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Power Flow Enhancement and Control of Transmission System Using Thyristor Controlled Series Capacitor (TCSC) FACTS Controller

Naman Vashishth[1], J. G. Jamnani[2]
[12] *School of Technology, PDPU, Gandhinagar, India*

Abstract: *This paper includes series compensation of 400 kV transmission line by Thyristor controlled series capacitor (TCSC), one of the device of flexible alternating current transmission system (FACTS) family. It provides variable capacitive and inductive reactance to compensate inductive reactance of transmission line, which results power flow control of transmission line. The reactance characteristics curve of TCSC for differing firing angle of TCSC is plotted, which decides capacitive and inductive region of TCSC. In capacitive region power flow increases and inductive region power flow decreases. Uncompensated 400 kV transmission line, compensated 400 kV transmission line with fixed capacitance and compensated 400 kV transmission line with TCSC is modelled with MATLAB/SIMULINK. Simulation results of above are compared and analyzed for power flow control and voltage profile improvement. Performance of TCSC for different degree of compensation is also considered on the same modelled system.*

Keywords: *Series Compensation, HVAC, Thyristor Controlled Series Compensation (TCSC)*

I. Introduction

The basic Thyristor Controlled Series Capacitor scheme introduced by Vithayathil, for "Rapid Adjustment Of Network Impedance", in 1986 [1]. Earlier to this Fixed Capacitors (FC) was first used in United States by "NY Power & Light" to increase the power transfer capability, in 1928 [5]. The important aim to implement TCSC on the transmission line is to maximize the active power flow through the existing transmission line. In addition to this transmission line impedance, voltage magnitudes, phase angles, active and reactive power flow can be controlled. Variation of all mention parameters depend on variation in transmission line impedance, which is done by TCSC, connected in series with transmission line. TCSC also limit the fault current while operating in inductive region.

The system data of existing 3-phase, 400 kV transmission line between Khamman – Kalpakam is considered for simulation. Modelling, operation and reactance characteristics curve of TCSC are mentioned in section II. Information about test system data, results and waveforms for uncompensated transmission line, compensated transmission line with fixed capacitor and compensated transmission line with TCSC are mentioned in section III. Simulation results for different firing angle and different degree of compensation "K" is also mentioned in section III.

II. TCSC Model, Operation And Reactance Characteristic Curve

The basic Thyristor Controlled Series Capacitor scheme consists of the series compensating capacitor shunted by a Thyristor Controlled Reactor (TCR) as shown in Fig.1. In TCR, inductor and back to back thyristor are connected in series. In practical TCSC implementation, several such basic compensators may be connected in series to obtain the desired voltage rating and operating characteristics.

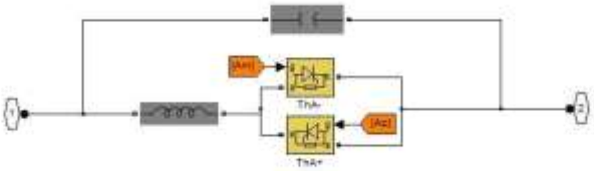

Fig.1 Basic model of TCSC

The basic idea behind the TCSC scheme is to provide a continuously variable capacitor by means of partially canceling the effective compensating capacitance by the TCR. The TCR at the fundamental system frequency provides continuously variable inductive impedance, controllable by delay angle (α).

The steady-state impedance [X_{TCSC}] of TCSC is a parallel *LC* circuit, which consist fixed capacitive impedance (X_C) and a variable inductive impedance $X_L(\alpha)$ controlled by delay angle (α). Mathematical expression of [$X_{TCSC}(\alpha)$] and $X_L(\alpha)$ are as following,

$$X_{TCSC}(\alpha) = -X_C + C_1\big(2(\pi-\alpha) + \sin(2(\pi-\alpha)\big) - C_2\cos^2(\pi-\alpha)\big(\omega\tan(\omega(\pi-\alpha)) - \tan(\pi-\alpha)\big)$$

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

$$C_1 = \frac{X_C + X_{LC}}{\pi} \qquad C_2 = 4\frac{X^2{}_{LC}}{X_L\pi} \qquad X_{LC} = \frac{X_L X_c}{X_C - X_L}$$

The delay angle (α) is being measured from the zero crossing of the line current or crest of the capacitor voltage. As the impedance of the controlled reactor, is varied from its maximum to minimum value, simultaneously TCSC increases its minimum capacitive impedance, until parallel resonance is established and impedance of TCSC theoretically become infinite [1].

Decreasing impedance of controlled reactor further, the impedance of the TCSC become inductive, reaching to its minimum value at $\alpha = 0°$, where capacitor effect is bypassed by the TCR. Generally value of X_L is kept smaller than X_C [1]. TCSC controls the power flow in both the region, power flow can be increased in capacitive region and decreased in inductive region compared to uncompensated transmission system. Reactance curve for different firing angle can be obtained by above equations.

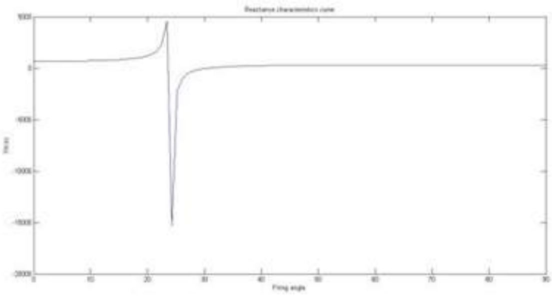

Fig.2 Reactance characteristic curve of TCSC

III. Simulation And Results

Power transmission system modelled using MATLAB/SIMULINK. Results for uncompensated 400 kV transmission line, compensated 400 kV transmission line with fixed capacitor and compensated 400 kV transmission line with TCSC are compared. Simulation results for different firing angle and different degree of compensation "K" are also recorded for deciding operating range of TCSC.

A. TEST SYSTEM DATA

A 3-phase, 400 kV and 364 km long transmission line considered for the simulation. This is actual transmission line between Kalpakam – Khamman, Andhra Pradesh, India [6]. Technical specifications of this transmission line are given in Table. 1.

TECHNICAL SPECIFICATIONS	
Generator	11 kV
Transformer	1000 MVA, 11/400 kV
System Voltage	400 kV
Distance	364 km
Line Resistance [R1, R0]	[0.0308, 0.2118] Ohm/km
Line Capacitance [C1, C0]	[11.0474e-9, 7.1301e-9] F/km
Line Inductance [L1, L0]	[0.9337e-3, 4.1264e-3] H/km
Load	350 MW, 150 MVar

Table. 1 : Technical specifications of transmission system

10% load of actual load increasing at 0.5 sec and 1.0 sec, which is 385 MW, 185 MVar and 420 MW, 210 MVar respectively. Degree of compensation is 60% for fixed capacitor and TCSC both. $\omega = 2.716$

TECHNICAL SPECIFICATIONS OF TCSC	
Capacitor	49.6867 µF
Inductor	0.027 H

Table. 2 : Technical specifications of TCSC

B. UNCOMPENSATED 400 kV TRANSMISSION LINE

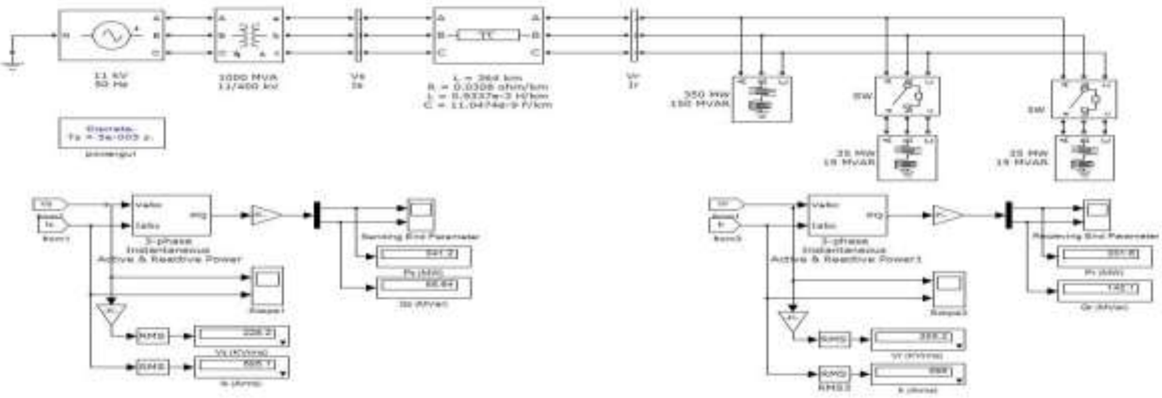

Fig. 3 Uncompensated 400 kV transmission line model

C. COMPENSATED 400 kV TRANSMISSION LINE WITH FIXED CAPACITOR

Degree of compensation is 60% and value of capacitor is 49.6867 µF given in Table. 2.

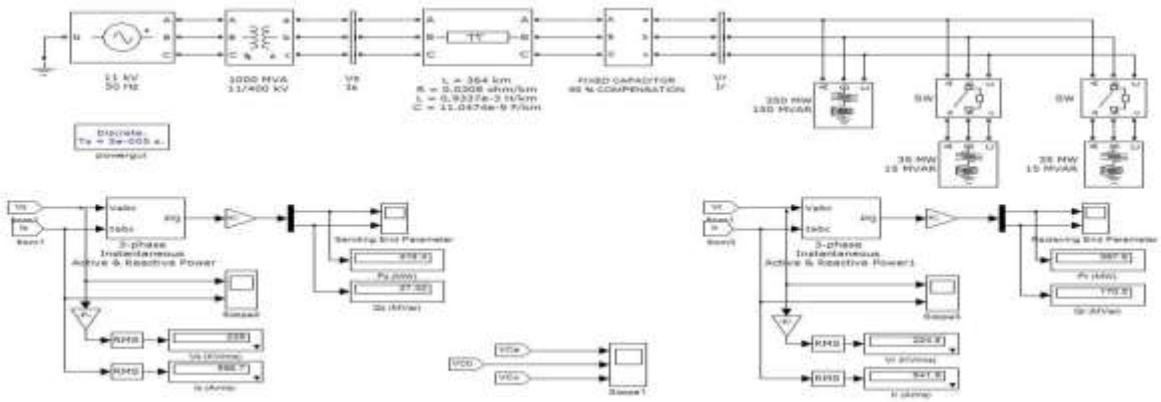

Fig. 4 Compensated 400 kV transmission line with fixed capacitor

D. COMPENSATED 400 kV TRANSMISSION LINE WITH TCSC

Degree of compensation is 60%, according to that value of capacitor and inductor are 49.6867 µF and 0.027 H respectively for $\omega = 2.716$.

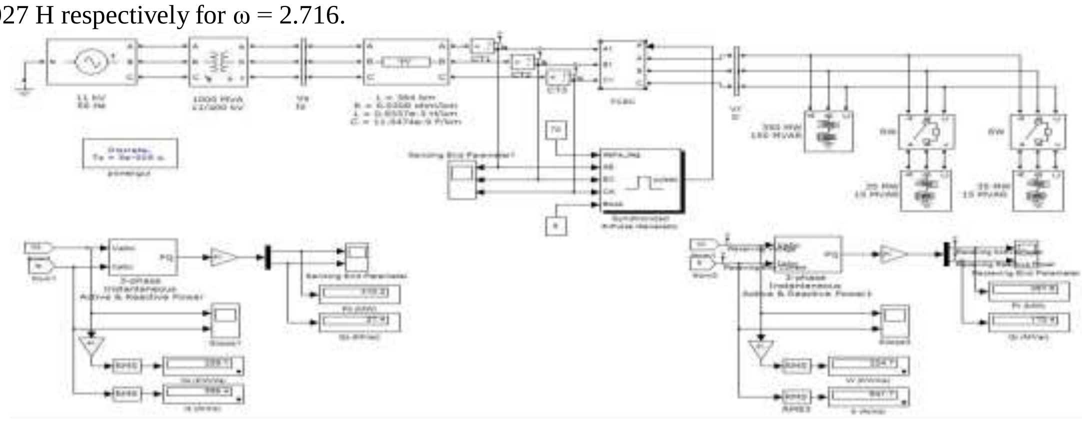

Fig. 5 Compensated 400 kV transmission line with TCSC

Firing pulses are generated to trigger the thyristors at particular firing angle, which is measured from zero crossing of the line current [2]. As the thyristors triggered, certain amount of current passes through it, due to which voltage across the capacitor varies and overall impedance of TCSC is also varies. As a result of this, voltage magnitude and active power flow through the transmission line increases. Active power flow and voltage magnitude can vary by triggering thyristors at different firing angle between 0° to 90°. If TCSC operated in inductive region, active power decreases and in capacitive region, active power increases.

E. RESULT ANALYSIS AND WAVEFORMS

Load	Vs (kV)	Is (A)	Vr (kV)	Ir (A)	Vd (kV)	Pr (MW)	Qr
100%	398.4	443.5	369.1	508	29.3	298.8	127.9
110%	396.8	474.4	362.3	547.9	34.5	316	135.4
120%	395.2	505.1	355.4	586	39.8	331.6	142.1

Table. 3 : Simulation results of uncompensated 400 kV transmission line

Load	Vs (kV)	Is (A)	Vr (kV)	Ir (A)	Vd (kV)	Pr (MW)	Qr (Mvar)
100%	399.6	514.5	398	547.3	1.6	346.8	148.5
110%	398.1	556.4	393.6	595.1	4.5	372.8	159.7
120%	396.6	598.4	389.2	641.7	7.4	397.6	170.4

Table. 4 : Simulation results of 400 kV transmission line compensated with TCSC

At 100% loading condition without compensation and with TCSC, receiving end voltage (Vr) is 369.1 kV and 398 kV respectively. Cleary observe that voltage profile improving. Similar results for 110% and 120% loading conditions. Now, active power (Pr) at 100% loading condition without compensation and with TCSC is 298.8 MW and 346.8 MW respectively. Cleary observe that active power flow increasing. Similar results for 110% and 120% loading conditions. Waveforms of active power and voltage magnitude are given in Fig. 6 and Fig. 7 respectively.

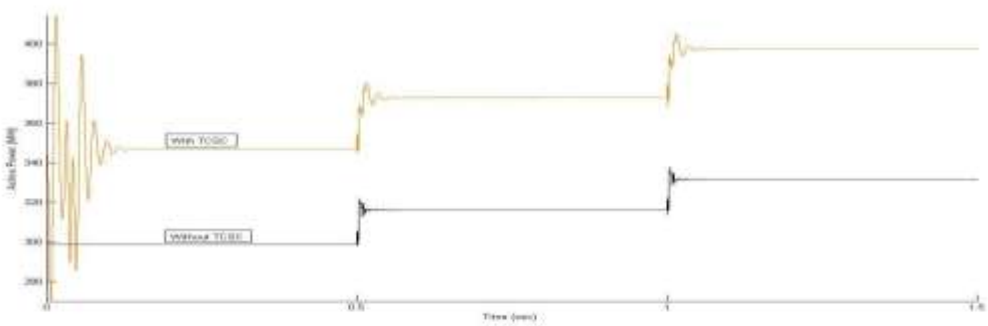

Fig. 6 Active power with TCSC and without TCSC

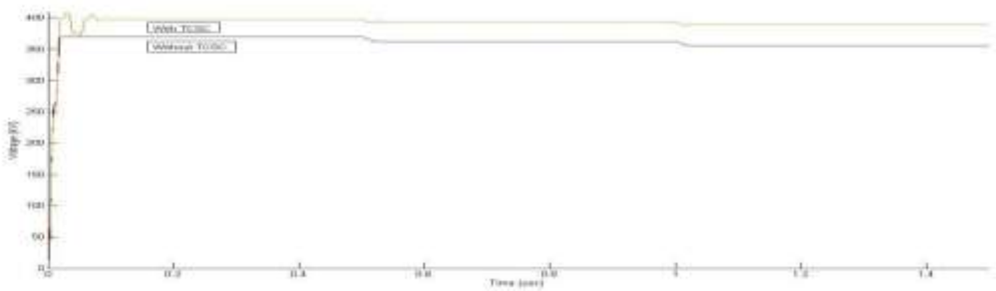

Fig. 7 Voltage with TCSC and without TCSC

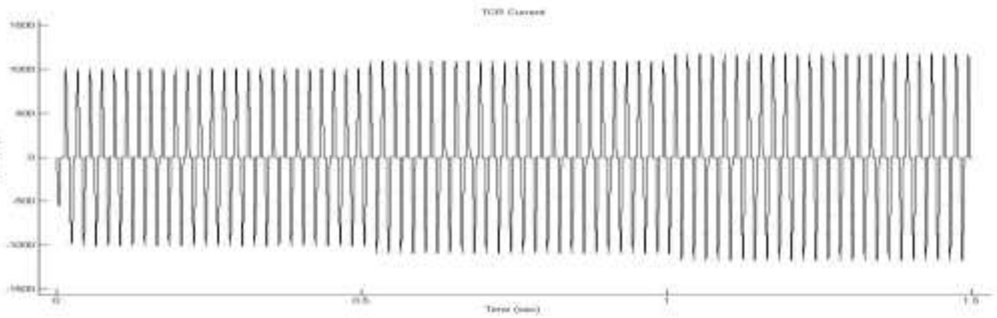

Fig. 8 TCR current

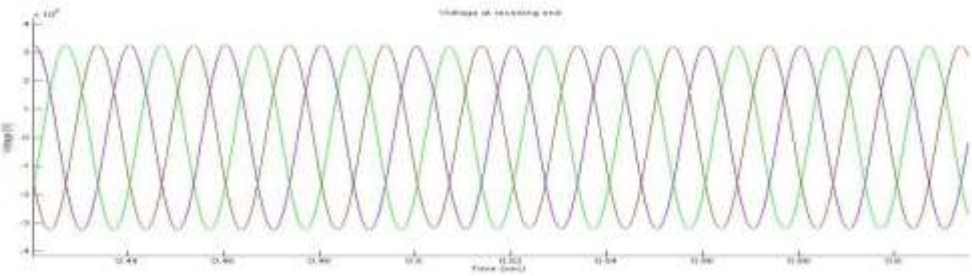

Fig. 9 Receiving end voltage

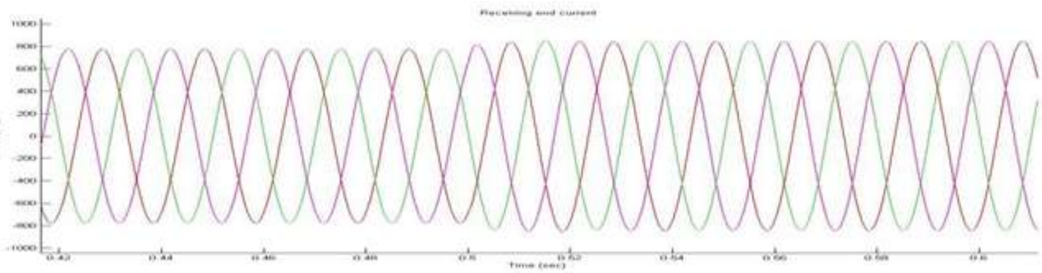

Fig. 10 Receiving end current

F. CAPACITIVE AND INDUCTIVE MODE

TCSC provides variable inductive and capacitive reactance to transmission line. According to that, it has two mode of operation, Capacitive and Inductive. In inductive mode of operation, inductive reactance of TCSC is added with the inductive reactance of transmission line thus voltage and active power decreases as compared to uncompensated system. In capacitive mode of operation, capacitive reactance of TCSC compensate the inductive reactance of transmission line thus voltage and active power increases as compared to uncompensated system.

For the same system parameters and ratings, voltage and active power, without TCSC and with TCSC are compared at different firing angle given in Table. 5. Inductive and capacitive region can be decided from the reactance characteristics curve given in Fig. 2.

(1) Capacitive Region : 40° - 90° (2) Inductive Region : 0° - 39°

Operating region of TCSC in inductive mode is 27° - 39°, because below 27° active power and voltage remain constant as per reactance characteristics curve, similarly operating region of TCSC in capacitive mode is 40° - 50°, because above 50° active power and voltage remain constant.

Capacitive Region					**Inductive Region**				
	Power (MW)		**Voltage (kV)**			**Power (MW)**		**Voltage (kV)**	
Firing Angle	Without TCSC	With TCSC	Without TCSC	With TCSC	**Firing Angle**	Without TCSC	With TCSC	Without TCSC	With TCSC
40°		302		370.5	39°		298		368
41°		308		373.7	38°		293		364.9
42°		312		376.2	37°		289.5		362.7
43°		318		379.7	36°		285.5		360.2
44°		322.5		382.4	35°		282		358.1
45°		327		384.7	34°		279.5		356.2
46°	298.8	332	369.1	387.9	33°		276.5		354.4
47°		336		390	32°	298.8	274	369.1	352.7
48°		341		392.3	31°		271.5		351
49°		344		394.3	30°		270		350.1
50°		346.8		398	29°		268		348.8
					28°		267		348
					27°		266.5		347.5

Table. 5 : Voltage and active power at different firing angle

IV. Conclusions

Main aim of modeling this transmission system in MATLAB/SIMULINK to reduce the voltage drop, improve voltage profile and increase active power flow. The existing 400 kV transmission system is unable to transfer the load demand thus TCSC is implemented on the existing 400 kV transmission system with 60% degree of compensation, which transfers the required load demand with less voltage drop and keeping voltage with in limit. Simultaneously for different loading conditions, TCSC can be operated with different firing angle to achieve required load demand by maintaining voltage with in limit.

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