Varma, "Thyristor Based FACTS Controller for Electrical transmission Systems", IEEE Press.

