International Journal of Engineering Research and Development (IJERD) ISSN: 2278-067X
Recent trends in Electrical and Electronics & Communication Engineering
(RTEECE 17th – 18th April 2015)

Enhancement of Transient Stability of Power System with Variable Series Compensation

Vaibhav Desai[1], Vivek Pandya[2], Anilkumar Markana[3]
[123]School of Technology, Pandit Deendayal Petroleum University, India
[1]desaivaibhav212@gmail.com
[2]vivek.pandya@sot.pdpu.ac.in
[3]anil.markana@spt.pdpu.ac.in

Abstract:- *This paper shows analysis for enhancement of transient stability of power system with variable series compensation of transmission line. Thyristor Controlled Series Capacitor (TCSC) is considered for variable series compensation. Using PID control strategy required firing pulses for TCSC is generated. Simulations of fixed and variable series compensation for different fault clearing time are carried out on Single Machine Infinite Bus (SMIB) using MatLab Simulink. Fault clearing angle, first angular swing and stability margin are used to analyze transient stability for different series compensation level. The simulation results show effectiveness of variable series compensation.*

Keywords:- *FACTS, TCSC, Series Compensation, Transient Stability.*

I. INTRODUCTION

Modern power system is continuously subjected to disturbances, which turns out as the problem of transient stability. Transient instability may lead power system to the blackout with cascaded tripping. Therefore, it is important to improve transient stability margin for reliable operation of power system. One of the methods to improve transient stability is series compensation of lines. Concept of the series compensation is to cancel a part of the transmission line reactance by inserting series capacitor. This increases maximum power transfer capability of a line and also the reactive power absorbed by the line can be reduced. By reducing effective inductive reactance of the line peak synchronizing power capability, steady state stability and therefore transient stability of the system can be increased.

Flexible Alternating Current Transmission System (FACTS) controllers have been proposed and implemented for variable series compensation. Thyristor Controlled Series Capacitor (TCSC) is the most preferred device for improving the system performance over other FACTS family members for its simplicity and ease of operation under normal as well as abnormal condition. TCSC allows rapid and continuous changes of line reactance. It has application in accurately regulating the power flow in transmission line, damping inter-area power oscillations and improving transient stability. Firing angle required for TCSC can be generated using different control methodologies.

A lot of research work has been carried out in series compensation. In 1966, Kimbark [1] analyzed the improvement in transient stability of power system using switched series capacitors. In which maximum amount of compensation was inserted at the same time when the faulted line was switched out. Ramarao [2] analyzed transient stability with optimal control using bang-bang control of line reactance. However, both methods were not able to provide the flexible adjustment of series capacitance. D. Pavh and R. Mihalic [3] analyzed improvement in transient stability of line by means of controlled series compensation. Z. Xuequiang [4] simulated TCSC on transmission line and observed that TCSC can improve dynamic performance of the power system. Different control strategies like robust control and optimal control for TCSC can be found in [5-8].In this paper, first maximum swing of machine (δ_{swing}) and transient stability margin are calculated for different level of compensation for the evolution of transient stability.

II. CONCEPT OF SERIES COMPENSATION FOR STABILITY

Consider Single Machine Infinite Bus (SMIB) system with two parallel lines. Assume that L-g fault at middle of the second line has occurred as shown in Fig 1. The machine will start swinging as the fault occurs. Initially machine was running at δ_0 and fault was cleared at δ_C. After clearance of fault, machine will go up to δ_2 (maximum swing) in first swing where accelerating area equals decelerating area $A2 = A_1$.

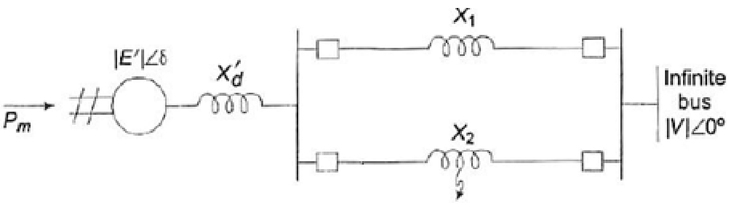

Fig. 1: SMIB System

Power angle curve of SMIB system for pre fault P_{eI}, during fault P_{eII} and post fault P_{eIII} condition is as shown in Fig 2.

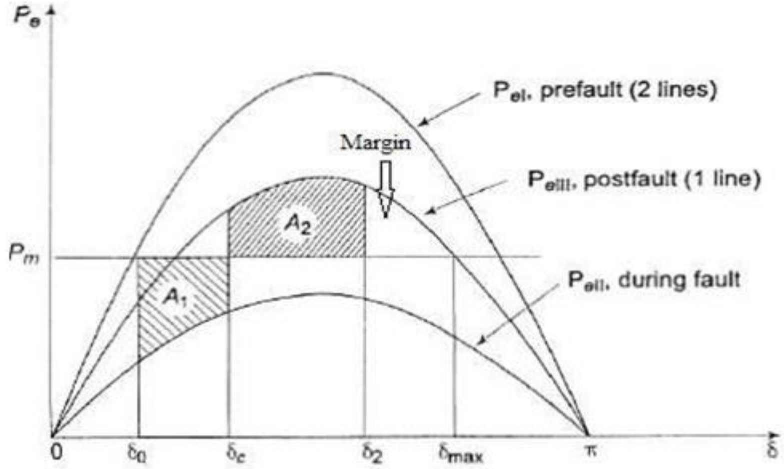

Fig. 2: Power vs. Angle Curve of System

Inserting the series capacitor in transmission line, peak synchronizing power capability P_{max} increases. As a result, the generator can have more stability margin for the same initial operating power. With increase in peak synchronizing capability, the available decelerating energy (area A_2) in Fig. 2 also increases. With a corresponding increase in P_{max} of curve P_{eII}, the accelerating energy (area A_1) also decreases in direction toward greater first swing stability. Also, series capacitor helps to damp out post fault oscillation [9].

III. SYSTEM MODEL

A. SMIB Model

The dynamics of a Single Machine Infinite Bus (SMIB) is governed by the non linear Eq. (1), it is known as swing equation [10],

$$\frac{H}{\pi f}\frac{d^2\delta}{dt^2} = P_m - P_e \tag{1}$$

Where,

$$P_e = \frac{E\,V}{X - X_{comp}}\sin\delta \tag{2}$$

Here,

P_e = Electrical power output
δ = Power angle
P_m = Mechanical power input
H = Inertia constant in MJ/MVA
E = Induced emf in generator
V = Infinite bus voltage
X = Total reactance
X_{comp} = Compensative reactance

B. TCSC Model

TCSC is an important device in the FACTS family. It can have various roles in the operation and control of power system, such as scheduling power flow, providing voltage support, enhancing transient stability and damping the power oscillation. TCSC module consists of a series capacitor and a parallel path with thyristor valve in series with inductor. Basic model of TCSC is shown in the Fig. 3.

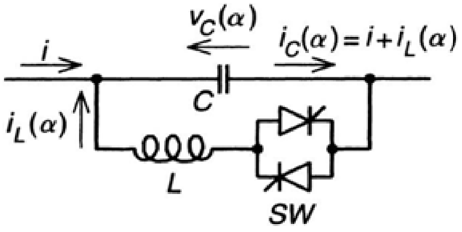

Fig. 3: Model of TCSC [11]

TCSC is controllable power electronic element in power circuit and line impedance can be adjusted by the phase control of its thyristor switches. Reactive impedance of TCSC (X_{TCSC}) can be adjusted by firing angle α. Relationship between X_{TCSC} and α is given by Eq. (3) and Eq. (4) [11].

$$X_{TCSC} = \frac{X_c\, X_L(\alpha)}{X_L(\alpha) - X_c} \tag{3}$$

Where,

$$X_L(\alpha) = X_L \frac{\pi}{\pi - 2\alpha - \sin\alpha} \tag{4}$$

The impedance of the controlled reactor $X_L(\alpha)$ is varied from its maximum (infinity) toward its minimum (ωL), the TCSC increases its minimum capacitive impedance, $X_{TCSC,min} = X_C = 1/\omega C$ until parallel resonance at $X_C = X_L(\alpha)$ is established and $X_{TCSC,max}$ theoretically becomes infinite. Decreasing $X_L(\alpha)$ further, of $X_L\, X_C /(X_L - X_C)$ at α = 0, where capacitor effect bypassed by TCR. Therefore, in usual TCSC arrangement in which the impedance of TCR reactor X_L is kept smaller than that of capacitor X_C . TCSC has two operating regions, which is shown in Fig. 4.

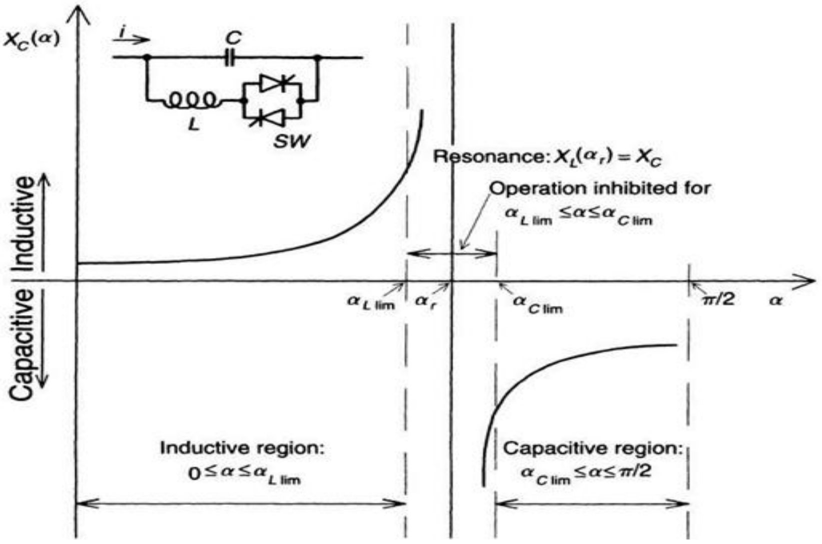

Fig. 4: Characteristic of TCSC [11]

From Fig. 4 it can be seen that TCSC has two operating regions. One is inductive and the other is capacitive. TCSC operates in capacitive region when $\alpha_{Clim} \le \alpha \le \pi/2$ and in inductive region when $0 \le \alpha \le \alpha_{Llim}$. For enhancement of transient stability it is necessary to operate TCSC in capacitive region.

IV. CONTROL METHODOLOGY

A PID controller has been employed to generate firing angle required for TCSC. Block diagram of proposed PID control is as shown in Fig. 5.

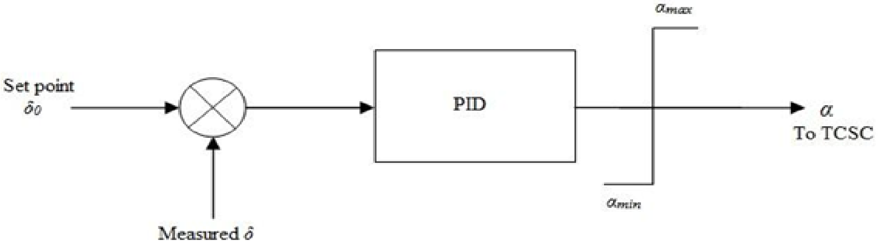

Fig. 1: PID Control

Controller is designed such that it provides different compensation levels for different firing angles as shown in Table I.

Table I: Fixed Compensation with Firing Angle

% Compensation	Firing Angle
30	56.20
40	52.33
50	50.05
60	48.54
70	47.47
80	46.68

To limit operation of TCSC in capacitive region, α_{min} = 45.56º and α_{max} = 90º set. Controller parameters are tuned as K_P = 80, K_I = 10 sec−1, K_D = 100 sec.

V. SIMULATION RESULTS AND DISCUSSION

SMIB system with TCSC model is simulated in MatLab Simulink. Three phase to ground fault is assumed at 1 sec for different duration of time on generator bus. Active power transfer to infinite bus reduced to 0 for fault duration. Operation of TCSC is shown in Fig. 5 and 6 with variable compensation for fault clearing time 0.3 sec and 0.2 sec respectively. From which, it can be seen that after clearance of fault variable compensation is not only improving first swing stability, but also helps out in damping of post fault oscillations. Also, from Fig. 6 and Fig. 7 it can be observed that with lesser fault clearing time system comes back to stable condition rapidly.

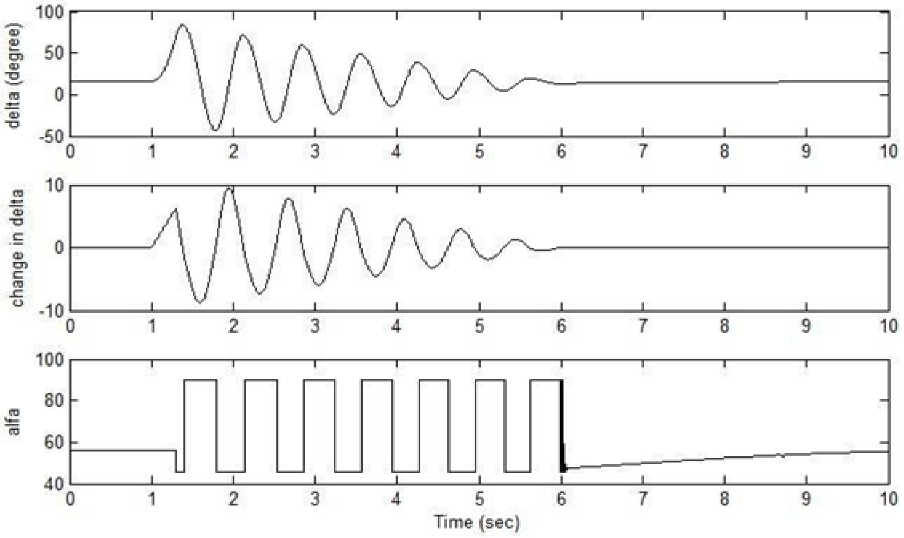

Fig. 2: TCSC Operation for fault clearing time t = 0.3 sec

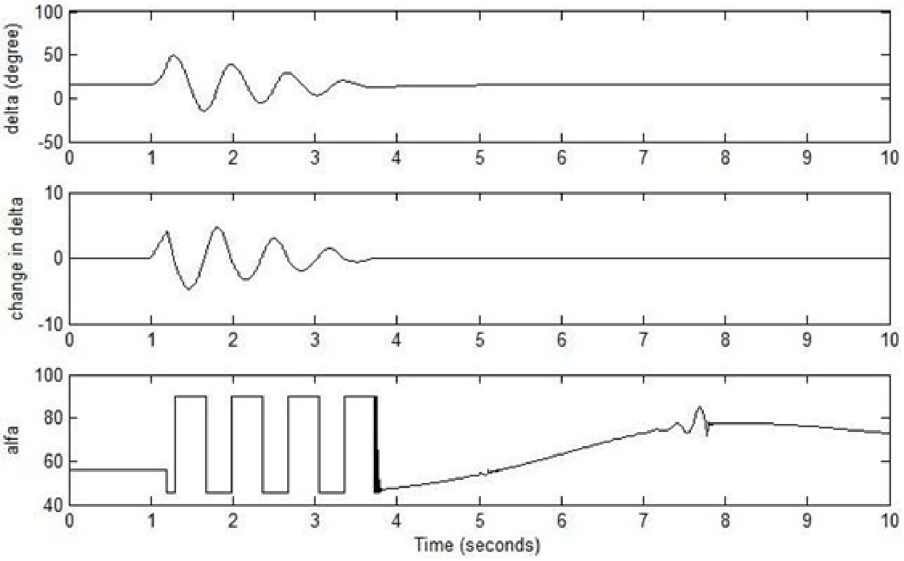

Fig. 3: TCSC Operation for fault clearing time t = 0.2 sec

Comparative analysis is done for different compensation level (with fixed and variable compensation mode) for fault clearing time 0.3 sec and 0.2 sec as follows.

A. Fault Clearing time 0.3 sec

Fault clearing angle δ_C, maximum angular swing δ_{swing} , and transient stability margin are calculated for different compensation level with fixed compensation and with variable compensation as shown in Table II and III for fault clearing time 0.3 sec respectively.

It is observed that with increase in compensation level of variable compensation of line, fault clearing angle δ_C and maximum angular swing δ_{swing} have decreased and stability margin has increased as compared to line with fixed compensation. Also, critical clearing angle δ_{cr} and critical fault clearing time t_{cr} have increased. Percentage improvement in stability margin is higher with variable compensation than with fixed compensation.

Table II: Fixed Series Compensation for 0.3 sec

% Compensation	**δ_0**	**δ_c**	**δmax**	**Margin**	**% Improvement**	**δcr**	**tcr**
0	17.1	71.10	94.08	65.71	0	101.97	0.3761
30	15.52	69.52	89.85	70.59	7.43	105.53	0.3873
40	14.99	68.99	88.48	72.10	9.72	106.76	0.3911
50	14.47	68.47	87.15	73.55	11.93	108.01	0.3948
60	13.95	67.95	85.83	74.95	14.06	109.28	0.3986
70	13.43	67.43	84.53	76.31	16.13	110.59	0.4024
80	12.91	66.91	83.27	77.60	18.09	111.91	0.4062

Table III: Variable Series Compensation for 0.3 sec

% Compensation	**δ_0**	**δ_c**	**δmax**	**Margin**	**% Improvement**	**δcr**	**tcr**
0	17.10	71.10	94.08	65.71	0	101.97	0.3761
30	15.52	69.52	84.08	79.16	20.47	105.53	0.3873
40	14.99	68.99	83.60	79.31	20.70	106.76	0.3911
50	14.47	68.47	83.12	79.44	20.89	108.01	0.3948
60	13.95	67.95	82.64	79.58	21.11	109.28	0.3986
70	13.43	67.43	82.17	79.71	21.31	110.59	0.4024
80	12.91	66.91	81.70	79.83	21.49	111.91	0.4062

B. Fault Clearing time 0.2 sec

Fault clearing angle δ_C, maximum angular swing δ_{swing} , and transient stability margin are calculated for different compensation level with fixed compensation and with variable compensation as shown in Table IV and V for fault clearing time 0.2 sec respectively.

Table IV: Fixed Series Compensation for 0.2 sec

% Compensation	**$\delta 0$**	**δc**	**δmax**	**Margin**	**% Improvement**	**δcr**	**tcr**
0	17.10	41.10	56.56	88.63	0	101.97	0.3761
30	15.52	39.52	53.59	90.34	1.93	105.53	0.3873
40	14.99	38.99	52.6	90.87	2.53	106.76	0.3911
50	14.47	38.47	51.63	91.38	3.10	108.01	0.3948
60	13.95	37.95	50.66	91.88	3.67	109.28	0.3986
70	13.43	37.43	49.68	92.37	4.22	110.59	0.4024
80	12.91	36.91	48.73	92.82	4.73	111.91	0.4062

Table IV: Variable Series Compensation for 0.2 sec

% Compensation	**$\delta 0$**	**δc**	**δmax**	**Margin**	**% Improvement**	**δcr**	**tcr**
0	17.10	41.10	56.56	88.63	0	101.97	0.3761
30	15.52	39.52	49.54	93.50	5.49	105.53	0.3873
40	14.99	38.99	49.13	93.53	5.53	106.76	0.3911
50	14.47	38.47	48.73	93.56	5.56	108.01	0.3948
60	13.95	37.95	48.34	93.59	5.60	109.28	0.3986
70	13.43	37.43	47.95	93.62	5.63	110.59	0.4024
80	12.91	36.91	47.57	93.65	5.66	111.91	0.4062

From Table II, III and Table IV, V it can be observe that transient stability is highly affected by fault time duration. With higher fault clearing time 0.3 sec maximum swing is more and stability margin are less. However percentage improvement in stability margin is higher with series compensation for higher fault clearing time.

VI. CONCLUSIONS

Transient stability enhancement of SMIB system with series compensation has been demonstrated in this work using PID based TCSC controller. Dynamic response of SMIB system to short circuit on generator bus is analysed for different compensation level.

It is observed that with increase in compensation level of transmission line, first swing of the machine and clearing angle has reduced. Critical clearing angle and transient stability margin of machine have increased. For 50% compensation of line transient stability is enhanced by **20.89%** and **5.56%** for fault clearing time 0.3 sec and 0.2 sec respectively. Also, PID based TCSC controller provides damping to post fault oscillations followed by first swing of machine.

APPENDIX

Data given for modelling are as follows in p.u. [12]:
Mechanical input to generator, $P_m = 0.8$,
Transient internal voltage $E = 1.3601$,

Infinite bus voltage $V = 1.0$,
Total reactance, $X = 0.45$,

Frequency $f = 50$ Hz,

Inertia constant $H = 6$ MJ/MVA,
Initial operating angle $\delta_0 = 17.1033^{\circ}$
Data for TCSC:
$X_C = 0.03$ and $X_L = 1/3$rd of X_C

REFERENCES

[1]. E. W. Kimbark, "Improvement of System Stability by Switch Series Capacitor," IEEE Transactions on Power Apparatus and System, VOL. PAS-85, NO. 2, 1966.
[2]. N. Ramarao and Danie k. Reitan, "Improvement of Power System Transient Stability Using Optimal Control:Bang-Bang Control of Reactance," IEEE Transactions on Power Apparatus and system, VOL. PAS-89, NO.5/6, May/June 1970.
[3]. Povh and R. Mihalic, "Enhancement of Transient Stability on AC Transmission by means of Controlled Series and Parallel Compensation," International Conference on AC and DC Power Transmission, pp. 8-12, 1991.
[4]. Zhao Xueqiang, "Study of TCSC Model and Perspective Application in Power System of China,"
[5]. IEEE 1999 International Conference on Power Electronics and Drives System, PEDS'99, Hong Kong, July 1999.
[6]. Dolan. P.S., Smith, J.R., and Mittelstadt, W.A.: 'A study of TCSC optimal damping control parameters for different operating conditions', IEEE Trans. Power Syst., 1995, 10, pp. 1972-1978
[7]. Zhao, Q., and Jiang, J.: 'A TCSC damping controller design using robust control theory', Electrical Power Energy Syst., 1998, 20, (1), pp. 25-33
[8]. Bhil S. K., Kamath A. K., Singh N. M., Wagh S.R. 'Transient Stability Enhancement of Power System using MPC based TCSC Controller', Power & Energy Society General Meeting, 2009. PES'09. IEEE, 10.1109/PES.2009.5275605
[9]. Kosterev, D.N., Kolodziej, W.J., Mohler, R.R., Mittelstadt, W.A., and: 'Robust transient stability control using thyristor controlled series compensation'. Proceedings of the 4th IEEE conference on Control applications, 1995, pp. 215-220
[10]. Timothy J.E. Miller, Reactive Power Control in Electrical Power Systems, Indian Edition, Wiley India, New Delhi, 2010.
[11]. P Kothari and I. J. Nagrath, Modern Power System Analysis, 4th ed. Tata Mc-Graw Hill, New Delhi, 2012.
[12]. N. Hingorani and L. Gyugyi, Undrstanding FACTS, IEEE Press, Wiley, New Delhi, 2013.
[13]. T. K. Nagskar and M. S. Sukhija, Power System Analysis, Oxford University Press, New Delhi, 2013 .