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Investigation of Split TCSC on Kanpur-Ballabhgarh Transmission System

S. Meikandasivam, D. Vijayakumar, Rajesh Kumar Nema, Shailendra Kumar Jain

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Abstract**—**This paper investigates the performance of the single TCSC and proposed split TCSC on transmission system where India's first TCSC project is installed in Kanpur - Ballabhgarh (KB) line to ensure the fine tuning of line reactance by proposed split TCSC in place of existing KB TCSC. A three phase KB transmission system is developed in MATLAB/Simulink (SimPowerSystems) for
a) without any compensation,
b) with fixed capacitor (FC),
c) with FC + existing KB TCSC and
d) with FC + proposed split TCSC
The KB system is analyzed for a step variation of load and performance of the system is investigated with a closed loop reactance control method.

Keywords**—**Single TCSC, Split TCSC, TCSC Reactance characteristic curve, Power flow analysis, Sensitivity analysis.

NOMENCLATURE

α	Firing angle in degrees
X_L	Inductive Reactance of TCR in ohms
X_C	Capacitive reactance in ohms
$X_L(\alpha)$	Variable Inductive Reactance of TCR with respect to firing angle (α) in ohms.
$X_{TCSC}(\alpha)$	Net reactance across TCSC in ohms.
$X_{TCSC}(\alpha 1)$	Reactances of Split TCSC varies with firing angle $\alpha 1$
$X_{TCSC}(\alpha 2)$	Reactances of Split TCSC varies with firing angle $\alpha 2$
ω	Constant, $\sqrt{(X_C/X_L)}$.
ΔX	Change in reactance in ohms
K	Degree of series compensation
K1 & K2	Degree of series compensation for split TCSC
X_{Total}	Effective transmission line reactance including single TCSC reactance in ohms

I. INTRODUCTION

FIRST series controlled compensation project commissioned in India over 400 kV, 400km long Kanpur and Ballabhgarh (KB) transmission line and is designated as 'Kanpur-Ballabhgarh TCSC' project. The Thevenin's equivalent resistance and inductance are (0.1 Ω, 0.043 H), and (0.1Ω, 0.026 H) at Kanpur and Ballabhgarh end respectively on which actual line inductance is 1.044 mH/km [1]. The two fixed capacitors (FC) with 27% and 8% of line reactance were installed to provide a total of 35% compensation [1], [2]. The FC with 8% compensation is made variable up to 20% by shunting a TCR device and termed as TCSC. The arrangement is shown in Fig. 1. The second FC keeps on providing 27% fixed compensation. The overall arrangement is now capable of providing 47% of compensation with variation in the range from 35% (8% (TCSC) + 27% (FC)) to 47% (20% (TCSC) + 27% (FC)). The purpose of installed KB TCSC is to improve the power carrying capability of the transmission line.

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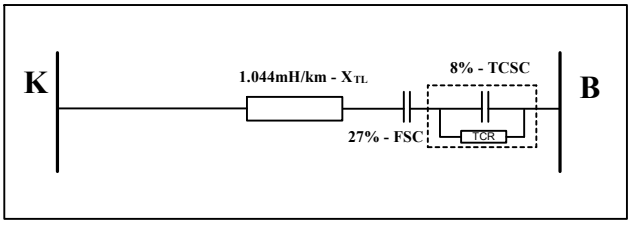


Fig. 1 Single line diagram of Kanpur –Ballabhgarh transmission system

Certain difficulties are observed while analyzing the reactance characteristics of KB TCSC project [3], [4]. The observed difficulties compose transmission system rigid to control the line parameters such as voltage, current and phase angle. Thus implementing single TCSC devices in the transmission system fails to transmit the power securely.

To evade the difficulties of single TCSC, concept of split TCSC is proposed in place of Kanpur-Ballabhgarh (KB) TCSC device to precisely control the power flow in the KB transmission line. Literature [4] enumerates only the reactance characteristics of split TCSC on KB transmission line. To examine the performance of proposed split TCSC, a KB transmission system is developed in MATLAB/SIMULINK platform and tested for sudden variation of load.

II. REACTANCE ANALYSIS OF EXISTING KB TCSC

The intended reactance characteristics may be plotted using TCSC reactance equation [5], [6] which gives variation in reactance value for change in firing angle, as:

A. Technical Data of KB TCSC

Inductance / km (L)	$= 1.044$ *mH,*
Length of Line	$= 400$ *km,*
Total line reactance (X_{TL})	$= 131.1929\ \Omega$,
Fixed Capacitance	$= 90.7\ \mu F$
KB TCSC Capacitor (C)	$= 306\ \mu F$
KB TCSC Inductor (L)	$= 4.4$ *mH*

$$X_{TCSC}(\alpha) = -10.4 + 3.8186(2(\pi - \alpha) + \sin(2(\pi - \alpha))) - 2.3408\cos^2(\pi - \alpha)(\omega\tan\omega(\pi - \alpha)) - \tan(\pi - \alpha)$$

$$\omega = \sqrt{\frac{X_C}{X_L}} = \sqrt{\frac{10.4}{1.38}} = 2.7452$$

Fig. 2 shows existing KB TCSC reactance characteristic curve drawn by solving above equation for varying firing angle (α) in steps of 1° in the range from 90° to 180°. The calculated data for reactance characteristic curve is also tabulated in Table I.

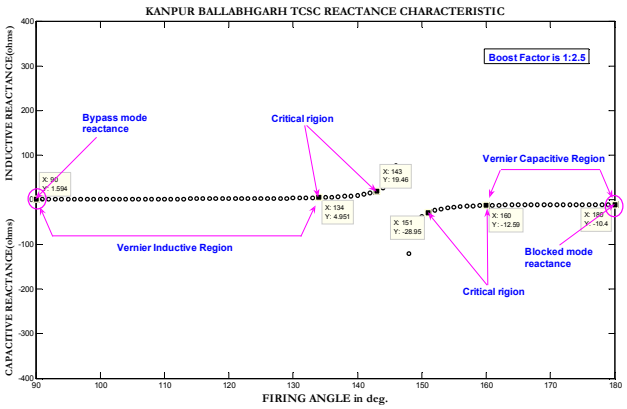


Fig. 2 Reactance characteristic curve of Kanpur –Ballabhgarh TCSC project

TABLE I
SALIENT POINTS FROM EXISTING KB TCSC REACTANCE CHARACTERISTIC

Modes/Regions	Reactance		Firing angle
	Ω	%	deg.
Without any compensation	131.1929	-	-
FC	35.56	27	-
Bypass mode reactance	1.594	1.2	90
Blocked mode	-10.4	-8	180
Resonance region	19.46 – 28.95	14.83 – -22	143 – 151
Vernier inductive region	1.594 – 4.951	1.2 – 3.77	90 – 134
Vernier capacitive region	10.4 – 12.59	-8 – -9.6	180 – 160
Critical inductive region	4.951 – 19.46	3.77 – 14.83	134 – 143
Critical capacitive region	12.59 – 28.95	-9.6 – -22	160 – 151

The following observations with regard to four modes of operation including critical regions can be made:

1. The existing KB TCSC reactance varies from bypass mode inductive reactance to blocked mode capacitive reactance i.e., from 1.594 Ω to -10.4 Ω between 90° to 180° of firing angle.
2. The resonance region for ω = 2.7432 occurs between firing angle of 143° and 151°.
3. TCSC reactance starts increasing slowly from 90° and 180° and reaches infinity at resonance point.
4. The vernier inductive and capacitive regions reflect smooth variation of reactance wherein critical regions show large elapse of reactance.
5. Table II shows the values of change in reactance ΔX on both inductive and capacitive critical regions. It may be observed that maximum change in reactance ΔX in critical region is 5.053 Ω (i.e. 3.84%).

From the observations made for reactance characteristic of existing KB TCSC, following difficulties are pointed out:

- The compensation less than bypass (1.594 Ω / 1.2%) and blocked mode reactances (-10.4 Ω / -8%) are not possible. This blocks smooth transition from inductive to capacitive region.
- The tuning of TCSC in vernier regions is easily achievable, but because of large change in reactance ΔX at both inductive and capacitive critical regions, fine tuning of line reactance is not possible.
- Around 83 firing points are available between 90° to 180° of firing angle with resonance region limitation between 143° to 151°.

TABLE II
ELAPSE OF REACTANCE ΔX AT CRITICAL REGION

Inductive Mode				Capacitive Mode			
Firing angle	TCSC X_L	ΔX_L	% of ΔX_L	Firing angle	TCSC X_C	ΔX_C	% of ΔX_C
deg.	Ω	Ω	%	deg.	Ω	Ω	%
134	4.95	-	-	**151**	-28.94	-	-
135	5.44	0.49	0.37	**152**	-23.895	**5.05**	**3.84**
136	6.04	0.59	0.45	**153**	-20.62	3.27	2.48
137	6.77	0.73	0.55	**154**	-18.35	2.27	1.73
138	7.68	0.91	0.69	**155**	-16.69	1.65	1.26
139	8.84	1.15	0.87	**156**	-15.44	1.25	0.95
140	10.34	1.50	1.14	**157**	-14.46	0.97	0.74
141	12.37	2.02	1.53	**158**	-13.70	0.76	0.58
142	15.21	2.84	2.15	**159**	-13.08	0.61	0.47
143	19.45	**4.24**	**3.22**	**160**	-12.58	0.49	0.38

III. REACTANCE ANALYSIS OF PROPOSED SPLIT TCSC

From the observations made on reactance characteristics in Section II, the obvious difficulty of fine tuning and elapse of reactance in critical regions with existing KB TCSC are pointed out. This section alternatively proposes split TCSC in place of existing KB TCSC as a viable solution to these difficulties. The [*N+1* x *N+1*] optimal ways of firing angles

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are now possible with split TCSC for same amount of compensation *K*. This allows the fine-tuning of line reactance and precise control over power transfer.

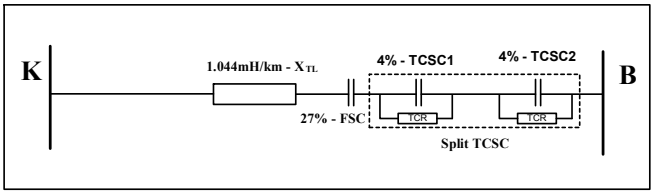


Fig. 3 Split TCSC connected with KB Transmission line

Fig. 3 shows Kanpur- Ballabhgarh 400 kV, 400 km line with proposed split TCSC device (TCSC1 & TCSC2) in place of existing KB TCSC. The degree of compensation *K* of proposed split TCSC can be splitted into two parts *K1* & *K2*. The compensation *K1* can be set at any value between 1% - 7% for TCSC1 and complementary compensation K2 can be set between 7% - 1% for TCSC2 so as to get same 8% of compensation as provided by single TCSC. To begin with, an equal compensation of 4% is considered for both TCSC. Now with *K1* = *K2* = 4%, the computed values of TCSC's capacitances (*C1*, *C2*) and inductances (*L1*, *L2*) are,

$$\text{Split TCSC Capacitors}\,(C1\ \&\ C2) = 612\ \mu F$$

$$\text{Split TCSC Inductors}\,(L1\ \&\ L2) = 2.2\ mH$$

$$\omega = \sqrt{\frac{X_C}{X_L}} = \sqrt{\frac{5.2}{0.69}} = 2.7452$$

Individual TCSC's reactances of proposed split TCSC can be calculated using TCSC reactance equation as [5], [6],

$$X_{TCSC1}(\alpha) = X_{TCSC2}(\alpha) = -5.2 + 1.9093(2(\pi - \alpha) + \sin(2(\pi - \alpha))) - 1.1704\cos^2(\pi - \alpha)(\omega\tan\omega(\pi - \alpha)) - \tan(\pi - \alpha)$$

To plot the reactance characteristics, the firing angle 'α' is varied from 90° to 180°.

The tuning can be achieved as:

1. Operate TCSC1 at 90° and firing angle for TCSC2 is varied from 90° to 180° giving 91 operating points. The data is compiled in matrix form as 91 columns. There is one more column corresponding to operation of TCSC2 in cutoff mode, this makes total number of 92 columns in the matrix.
2. Operate TCSC2 at 90° and firing angle for TCSC1 is varied from 90° to 180°, which again gives 91 operating points. The data is compiled as 91 rows in matrix. There is one more row corresponding to operation of TCSC1 in cutoff mode, which makes total 92 rows in matrix.
3. The split TCSC matrix now has dimension of [92 x 92] (if firing angle is made to vary in steps of 1 degree).

Symbolically, the split TCSC reactance matrix can be written as:

$$X_{splitTCSC}(\alpha 1,\alpha 2) = \begin{bmatrix} X_{TCSC1}(90) + X_{TCSC2}(90) & L & X_{TCSC1}(90) + X_{TCSC2}(180) & X_{TCSC1}(90) + X_{TCSC2}(cutoff) \\ M & O & M & M \\ X_{TCSC1}(180) + X_{TCSC2}(90) & L & X_{TCSC1}(180) + X_{TCSC2}(180) & X_{TCSC1}(180) + X_{TCSC2}(cutoff) \\ X_{TCSC1}(cutoff) + X_{TCSC2}(90) & L & X_{TCSC1}(cutoff) + X_{TCSC2}(180) & X_{TCSC1}(cutoff) + X_{TCSC2}(cutoff) \end{bmatrix}$$

Matrix demension : [N + 1 x N + 1]

With above possible range of [*N+1* x *N+1*] operations, the reactance characteristics of proposed split TCSC are plotted as shown in Fig. 4. Around 91 reactance characteristic curves are now possible by tuning firing angles of TCSC1 & TCSC2 from 90° to 180° in steps of 1°. Two more curves are possible through cutoff mode operations. From the reactance characteristic curves following observations are made,

- Continuous compensation from 19.46 Ω in inductive region to -28.95 Ω in capacitive region is possible.
- Compensation between 19.46 Ω to -28.95 Ω can be tuned with 6723 firing points excluding resonance region.
- The observed maximum and minimum change in reactances (ΔX) are 0.8325 Ω and 0.0001 Ω (0.63% and 0%).

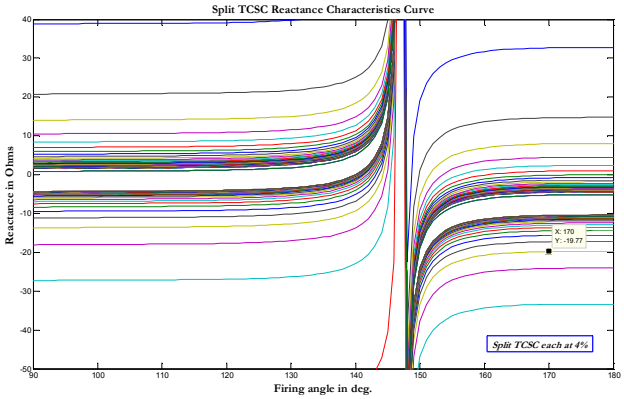


Fig. 4 Split TCSC reactance characteristic curve

Figs. 5 and 6 show comparison of reactance characteristic curves of existing KB and proposed split TCSC drawn with respect to number of firing points. Figs. 5 (a) & (b) are drawn for comparing the compensations less than bypass and blocked mode reactances of existing KB and proposed split TCSC. Figs. 6 (a) & (b) compare the critical region reactances of existing KB and proposed split TCSC. The compared data for existing KB and proposed split TCSC reactance characteristics are tabulated in Table III and following observations are made:

- The split TCSC has obvious advantage of [92 x 92] firing points over single TCSC which has only 91 operating points for same 1° steps of variation in firing angle.
- The compensation less than bypass mode and blocked mode reactances are not possible in existing KB TCSC whereas in proposed split TCSC, compensation between 1.594 Ω to -10.4. Ω can be achieved with as many as 3135 available firing points.
- A smooth transition between inductive to capacitive regions is possible.
- The inductive and capacitive critical region reactances of existing KB TCSC are tuned with 10 firing points

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respectively; hence elapse of reactance is large. But split TCSC tunes the critical region reactances with 1550 firing points and elapse of reactance is so small.

- The vernier region reactances are further micro tuned for around 2048 firing points.

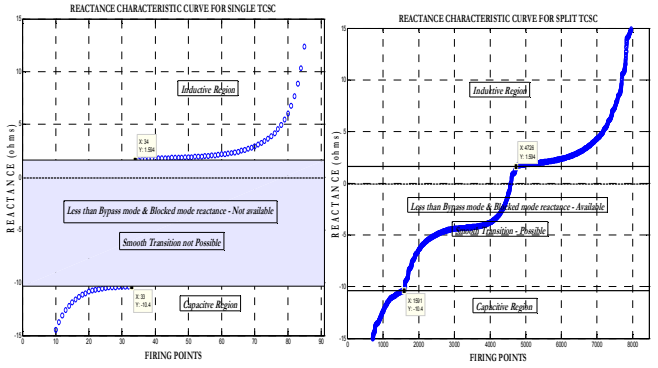


Fig. 5 Reactance curves (a) existing KB TCSC and (b) proposed split TCSC

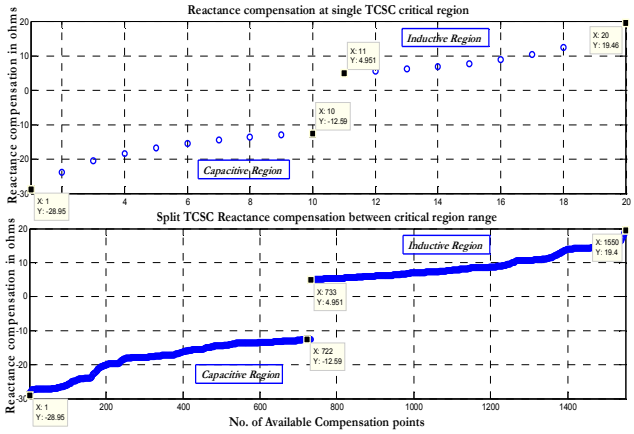


Fig. 6 Reactance compensation at critical region (a) existing KB TCSC (b) Split TCSC

TABLE III
COMPARISON BETWEEN EXISTING KB AND PROPOSED SPLIT TCSC

Existing KB TCSC		
	Reactance	firing points
Non availability portion of compensation	$-10.4 < X_{comp} < 1.594$	-
Vernier inductive region	1.594 – 4.951	44
Vernier capacitive region	10.4 – 12.59	20
Critical inductive region	4.951 – 19.46	8
Critical inductive region	12.59 – 28.95	8
Proposed split TCSC		
Availability of non available comp. portion	$-10.4 < X_{comp} < 1.594$	3135
Verinier inductive region	1.594 – 4.951	2048
Verinier capacitive region	10.4 – 12.59	
Critical inductive region	4.951 – 19.46	818
Critical inductive region	12.59 – 28.95	722

IV. SIMULINK MODEL OF KB TCSC PROJECT

The study conducted with proposed split TCSC shows micro tuning of line reactance and makes KB transmission line much flexible for power transmission at any minute rate. In order to analyze the TCSC with KB transmission system, the load 710 MW is chosen to get nominal voltage in Ballabhgarh end (230.5 kV i.e., approximately 230 kV) at 180^o of firing angle. Further any change in load is taken care by tuning TCSC in capacitive mode. So that while tuning the TCSC, end side voltages can be altered in and around the nominal value – 230 kV. Though, it's a reverse process of assigning values to the load, main objective of the study is to analyze the effect of existing KB and proposed split TCSC for sudden variation of load.

A. Simulink Schematic

A reactance based closed loop controller is designed to control both existing KB and proposed split TCSC devices for a dynamic load which is connected at Ballabhgarh end of the transmission line. Fig. 7 shows the block diagram of reactance based closed loop controller for KB TCSC system. The net change in reactance at load end is considered as an error signal. The error signal is processed and compared with TCSC reactance to generate appropriate firing pulses. The firing pulses are synchronized with positive zero crossing line current signal. The TCSC device is tuned as per the firing pulses generated from the control circuit.

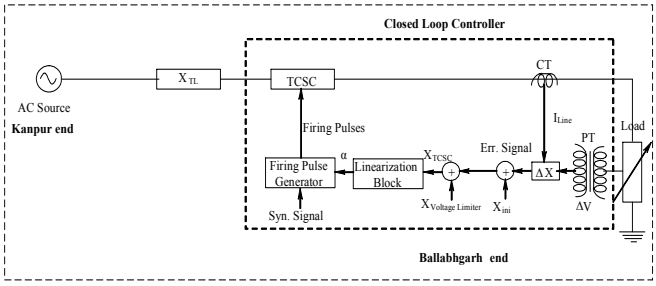


Fig. 7 Block diagram of KB TCSC model with closed loop controller model

In case of split TCSC, two firing pulses have to be generated for TCSC1 & TCSC2 to supply required power for the dynamic load. Figs. 8 & 9 show MATLAB/Simulink based KB transmission system which is upgraded with existing KB and proposed split TCSC models. The control circuit for existing KB and proposed split TCSC are designed with reactance control method as described in Fig. 7.

The load connected at the Ballabhgarh end is made to vary from 710 MW to 750 MW for fraction of seconds and respective effect in KB system is observed and analyzed. The KB transmission line is simulated and results are compared for (i) without any compensation, (ii) with FC, (iii) with FC+KB TCSC and (iv) with FC+split TCSC device.

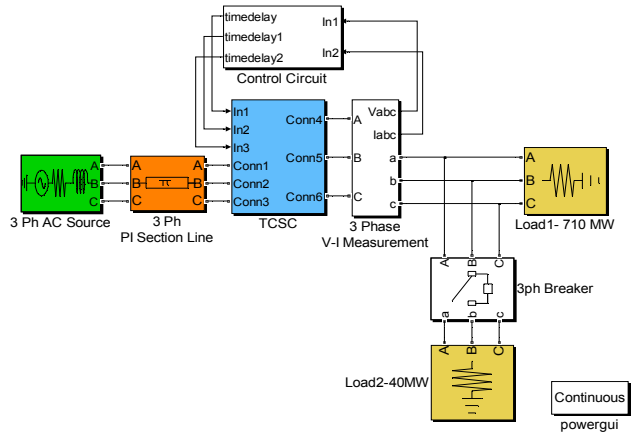


Fig. 8 Model of KB TCSC project with closed loop controller

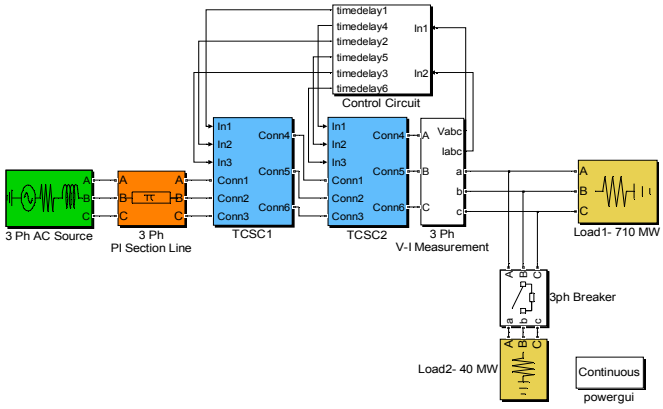


Fig. 9 Model of KB split TCSC project with closed loop controller

V. Results and Discussions

A MATLAB/Simulink based Kanpur-Ballabhgarh transmission system simulation is performed and simulation results are shown in Appendix A to D. A load of 710 MW which is connected at Ballabhgarh end and additional load of 40 MW is suddenly included between 0.2 to 1 second to realize the affect of existing KB and proposed split TCSC. Both the TCSCs are tuned precisely to transfer the demanded power by the dynamic load. The designed TCSC controller maintains the end side voltage at 230 kV with + 0.5 kV for sudden variation of load. The simulation is also performed for the cases; with and without fixed capacitor (FC). Appendix A compares the waveforms of end side voltage, line current and power flows of KB transmission system for different cases (i) without any compensation device (dark Green), (ii) with fixed capacitor FC (pink), (iii) with existing KB TCSC (red) and (iv) with proposed split TCSC (blue). All the 4 cases are described in 3 interims with respect to load variations,

A. Simulation period: 0.0 to 0.2 second
B. Simulation period: 0.2 to 1.0 second
C. Simulation period: 1.0 to 1.5 second

A. Simulation Period: 0.0 to 0.2 Second

Without any compensation device, the KB system becomes overloaded and voltage at receiving end side is dropped to 212.5 kV as shown in Appendix A (dark green color). The load receives only 600 MW of power and not satisfies the demand of load. By connecting 90.7 µF of FC, the power transferred through transmission line is 683.4 MW with an end side voltage of 226.5 kV as shown in Appendix A (pink color). If existing KB TCSC is connected with FC, then load receives the power of 707.7 MW at an end side voltage of 230.5 kV as shown in Appendix A (red color). The controller is designed to operate at 180° of firing angle for steady state condition. The proposed split TCSC is also made to operate in place of existing KB TCSC and both TCSC1 and TCSC2 are initially tuned to operate at 180°. The power transfer is 707.7 MW and load voltage is 230.5 kV as shown in Appendix A (blue color).

B. For Simulation Period: 0.2 to 1.0 Second (Sudden Increase of Load at 0.2 sec.)

A 40 MW of resistive load is suddenly included with existing 710 MW of resistive load at 0.2 second. The system without any compensation device further overloads and transfers only 609 MW of power. The end side voltage is further reduced to 208.2 kV as shown in Appendix A (dark green color). With FC, the system receives the power of 700.2 MW and voltage of 223 kV as shown in Appendix A (pink color). For KB transmission system with existing TCSC, firing angle is tuned to 154° and satisfies the power demand by maintaining the end side voltage at 230 kV as shown in Appendix A (red color). In case of split TCSC, both TCSC1 and TCSC2 are tuned to 149° and 158° respectively to offer the power flow required at load end as shown in Appendix A (blue color).

C. For Simulation Period: 1.0 to 1.5 Second (Sudden Decrease of Load at 1 sec.)

The increased 40MW load is removed at simulation time 1.0 second and sudden changes in system parameters are observed. The firing angles of both existing KB and proposed split TCSC are tuned back to initial position - 180° and supplies required amount of power by sustaining 230 kV at end side as shown in Appendix A.

Due to sudden variation of load, steady state condition of KB system affected. The control circuit generates firing pulses to restore the steady state condition of the system. Appendix B and C show firing angle variations required for tuning existing KB and proposed split TCSC under different load conditions. Appendix B and C also show waveforms of TCSC voltage (V_{TCSC}), TCR current (I_{TCR}) and capacitor current (I_{CAP}) compared with respect to line current (I_L). The developed closed loop control system effectively tunes the existing KB and proposed split TCSC device to maintain the steady state condition. Due to sudden variation in load at 0.2 sec. and 1 sec., the stability of the system is regained within 0.3 sec and 0.1 sec. respectively as shown in Appendix A. Though, line voltage shows existence of small voltage oscillation in the system. The voltage oscillation can be efficiently mitigated by designing a robust PI controller.

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VI. Conclusion

The concept of split TCSC is evolved to overcome the difficulties pointed out for single TCSC. The study on reactance characteristics is conducted for examining the benefits of proposed split TCSC in place of existing KB TCSC. The flexibility of the transmission line is improved by introduction of split TCSC and allowing power flow at any micro rate.

The Kanpur Ballabhgarh TCSC project is modeled in MATLAB/Simulink by connecting a dynamic load. The proposed split TCSC is implemented in place of existing KB TCSC at Ballabhgarh end and exposes precise control over KB transmission system. The closed loop controller effectively tunes existing KB and proposed split TCSC for compensating sudden increase in load. But controller is not designed for multi objective functions such as to mitigate power oscillation and to improve transient stability.

Appendix A

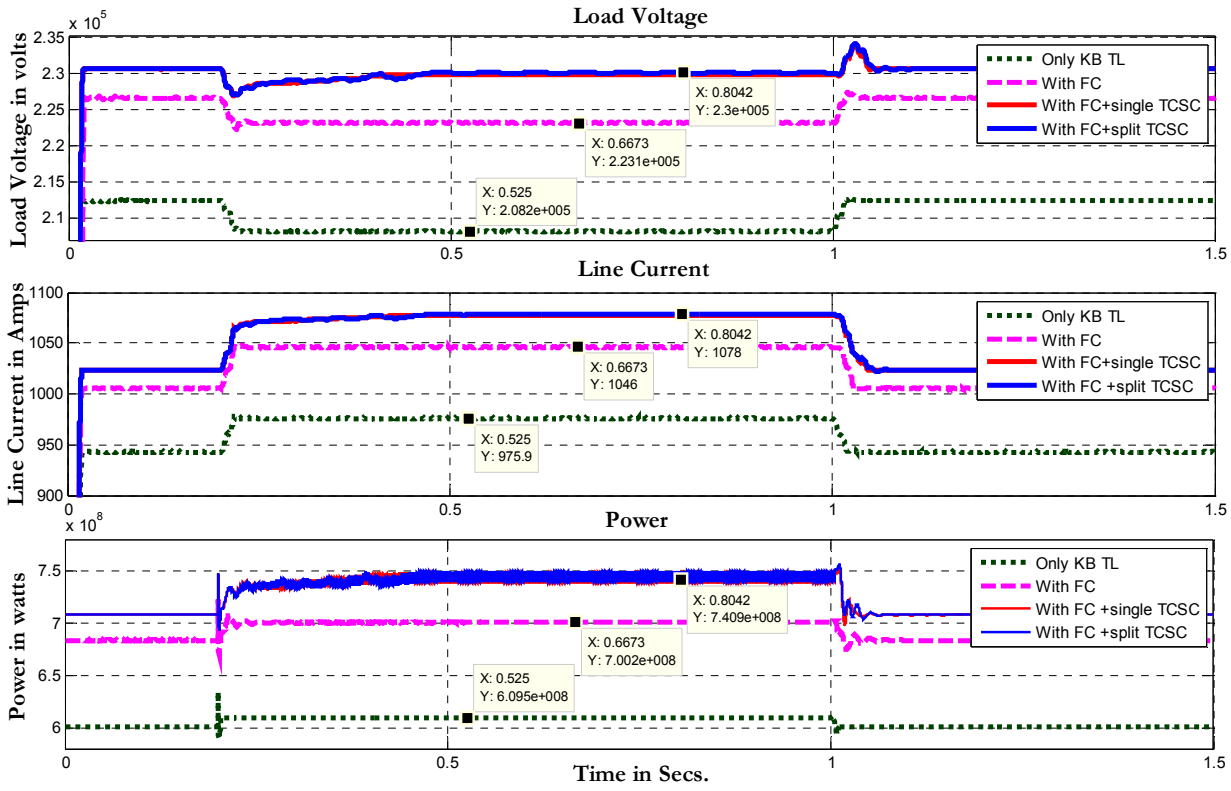


Fig. 10 Transient response for different cases

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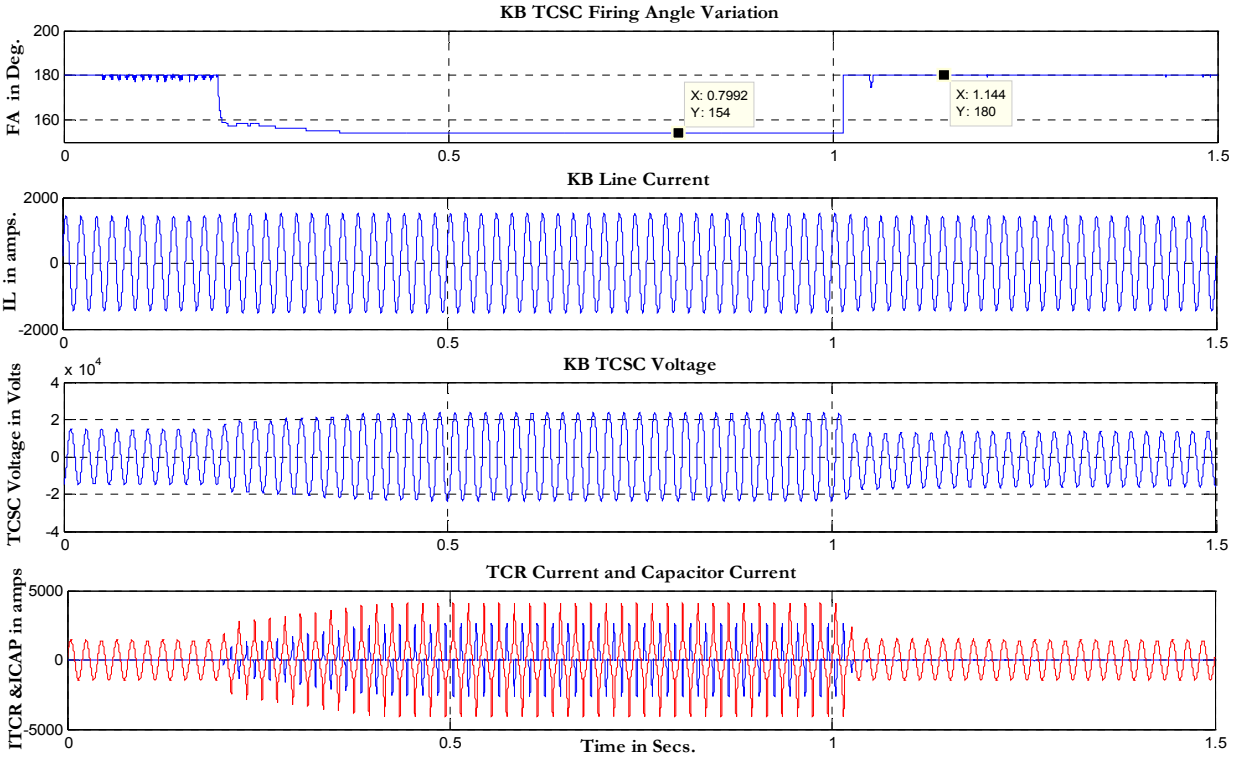


Fig. 11 Waveform of single TCSC parameters: Firing angle, I_L, V_{TCSC}, I_{TCR}, I_{CAP}

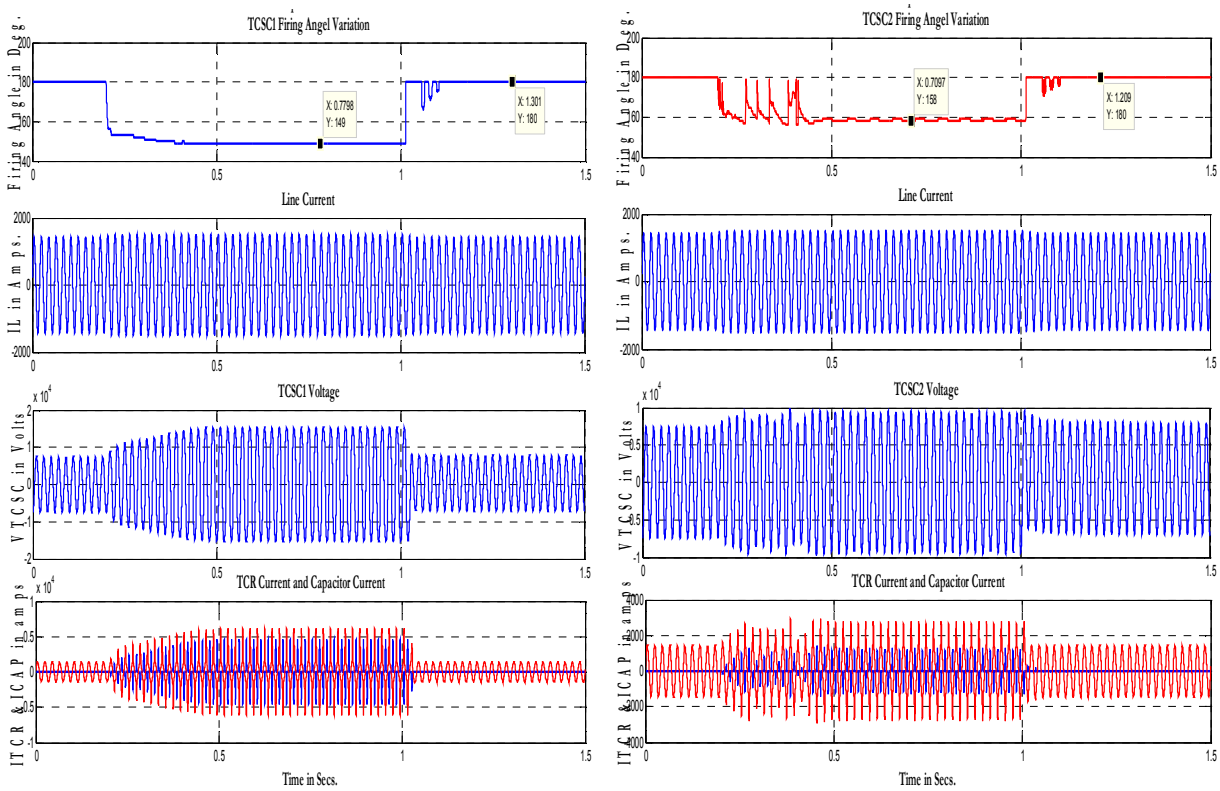


Fig. 12 Waveforms of proposed split TCSC parameters: Firing angle, I_L, V_{TCSC}, I_{TCR}, I_{CAP}

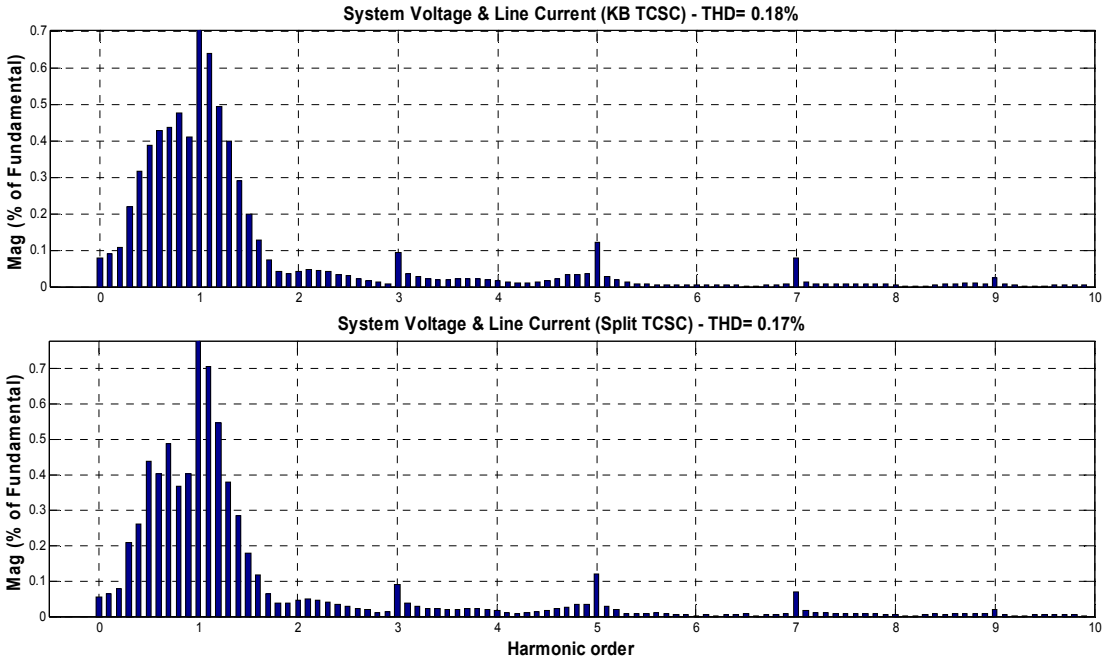


Fig. 13 System voltage and line current total harmonic distortion

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