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Meeting Power Challenges with TCSC and Next Generation TCSC: SPLIT TCSC

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Abstract

The electricity demand is continuously increasing due to population growth and development. There is a lack of generation and transmission facilities, so the existing system is used to transfer more power to meet the rising power demand. This causes overexploitation of the present power system and gives rise to stability problems. The power transfer capacity of the existing transmission lines can be increased by using fixed capacitors by varying the impedance of the transmission lines, but they have associated SSR problems. In this situation FACTS devices TCSC are used to control power flow in the system. TCSC mitigate power oscillation, stability problems and various power quality problems like voltage sag and voltage swell created due to disturbances or faults. In the proposed work the TCSC is used to increase the power flow capacity of the system without the need for investment in new lines and systems. The active power transfer with different controllers is discussed. The two modules of TCSC with different ratings are taken and analysed. Then there are some problems in ordinary TCSC too. On tuning the ordinary TCSC in the critical region of the reactance characteristic curve there is observed a large gap of reactance at both the inductive and capacitive critical regions. Because of the large elapse/gap of reactance in this region small change of power demand is not possible in the power system which reduces the flexibility of the power system, and it becomes rigid. These challenges of ordinary TCSC are met here by the next generation device of TCSC: Split TCSC in the power system. Split TCSC tunes the critical region reactance with many firing points and hence elapse of reactance is very small which allows for fine tuning of power flow over the transmission line thus mitigating the problems of ordinary TCSC. Split TCSC includes all the other benefits of ordinary TCSC such as increased power flow, stability improvement, damping oscillations, and mitigating SSR as it belongs to the family of TCSC. Thus, in the proposed work the power challenges are met using TCSC and Split TCSC.

Keywords: Firing Angle, Power Flow, Power System, Reactance, TCSC, Transmission Line

1. Introduction

Electrical energy is an important element of life. Life without electrical energy cannot be imagined. It improves the living standard, health safety and wellbeing of citizens. It is very important for the economic development of the country. But the demand for electrical power is continuously increasing due to which the existing power system is made to work under highly stressed conditions. The rising power demand requires the installation of new generating plants which is a costly matter. There is overloading of the existing lines to transfer the increased demand for power. The cost of the erection of new generating plants and transmission lines is transferred to the consumers in the form of a hike in electricity tariff. This affects the financial health of the country. So, the existing power system must be used efficiently. The fixed capacitors were used earlier to improve the power system's power transfer capacity. It provides fixed compensation, is subject to wear and tear and has associated problems of

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series resonance. These power challenges are mitigated using TCSC, a power electronics-based device which is fast, accurate and provides dynamic compensation. The most important role of TCSC is to increase the power transmission capacity of the system by varying the impedance of the transmission line with the change in the firing angle of thyristors. It is in the favour of both the utility and the consumers as there is no need to invest in new power plants and transmission lines. The TCSC circuit is made up of a series capacitor in parallel with an inductor controlled by a thyristor called TCR. By varying the firing angles of the thyristor, the TCSC provides variable compensation as required in the system at a point in time. This device has many other benefits like damping oscillations, increasing the transient stability of the system, and limiting short circuit current.

2. Literature Review

The different FACTS devices were used in the system and their performance was evaluated /compared for improving the transmission line power flow. The different values of capacitors were used, and the values of power were noted. All the simulations were done in MATLAB. It was found that the losses in the system were minimized, and the harmonic content was also reduced[1-4]. The TCSC was used for the simulation and analysis of power flow in the Kanpur Ballabhgarh power transmission line. It was suggested that TCSC parameters should be properly selected. The control system was based on RS Flip flop. Various plots of different parameters of TCSC were done for both inductive and capacitive working regions of TCSC. The hardware implementation of TCSC was done. Various images of hardware circuits were captured, and waveforms were plotted for different firing angles. The comparison of power was done without TCSC and with TCSC as the system and the closed-loop system was designed. The waveshapes of power, impedance and firing angle were plotted for different values of compensation and firing angle The values of TCSC inductor and capacitor were calculated for each value of compensation[5-7]. The TCSC was used in the Kalpakam Khamman line for the same reason of power flow. The comparison of the system without any compensation, with using fixed capacitors and using fixed capacitors and TCSC in the system was done. The control circuit used for TCSC was based on constant power. The harmonic analysis was done using the FFT tool of MATLAB. The table was prepared for different parameters of the system with different loading conditions[8,9]. TCSC was used to assess the transient stability of the multimachine system based on simulation. The mathematical modelling and the Y matrix were developed. The fault clearing time was calculated and curves for angular velocities, generator powers were plotted. It was suggested to use ANN and fuzzy-based logic to improve the system. The work was done with the UPFC controller to improve the static and dynamic performance of the system. This was also based on the multimachine system. The load flow analysis of the system was performed[10-13].

3. Thyristor Controlled Series Capacitor (TCSC)

TCSC is a series FACTS device consisting of a series capacitor and a TCR. The TCR is connected in parallel to the capacitor. By changing the firing angle of the thyristor, the TCSC is used to provide variable compensation. There are different operating modes of TCSC which are bypass mode, blocked thyristor mode and partially conducting mode. The partially conducting modes are again divided into two types: Inductive boost and capacitive boost modes. In the inductive mode of TCSC the power flow decreases and in capacitive mode the power flow increases. The TCSC reactance characteristic curve between firing angle and reactance is plotted to show the inductive and capacitive regions of TCSC. In between these two regions, there is a resonance region where the operation of TCSC is prohibited. The inherent property of TCSC is to improve the power flow in the line and improve the stability of the system[14,15].

4. Test System

The series compensation by TCSC is done in the proposed work over 400 kV and 400 km long Kanpur Ballabhgarh transmission line. The inductance of the line = 1.044 mH /km. The total inductance of 400 km line = 0.4176 H. The TCSC inductor (L) and (C) values are 4.4 mH and capacitor (C) 306 μF respectively. The value of the fixed capacitor is 90.7 e-06. The simulation diagram includes the transmission line, source, load, control system, Firing unit for TCSC and scopes for active power, TCSC impedance and angle. For the first 0.5 sec, the TCSC is bypassed. The simulation is run, and various waveforms are observed on the scopes. The system is designed for without any controller, with a fixed capacitor only, with FC and TCSC, with TCSC only, with FC and two modules of TCSC.

5. Simulation Diagram

5.1 System Without TCSC

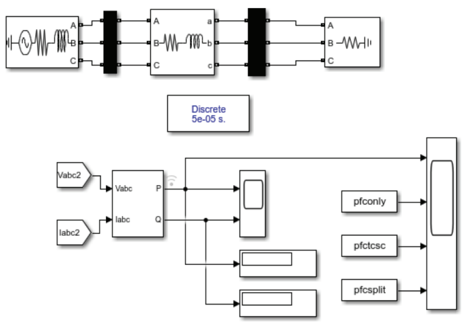

Figure 1. System without TCSC.

5.2 System with TCSC Only

The voltage and current of the TCSC are measured and fed as input to the system. It is used for calculating the TCSC impedance. There are thyristors inside the TCSC block. The firing unit consists of firing unit A phase, firing unit B phase and firing unit C phase. The TCSC works in constant impedance mode. Three single-phase PLLs in the firing circuit. For synchronisation, the line current is used. TCR pulse generator generates a firing pulse for one TCR and another TCR pulse generator generates the firing pulses for the other TCR. There is a block which generates a square wave synchronised with the line current. For positive (Sync +) and negative (Sync -) transitions.

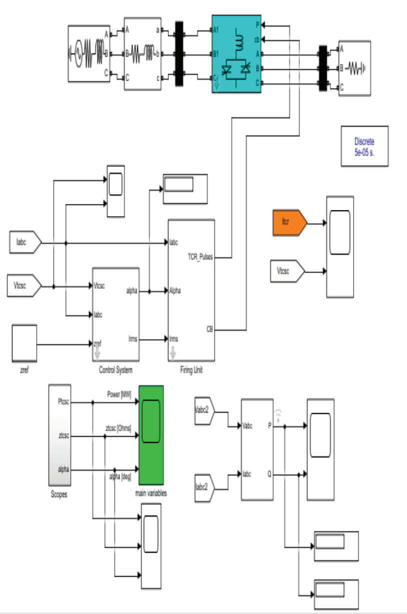

Figure 2. System with TCSC only.

6. Performance Analysis

The power flow decreases in the inductive mode and increases in the capacitive mode of TCSC as shown in the table below.

First, the TCSC power flow data is computed for ordinary TCSC in inductive mode by firing angle variation from 0° to 57° and for capacitive mode by firing angle variation from 90° to 59°. In the inductive mode, the power flow decreases from 0° to 57°. The TCSC power flow increases in capacitive mode from 90° to 59° as shown in Tables 2 and 3.

Table 1. Power flow of ordinary TCSC in inductive mode

S. No	Firing angle (°)	Power (Watts)
1	0	338.15
2	10	337.91
3	20	337.65
4	30	337.28
5	40	336.54
6	50	334.70
7	57	331.60

Table 2. Power flow of ordinary TCSC in capacitive mode

S. No	Firing angle(°)	Power (Watts)
1	59	345.247
2	60	345.243
3	70	344.669
4	80	344.467
5	90	344.445

7. System with Fixed Capacitor only

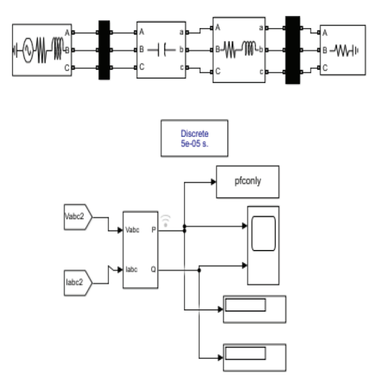

Figure 3. System with fixed capacitor only.

8. System with FC and TCSC

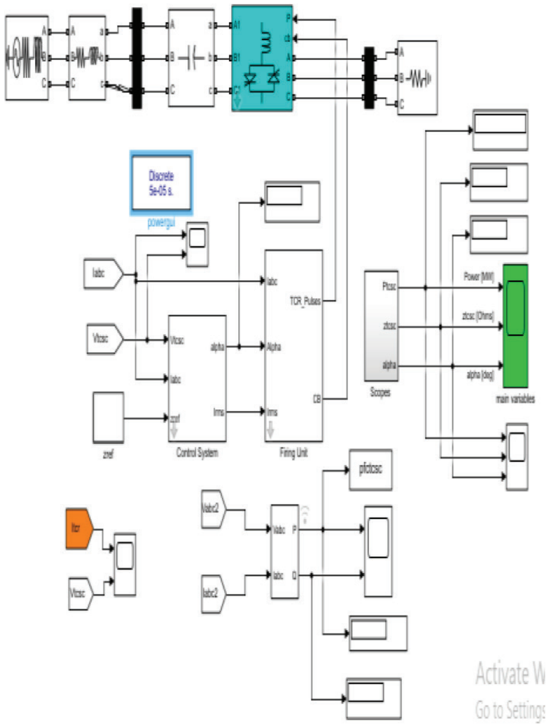

Figure 4. System with FC and TCSC.

9. System with FC and Two Modules of TCSC

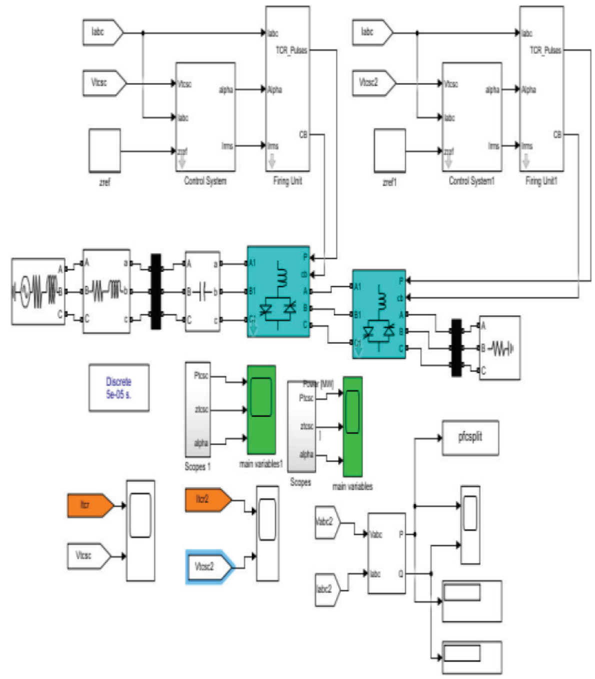

Figure 5. System with FC and two modules of TCSC.

Table 3. Active power transfer including FC and TCSC

S. No		Active Power (MW)	Result and analysis
1	Without compensation	339.40	
	With FC only	355.90	
2	With TCSC at a firing angle of 30°	337.30	Power transfer decreases as compared to the uncompensated case in inductive mode at an angle of 30
3	With TCSC at a firing angle of 75°	344.50	Power transfer increase as compared to uncompensated case in capacitive mode at angle 75
4	With FC and TCSC at a firing angle of 30°	353.90	Power transfer decreased as compared to the fixed capacitor-only case but more than that using only TCSC at 30° due to including FC
5	With FC and TCSC at a firing angle of 75°	360.40	Power transfer increases as compared to uncompensated cases but more than that using only TCSC due to including FC
6	With FC and two modules of TCSC. The ratings of L and C are kept the same as that of ordinary TCSC. Both firing angles are 75°	364.80	Power transfer is increased due to two modules of TCSC.
7.	With FC and two modules of TCSC. The rating of L is kept at half, and the rating of C is doubled as that of an ordinary single TCSC. Both Firing angles are 75°	360.40	Power transfer is the same as that of a single TCSC for this case.

Comparison of active power with the only line, only FC, with FC and TCSC, with FC and Split TCSC.

A. When the two modules of TCSC have half the values of L and double the value of C. The two modules taken together work as ordinary single TCSC. The firing angles are kept at 75°.

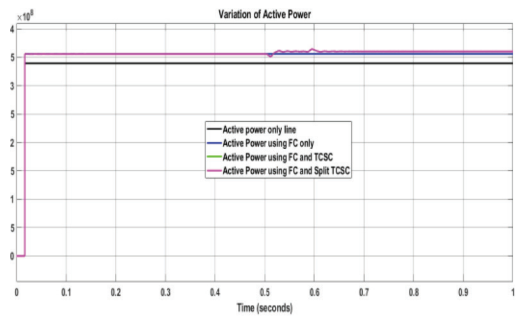

Figure 6. Variation of Active Power with two modules of TCSC.

B. When the two modules of TCSC have the same values of L and C as that of ordinary TCSC. The firing angles are kept at 75°.

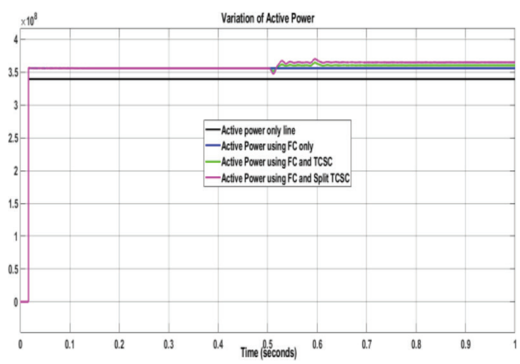

Figure 7. Variation of Active Power with two modules of TCSC.

10. Meeting Power Challenges with Next Generation TCSC: The Split TCSC

The ordinary TCSC worked successfully in the power system to provide increased power flow in the line, damping oscillations, and supplying the power with reliability, high efficiency and at a lower cost. The TCSC provided an excellent opportunity for network operators to control the power flow, increase the load ability of the system, minimise the system losses, and improve the power factor. The TCSC was commissioned in India for Kanpur Ballabhgarh 400 kV transmission line of 400 km length. The power flow was increased from 400 MW to nearly 600 MW using TCSC. However, some problems were observed when the impedance characteristic curve of TCSC was analysed in detail. Due to those problems, the transmission system becomes rigid for controlling the different parameters of the line such as the voltage, the current and the phase angle. The result was that using a single TCSC device the power flow was not secure in certain regions of the TCSC device characteristic curve. The TCSC device characteristic curve has different regions like the vernier region, the resonance region, and the critical region. These regions exist for both, the inductive and the capacitive modes of TCSC.

The other power challenges/problems with the ordinary TCSC are:

- Limits on minimum inductive and minimum capacitive reactance.
- Reactive power compensation for values of reactance less than that of bypass mode and blocked mode of operation is not possible.
- There is no continuous transition from the inductive working region to the capacitive working region of TCSC because of the discontinuity between those regions.
- It is easy to tune the TCSC in the vernier inductive and capacitive regions but not in both inductive and capacitive critical regions because of a large change in reactance ΔX in those regions.
- There is only enhancement of the apparent reactance in both inductive and capacitive regions. The TCSC can't reduce the reactance to less than the minimum inductive and minimum capacitive reactance.
- There is no possibility of meeting the power demand for any fine change in critical regions.
- No firing points are limited in ordinary TCSC.

11. Methodology

The placement of split TCSC to meet the challenges of ordinary TCSC. To meet these above power challenges of ordinary TCSC the next generation TCSC device which is the split TCSC is proposed here. The split TCSC is like an ordinary TCSC, but the difference is that in this device two single TCSCs are connected in a cascade. This is called split TCSC as it is split in terms of k which stands for degree of series compensation. By splitting the value of k into two parts such that k = (k1) +(k2) the split TCSC device provides the same degree of compensation as that of ordinary TCSC. Tuning of both the TCSC1 and TCSC2 is done efficiently. Due to this fine and proper tuning of line reactance is now possible e.g., in the ordinary TCSC if the degree of compensation is chosen to 50% then in the split TCSC for TCSC1 the compensation $k1$ can be varied from 1 to 49 % and for the other TCSC2 k2 can be varied from 49 to 1 % for getting the same 50% compensation as that of ordinary TCSC for the line.

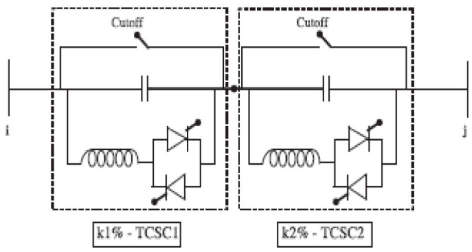

Figure 8. Split TCSC.

For using SPLIT TCSC two modules of TCSC are taken in place of one module of TCSC. The rating of each of the modules of split TCSC is taken half the MVA rating of ordinary TCSC is taken. The TCSC can be split into many modules for further meeting the small/minute change in power demand as well as improving the damping capacity of the system although it will also increase the cost. The increase in cost is justified as the limitations of ordinary TCSC are overcome using Split TCSC and will also make the changeover between inductive and capacitive regions smooth. The different modules can be operated independently in inductive mode only and capacitive mode only. Similar operation of both the modules is identical to that of a single module TCSC, but different operations like inductive and capacitive modes at different firing angles result in intermediate characteristics and solving the minimum reactance limits problem.

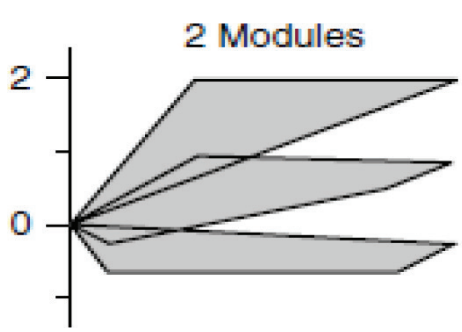

Figure 9(a). VI capability curve.

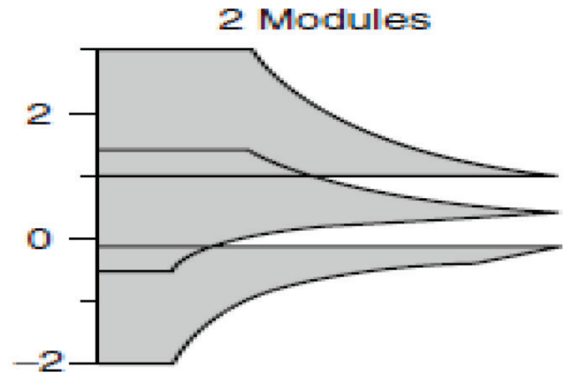

Figure 9(b). X-I capability curve.

12. Triggering Choices

Taking the working range of TCSC from 90º to 180º. Take 'n' as the possible number of firing steps between 90º and 180º. Now the reactance's possible for compensation are [(n + 1) * (n + 1)]. This will allow the fine/proper tuning of the reactance of the line with split TCSC. This tuning is done like:

- The TCSC1 is made to work at 90º. The TCSC2 firing angle is changed/varied from 90º to 180º which gives 91 operating points. This data will generate the 91 columns of the triggering matrix. One TCSC can be made to work in cut-off mode. So, there is one more column possible in the matrix of triggering choices so the total number of columns possible now is 92 in the triggering matrix.
- The TCSC2 is made to work at 90º. The TCSC1 firing angle is varied from 90º to 180º. This gives 91 operating points. The data will generate the 91 rows of the triggering matrix. The one TCSC can be made to work in cut-off mode. So, there is one more row possible in the matrix so the total number of total number of rows possible now is 92 in the triggering matrix.
- The triggering matrix dimension becomes [92x92]. The firing angle is varied in steps of 1 degree which widened the range of controllability and compensation range in split TCSC. There is the possibility of fine transfer of real power (AP) and Reactive Power (RP) transfer in line using split TCSC. The no of triggering choices is more due to which there are more degrees of freedom. One more thing is possible here which is the possibility of having many firing angle combinations which can provide the same value of line reactance.

13. Simulation Diagram

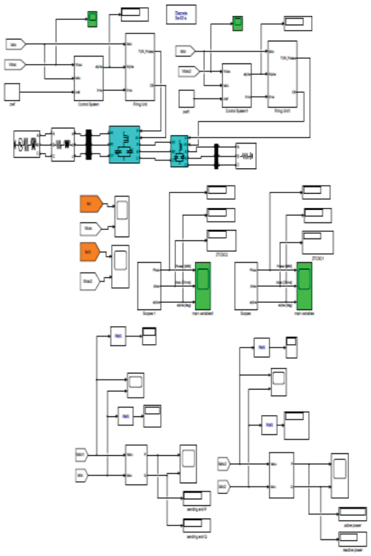

Figure 10. Split TCSC.

The simulation diagram consists of different MATLAB blocks such as the three-phase AC source, load, buses, and scope display. There are two TCSC blocks in which the values of inductor and capacitor are given. There are control and firing unit subsystems The model can be operated in capacitive as well as inductive mode using suitable firing angles. There are three single-phase Phase Locked Loops (PLL) in the firing unit. The reference impedance is given to the controller. It is compared with the measured impedance and the PI controller is used to minimize the impedance error. The PI controller is used to control the firing angle of thyristors in the system and this process is repeated till the error is minimized. The different values of firing angle can be given to the model.

14. Test System Technical Data

The same Kanpur Ballabhgarh system data is considered for split TCSC work also. The TCSC inductor (L) and (C) values are 4.4 mH and capacitor (C) 306 μF respectively for a 400 kV transmission line of 400 km length. The total line inductance is 0.4176 H. For split TCSC the values of TCSC inductor and TCSC capacitor are L = 2.2 mH and C = 612 μF. But both the TCSCs have the same values of L and C as the equal degree of series compensation is considered. (k = k1+k2) where k1 = k2.

The different regions of the TCSC reactance characteristic curve are:

Table 4. Regions of TCSC

S. No	Region	Angle(°)
1	Bypass mode region	0°
2	Blocked mode region	90°
3	Resonance region	Around 58°
4	Vernier inductive region	0°-46°
5	Critical inductive region	46°-57°
6	Vernier capacitive region	90°-79°
7	Critical capacitive region	79°-59°

15. Results and Discussions

15.1 Power Flow and Reactance Variation of Ordinary TCSC

First, the TCSC power flow data is computed for ordinary TCSC in inductive mode by firing angle variation from 0° to 57° and for capacitive mode by firing angle variation from 59° to 90°. In the inductive mode, the power flow decreases from 0° to 57°. The TCSC power flow increases in capacitive mode from 90° to 59° as shown in Tables 5 and 6 below. (The power values are taken in long format to show meeting small power demand problem by split TCSC)

Table 5. Power flow of ordinary TCSC in inductive mode

S. No	Firing angle (°)	Power (Watts)	Reactance (Ω)
1	0	338152677.14946	2.075
2	10	337914365.49397	2.503
3	20	337655538.09151	3.000
4	30	337284776.02446	3.697
5	40	336546430.11929	4.933
6	50	334703244.84833	7.619
7	57	331605501.44006	11.770

Table 6. Power flow of ordinary TCSC in Capacitive mode

S. No	Firing angle(°)	Power (Watts)	Reactance (Ω)
1	59	345243897.19543	-10.060
2	60	345243894.33833	-10.050
3	70	344669601.03749	-9.047
4	80	344467662.52338	-8.715
5	90	344445678.26225	-8.676

Table 7. Ordinary TCSC Inductive mode: Parameters variation from 0° to 57° with small angle change

S. No	Firing angle (°)	Power (Watts)	R	DX
Reactance in ohms = R Difference Reactance = DX				
1	0	338152677.14946	2.075	--
2	10	337914365.49397	2.503	0.428
3	20	337655538.09151	3.000	0.497
4	30	337284776.02446	3.697	0.697
5	35	336958323.99357	4.248	0.551
6	36	336861215.68578	4.346	0.098
7	37	336835709.06490	4.484	0.138
8	38	336736560.90954	4.645	0.161
9	39	336593775.91817	4.781	0.136
10	40	336546430.11929	4.933	0.152
11	41	336447170.40308	5.126	0.193
12	42	336265027.17958	5.329	0.203
13	43	336133291.78305	5.527	0.198
14	44	336063327.30959	5.760	0.233
15	45	335861728.17523	6.023	0.263
16	46	335626944.08394	6.247	0.224
17	47	335490567.16515	6.575	0.328
18	48	335281951.57992	6.904	0.329
19	49	334989700.88616	7.222	0.318
20	50	334703244.84833	7.619	0.397
21	51	334454611.99372	8.090	0.471
22	52	333997860.28316	8.572	0.482
23	53	333611657.11672	9.073	0.501
24	54	333274017.26973	9.660	0.587
25	55	332771664.95747	10.330	0.670
26	56	332176155.54252	11.000	0.670
27	57	331605501.44006	11.770	0.770

Table 8. Ordinary TCSC capacitive mode: Parameters variation from 59° to 90° with small angle change

S. No	FA (°)	Power (Watts)	X	DX
Difference (Reactance = DX)				
Reactance in ohms = X				
1	59	345243897.19543	-10.060	--
2	60	345243894.33833	-10.050	0.010
3	61	345243085.62359	-10.010	0.040
4	62	345079519.87448	-9.806	0.204
5	63	345090925.04916	-9.708	0.098
6	64	344978976.32634	-9.571	0.137

Table 8 continued...

7	65	344863133.30587	-9.424	0.147
8	66	344883310.37685	-9.353	0.071
9	67	344799684.36528	-9.266	0.087
10	68	344729346.28828	-9.163	0.103
11	69	344685957.55474	-9.088	0.075
12	70	344669601.03749	-9.047	0.041
13	71	344622022.16078	-8.976	0.071
14	72	344553508.98678	-8.906	0.070
15	73	344567288.64490	-8.887	0.019
16	74	344540054.38225	-8.845	0.042
17	75	344514726.60792	-8.802	0.043
18	76	344514358.82514	-8.783	0.019
19	77	344495190.63149	-8.764	0.019
20	78	344479979.84062	-8.738	0.026
21	79	344462482.59030	-8.718	0.020
22	80	344467662.52338	-8.715	0.003
23	81	344460050.60959	-8.701	0.014
24	82	344454021.97341	-8.690	0.011
25	83	344454178.74962	-8.689	0.001
26	84	344449930.92928	-8.683	0.006
27	85	344447636.39758	-8.681	0.002
28	86	344447075.62856	-8.677	0.004
29	87	344446919.09231	-8.677	0.000
30	90	344445678.26225	-8.676	0.001

Tables 7 and 8 are plotted for small changes in firing angle to meet the problems of ordinary TCSC. The tables are used for understanding the power problems of ordinary TCSC. Column 4 of the tables shows the variation of reactance with firing angle. Column 5 is the difference in reactance between the two consecutive rows. This is to show the variation of reactance in ordinary TCSC with a change in firing angles.

16. Mitigating Problems of Ordinary TCSC with Split TCSC

Problem 1: The values of reactance less than that of bypass mode region and blocked mode regions are not possible in ordinary TCSC for inductive and capacitive outputs respectively.

From Table 4, the bypass mode reactance and power are 2.075 Ω and 338152677.14946 watts. The blocked mode reactance and power flow are 8.676 Ω and 344445678.26225 watts. So, in the ordinary TCSC in inductive mode, the reactance varies from 2.075 Ω to 11.770 Ω and in the capacitive mode it varies from 8.676 Ω to 10.060 Ω as shown in Tables 5 and 6 above. The minimum inductive compensation by ordinary TCSC is 2.075 Ω only and the minimum capacitive reactance possible is 8.676 Ω. But by using split TCSC by operating one TCSC in cut-off mode and another in either inductive or capacitive mode values of reactance less than bypass and blocked mode reactances are possible. Now the minimum bypass mode reactance possible by split TCSC is 1.035 Ω and the minimum blocked mode reactance possible is 4.435 Ω as shown in Tables 9 and 10 below. As the values of reactances less than bypass and blocked mode are possible using split TCSC there is a corresponding small power flow possible which was not possible in ordinary TCSC.

Table 9. Half TCSC in Inductive mode

S. No	Firing angle (°)	Power (Watts)	Reactance (Ω)
1	0	338774269.90096	1.035
2	10	338649813.57033	1.249
3	20	338523975.71244	1.494
4	30	338341072.45952	1.841
5	40	337964706.00892	2.458
6	41	337915208.07638	2.555
7	42	337825616.20441	2.645
8	43	337759907.84930	2.743
9	44	337725374.63529	2.856
10	45	337624403.58654	2.987
11	46	337501454.36483	3.105
12	47	337434630.73635	3.252
13	48	337328002.99675	3.432
14	49	337180465.78365	3.590
15	50	337067566.51959	3.784
16	51	336941980.25188	4.004
17	52	336713445.38272	4.251
18	53	336516570.52597	4.496
19	54	336345763.43775	4.790
20	55	336119097.82678	5.098
21	56	335818832.77559	5.429
22	57	335548248.19951	5.808

Table 10. Half TCSC in capacitive mode

S. No	Firing angle(°)	Power (Watts)	Reactance(Ω)
1	59	342345561.66633	-5.030
2	60	342345432.17973	-5.022
3	61	342332668.00946	-4.995
4	62	342258981.68236	-4.902
5	63	342264496.69806	-4.853
6	64	342207732.10256	-4.783
7	65	342149390.01501	-4.710
8	66	342160065.73112	-4.674
9	67	342117521.67035	-4.631
10	68	342082302.24857	-4.580
11	69	342061389.02475	-4.542
12	70	342052375.10911	-4.522
13	71	342028428.26053	-4.488
14	75	341978092.53510	-4.403
15	80	341952983.94515	-4.359
16	85	341942955.52887	-4.349
17	90	341934322.28448	-4.335

Problem 2: Vernier and critical region reactances variation.

In ordinary TCSC in both, the vernier inductive and vernier capacitive regions there is a small change of reactance but in the critical inductive and critical capacitive regions, there is a large change of reactance as can be seen from Tables 7 and 8. Due to this in ordinary TCSC small change in power flow is possible in vernier inductive and vernier capacitive regions but not in critical inductive and critical capacitive working regions of ordinary TCSC. No fine-tuning of line reactance in critical regions of ordinary TCSC is possible. So, the use of split TCSC is done to solve this problem. In split TCSC one TCSC is made to work in inductive and the other in capacitive mode so there is the possibility of small variation of reactance and a small variation in power flow is possible. Both the TCSCs are made to work in either the inductive mode or the capacitive mode which will give the same result as that of ordinary TCSCs then. In the ordinary TCSC, there is a difference of 0.770 Ω between firing angles 56° and 57° as shown in Table 4, which is a big number whereas in split TCSC there are many combinations possible. Considering the case of a row, no 2 and 3 in the split TCSC table no. 9 the difference now is 0.091 Ω which is less than 0.770 Ω so a small change in power demand can be now met. Other differences are also seen in Table 12 which are less than 0.770 e.g., 0.733, 0.311, 0.352.

Table 11. Single TCSC

S. No	Firing angle (°)	Power (Watts)	Reactance (Ω)	Difference
1	56	332176155.54252	11.000	0.670
2	57	331605501.44006	11.770	0.770

Table 12. Split TCSC

Firing angle 1 = FA1, Firing angle 2 = FA2, Reactance 1 = X1, Reactance 2 = X2 Total Reactance = TX						
S. No	**FA1 (°)**	**FA2 (°)**	**Power Flow (Watts)**	**X1**	**X2**	**TX**
1	55	56	332506110.82426	5.057	5.398	10.455
2	56	57	331954110.62003	5.404	5.784	11.188
3	55	58	331946038.74808	5.056	6.223	11.279
4	56	58	331604650.92651	5.379	6.211	11.590
5	57	58	331376461.14068	5.741	6.201	11.942

S. No	FA1 (°)	FA2 (°)	Power Flow (Watts)	X1	X2	TXw
1	55	56	332506110.82426	5.057	5.398	10.455
2	56	57	331954110.62003	5.404	5.784	11.188
Difference D= row2 TX-row1TX = 0.733						
3	55	58	331946038.74808	5.056	6.223	11.279
Difference D= row3TX-row2TX=0.091						
4	56	58	331604650.92651	5.379	6.211	11.590
Difference D=row4TX-row3TX=0.311						
5	57	58	331376461.14068	5.741	6.201	11.942
Difference D=row5TX-row4TX=0.352						

Now there are different possible reactances between 11.000Ω and 11.770Ω. The difference between the reactance now possible as shown in the table are 0.733, 0.091, 0.311 and 0.352 which is less than 0.770 Ω in ordinary TCSC. So small difference is possible between reactance using split TCSC.

Problem 3. Limited triggering choices in ordinary TCSC.

In Ordinary TCSC there is only one choice for getting the reactance and power flow but in split TCSC, there is a combination of more triggering choices possible for getting the same reactance and power flow. Also, by using split TCSC both modules with the same firing angle the result of power flow is the same as that of single TCSC power flow and reactance. The table of triggering choices possible is now an 11 by 11 matrix if there is a difference of 10°s. If the difference of a minimum 1° is taken the matrix is 92 by 92 which gives a huge range of triggering choices possible by split TCSC.

Problem 4: In ordinary TCSC the power flow change for variation of less than 1° of firing angle is not possible which is possible using split TCSC.

In ordinary TCSC we cannot have power flow possible between these two angles (49° and 50°) given below in the table. But on using split TCSC we can have power flow possible between these two values as shown in the table. This is possible by giving different firing angles to two TCSCs (or using a split TCSC).

Table 14. Ordinary TCSC

S. No	Firing angle(°)	Power (Watts)	R
Reactance in ohms =R			
1	49°	334989700.88616	7.222
2	50°	334703244.84833	7.619

Table 13. Matrix of triggering choices

All angles in (°), Cut OFF=CO										
0,0	0,10	0,20	0,30	0,40	0,50	0,60	0,70	0,80	0,90	0, CO
10,0	10,10	10,20	10,30	10,40	10,50	10,60	10,70	10,80	10,90	10, CO
20,0	20,10	20,20	20,30	20,40	20,50	20,60	20,70	20,80	20,90	20, CO
30,0	30,10	30,20	30,30	30,40	30,50	30,60	30,70	30,80	30,90	30, CO
40,0	40,10	40,20	40,30	40,40	40,50	40,60	40,70	40,80	40,90	40, CO
50,0	50,10	50,20	50,30	50,40	50,50	50,60	50,70	50,80	50,90	50, CO
60,0	60,10	60,20	60,30	60,40	60,50	60,60	60,70	60,80	60,90	60, CO
70,0	70,10	70,20	70,30	70,40	70,50	70,60	70,70	70,80	70,90	70, CO
80,0	80,10	80,20	80,30	80,40	80,50	80,60	80,70	80,80	80,90	80, CO
90,0	90,10	90,20	90,30	90,40	90,50	90,60	90,70	90,80	90,90	90, CO
CO,0	CO,10	CO,20	CO,30	CO,40	CO,50	CO,60	CO,70	CO,80	CO,90	CO,CO

Table 15. Split TCSC

S. No	Firing angle 1(°)	Firing angle 2 (°)	Power (Watts)
1	56	17	334939446.08776
2	56	18	334921394.55612
3	56	19	334905868.36271
4	56	20	334903199.03381
5	56	21	334893343.19723
6	56	25	334823942.78742
7	56	28	334752548.20387
8	56	29	334662797.45351
9	56	30	334668235.44348
10	56	35	334512396.04965
11	57	58	331376461.14068

16.1 Plot of Variation of Reactance with Firing Angle in Ordinary TCSC

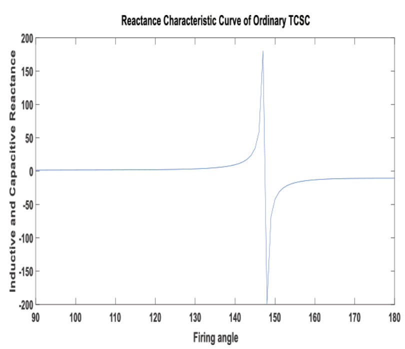

Figure 11. Reactance curve of ordinary TCSC.

16.2 Plot of Variation of Reactance with Firing Angle in Split TCSC

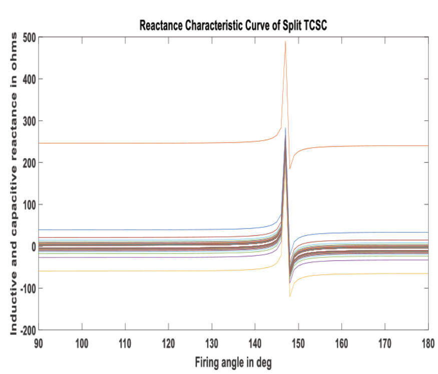

Figure 12. Reactance curve with Split TCSC.

Figure 11 shows the variation of firing angle with TCSC reactance. There is a vertical line in Figure 4 showing the change from inductive to capacitive mode around the resonance angle. At 90° the TCSC works in bypass mode and at 180° it works in capacitive mode. Multiple resonant points should be limited/avoided because they reduce the working operating range of the TCSC. Hence the parameters of TCSC which are L and C (inductor and capacitor should be selected carefully. Figure 5 shows multiple curves due to the use of split TCSC where there are more triggering choices. Due to using two TCSCs with half the ratings of the original ordinary TCSC. These curves are generated as now there is a matrix of triggering choices whose dimensions can be 92x92.

16.3 Plot of Firing Angle, Power, and Reactance in Ordinary TCSC

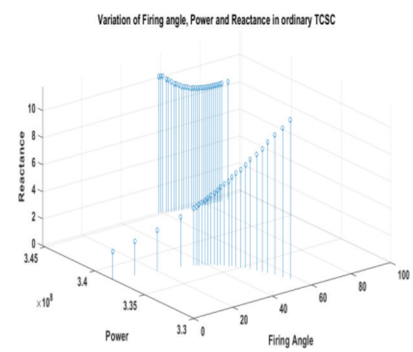

Figure 13. Firing angle, power, and reactance in ordinary TCSC

16.4 Scatter Plot of Firing Angle, Power, and Reactance in Ordinary TCSC

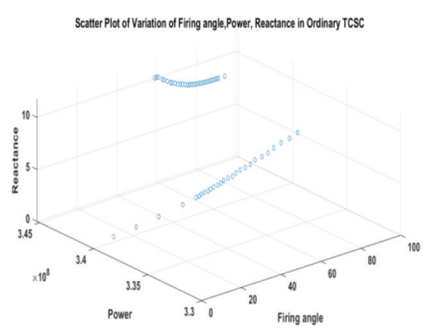

Figure 14. Firing angle, power, and reactance in ordinary TCSC.

16.5 Plot of Firing Angle, Power, and Reactance (With Half the Ratings of L and C) of Ordinary TCSC

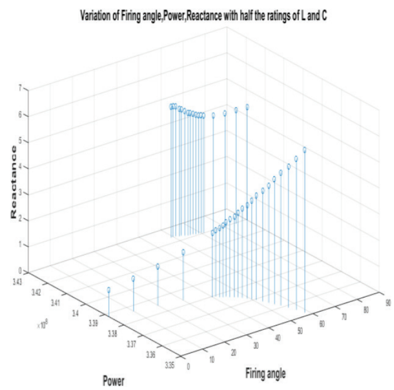

Figure 15. Firing angle, power, reactance.

16.6 Scatter Plot of Firing Angle, Power and Reactance (with Half the Ratings Of L and C) of Ordinary TCSC

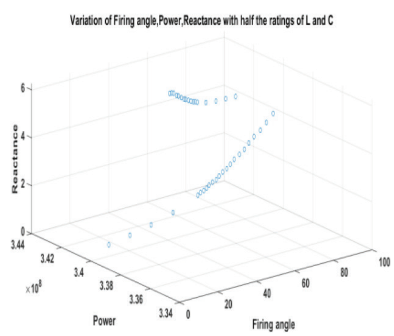

Figure 16. Firing angle, power, reactance with half ratings TCSC.

16.7 Compass Plot of Firing Angle and Power in Ordinary TCSC

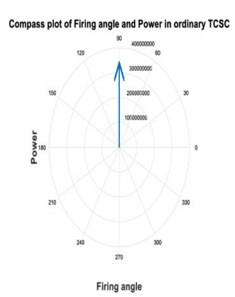

Figure 17. Compass plot between firing angle and power in ordinary TCSC.

17. Conclusion

In the present work, the TCSC is used to improve the power flow in the system without the need for new lines which saves investment costs. The TCSC also meets the challenges of power quality and power system oscillations. There are certain limitations with ordinary TCSC such as bypass and blocked mode reactance limitations, critical inductive and critical capacitive regions elapse of reactance problems, limited triggering choices, and problems with small changes in power demand. In the proposed work the challenges of meeting rising power demand as well as the challenge of providing smooth uninterrupted power with all types of variation (large as well as small too) in power demand is met successfully by the next-generation device Split TCSC device. Smooth power flow is now possible without any interruption between critical and vernier regions. Various plots of firing angle, power, and reactance for ordinary TCSC and split TCSC are also shown in the tables. Many reactance characteristic curves are now possible using split TCSC which increases meeting the small power demand capability. The present challenge of the power industry which is to provide smooth and uninterrupted power to all at low cost is accomplished using TCSC and Split TCSC devices. The other benefits of TCSC like enhancing the power quality, improving the efficiency of the system, and minimising losses are also obtained using split TCSC. There will be significant savings in energy generation cost and transmission line erection cost, the environment will be protected, and the quality of life along with health and safety will be improved using TCSC and next generation TCSC, split TCSC.

18. References

1. Mehta S, Prakash S. Performance evaluation of FACTS controllers for short transmission line. International Journal of Applied Engineering Research. 2018; 13(7): 5140-53.
2. Akter S, Saha A, Das P. Modelling, simulation, and comparison of various facts devices in power system. International Journal of Engineering Research and Technology (IJERT). 2012; 1(8):1-12.
3. Sankar S, Balaji S, Arul S. Simulation and comparison of various FACTS devices in power system. International Journal of Engineering Science and Technology. 2010; 2(4):538-47.
4. Nayeripour M and Mahdi MM. Analyze real switching angle limits in TCSC on capacitor and inductor values and

their selection factors. International Journal of Advanced Science and Technology. 2013; 57:25-36.

5. Hitendrasinh CC, Makwana V. Thyristor controlled series capacitor: Simulation and analysis. International Journal of Advance Engineering and Research Development. 2015; 2(5):796-806. https://doi.org/10.21090/IJAERD.0205111
6. Patel M, Brahmbhatt A. Design and simulation of series compensator for enhancement on ATC. International Journal of Advance Engineering and Research Development. 2016; 3(5):619-26. https://doi.org/10.21090/IJAERD.030597
7. Agarwal A, Kumar D. Application of thyristor-controlled series compensator in power systems. International Research Journal of Engineering and Technology. 2020; 7(6):2025-30.
8. Meikandasivam S, Nema RK, Jain SK. Microtuning of reactance by split TCSC on the transmission line. International Journal on Power and Energy Conversion 2010; 2(2): 95-108. https://doi.org/10.1504/IJPEC.2010.037040
9. Prudhviraj GVT, Meikandasivam RS, Vijayakumar D. Implementing TCSC device in Kalpakam-Khammam line for power flow enhancement. International Conference on Circuits, Power and Computing Technologies. 2013; 138-41. https://doi.org/10.1109/ICCPCT.2013.6528932
10. Bhatkar SA, Rahane AD, Dhawale RS, Sawarkar SN, Chavan NR. Simulation of harmonics filters to reduce harmonics distortion using MATLAB. National Conference Recent Innovations in Science and Engineering. 2017; 5(9):27-31.
11. Patel R, Bhatti TS, Kothari DP. MATLAB/Simulink-based transient stability analysis of a multimachine Power System. International Journal of Electrical Engineering Education. 2002; 39(4):320-36. https://doi.org/10.7227/IJEEE.39.4.3
12. Saini MK, Yadav NK, Mehra N. Transient stability analysis of multimachine power system with FACTS devices using MATLAB/Simulink environment. 2013; 16(1):46-50.
13. Singh S, Kumar P, Ram A. Modelling, and analysis of thyristor-controlled series capacitor using MATLAB/ Simulink. International Journal of New Innovations in Engineering and Technology (IJNIET). 2013; 1(3):61-6.
14. Jovcic D, Pillai GN. Analytical modelling of TCDC dynamics. IEEE Transactions on Power Delivery. 2005; 20(2):1097-104. https://doi.org/10.1109/TPWRD.2004.833904
15. Patel N, Bhatt C, Modi S. Influence of TCSC in an interconnected power systems modelling, analysis and interfacing. Technical Research Organisation India. 2016; 2(3):26-30.