Comparative Analysis of Various Locations of Compensation Devices Using CCT Assessment

Abstract: *In this paper, an attempt has been made to determine the proper location of STATCOM and series compensation working simultaneously for improving the transient stability in a multi machine power system. The transient stability condition is assessed by evaluating critical clearing time. The effect of variation of generator loading, reference source voltage of STATCOM and degree of compensation on transient stability condition has been studied for various locations of STATCOM and series capacitor. The Power system is modelled and simulated using MATLAB software package. The critical clearing time is obtained by increasing the fault time interval until the system loses its stability. The results indicate the importance of installing STATCOM to a power system due to their effect of not only on stabilizing the system voltages but also increasing the power system critical clearing time(CCT) in case of non-repeated three phase ground fault. Increasing the CCT can help in the reliability of the protection system and reduce the protection system rating and its cost.*

Keywords: *Power system, Transient Stability, Critical Clearing Time, STATCOM, Series Compensation.*

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1. INTRODUCTION

Deregulation of the electricity market and increased system size has made the analysis, required to survive a transient contingencies, complex. Additional complicating factors are the operation of the interconnected system with greater interdependence among its members, heavier transmission loadings and the concentration of some large generation units at light loads.

Flexible Alternating Current Transmission System (FACTS) devices are used extensively to increase the operational efficiency of interconnected power systems [1-2]. FACTS devices are capable of controlling the network condition in a very fast manner and this unique feature of FACTS devices can be exploited to improve the transient stability of a system, provided they are placed on optimal location. Reactive power compensation is an important issue in electrical power systems and FACTS devices play an important role in controlling the reactive power flow to the power network and hence the system voltage fluctuations and transient stability. These aspects are playing an increasingly significant role in the operation and control of the deregulated electricity market.

With the growing stress on today's power systems, many utilities increasingly face the threat of transient stability problems [3-5]. For large power systems, more than one compensator may be required to achieve the desired performance. So there is need to analyse the effect of simultaneously application of more than compensator in different locations of a system. The effectiveness of individual FACTS compensators on transient stability has been studied using preserving energy margin sensitivity in [6]. Previous works on the transient stability enhancement proved that shunt FACTS devices give maximum benefit from their stabilized voltage support when sited at the mid-point of the transmission line [7-8].

CCT is defined as maximum fault duration for which the system remains transiently stable. If the fault cleared after this time the power system will lose its stability. The calculation of CCT is very important from the protection point of view. This will aid to determine the characteristics of protection system required to the power systems. In practice, CCT can be obtained in one of two ways: by trial and error analysis of system post disturbance equations or by integrating fault-on equations and checking the value of Lyapunov energy function until it reaches a previously determined critical level [9-10]. For the first approach, many integration processes are necessary.

Second approach can evaluate the CCT in just one integration process, but the major problem is to find an analytical energy function which considers a precise model of generator and the effect of FACTS devices added to improve the transient behaviour of power system like STATCOM [11-12].

Trajectory Sensitivity has been proposed as an alternative to the TEF (transient energy function) based methods in [13]. Application of TSA(transient stability analysis) in transmission system protection to detect unstable power swings and electrical centres is described in [14].

In this paper CCT with respect to fault clearing time has been used to study the effect of FACTS controllers at various locations operating individually and simultaneously on transient stability. Also, the effect of variation of generator loading and degree of compensation on transient stability has been studied.

The paper is organized as follows. Section II gives a brief introduction of two area system with a shunt FACTS device. The computer simulation results for system under study are presented in Section IV. The conclusions are given in Section IV and references are given in Section V. The various parameters of the system are listed in Appendix.

2. SYSTEM MODELLING

A. Power System Model

The system is modelled with two hydraulic generating units of 1400 MVA and 700 MVA, respectively, in each area, connected via a 500 km long transmission line as shown in Fig.1. The two machines are equipped with a hydraulic turbine and governor (HTG), excitation system and power system stabilizer (PSS).These components are included in 'Reg M1' and 'Reg M2' subsystem blocks, respectively, as shown in Figure. Initial power outputs of the generators are P1 = 0.7 pu and P2 = 0.5 pu respectively.

The power system is simulated to evaluate CCT. The critical clearing time is obtained by increasing the fault time interval until the system loses its stability.

B. Simulation of Fault

A three phase ground fault is simulated as:

i. The pre-fault time is set as 0.1s, to initialize the system.

ii. The fault is then created at 0.1s at sending end bus. Simulation of this faulted condition continues till system loses its stability. The fault is cleared by opening of appropriate circuit breakers to isolate the faulted element after being detected by

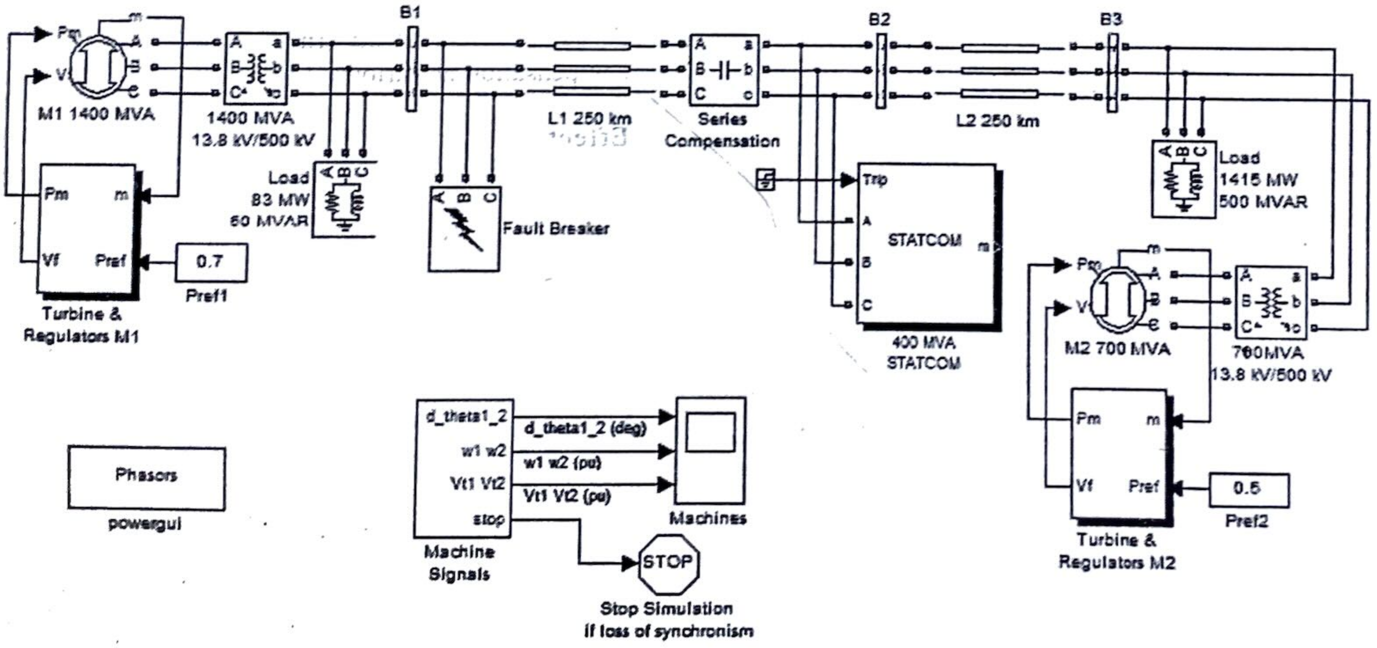

Fig.1: Simulink model of two-machine system with series compensation and STATCOM

protective relays. So, relay time and breaker interrupting time constitutes the total fault clearing time.

iii. On HV and EHV transmission systems, the normal relay times ranges from 15 to 30 ms (1 to 2 cycles) and circuit breaker interrupting times ranges from 30 to 70 ms (2 to 4 cycles).

iv. Simulation is carried out for 10-20s to observe the nature of transients. Hence behaviour of this model is studied deeply and results are shown by different graphs and tables. The original system is restored upon the clearance of the fault.

C. *STATCOM*

The STATCOM is a solid state synchronous voltage source which generates a balanced set of three sinusoidal voltages at the fundamental frequency with rapidly controllable amplitude and phase angle. The configuration of a STATCOM is shown in Fig.2.

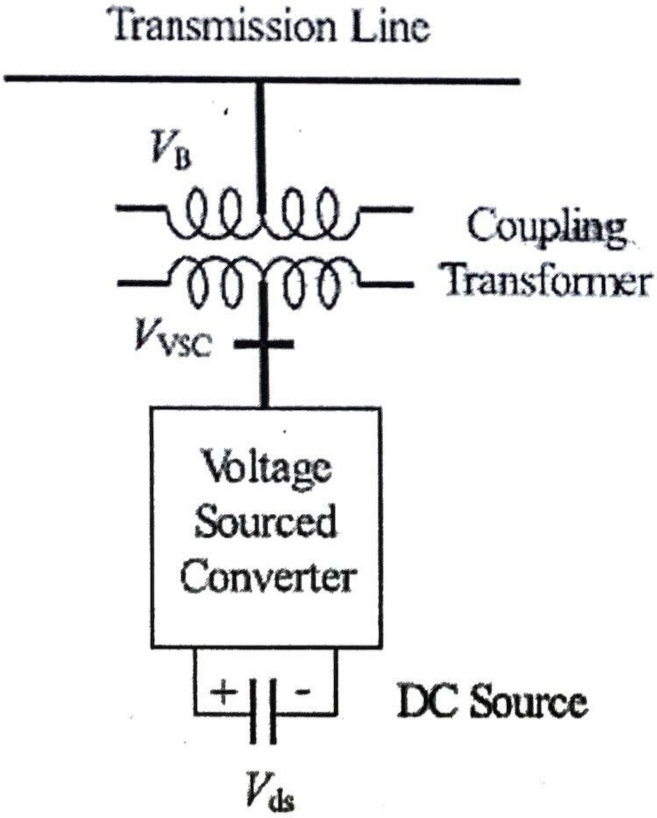

Fig.2: STATCOM

Basically it consists of a voltage source converter (VSC), a coupling transformer and a dc capacitor. It is capable of exchanging controllable real and reactive power independently, thereby helping in improving transient stability, voltage stability, and loadability.

3. RESULTS AND ANALYSIS

A three-phase ground fault is simulated as described above. The fault time is increased to find the critical stability margin, thus CCT is obtained. The value of CCT is observed to be 0.187s without any compensation in the system and results are shown in Fig.3.

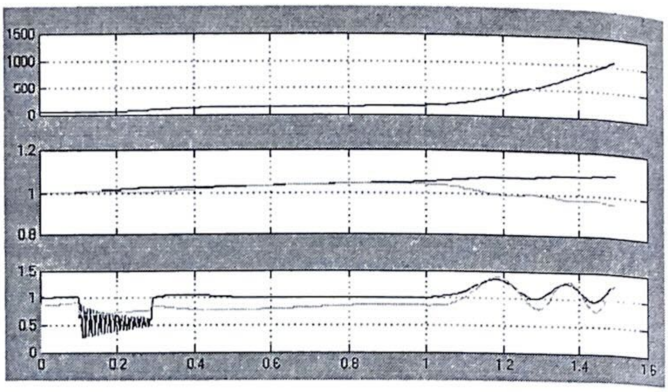

Fig.3: Simulation results without Compensation, CCT=0.187s

The graph in Fig.3 show different physical quantities such as load angle (δ), change in speeds (Δω), and terminal voltages (V_t) w.r.t. time in sec.

Analysis of model is done to study the following effects on transient stability enhancement.

a. Effect of STATCOM at various locations for transient stability enhancement

b. Effect of variation in degree of series compensation at various locations

c. Effect of variation in degree of series compensation with STATCOM at various locations

d. Effect of change in reference source voltage of STATCOM

e. Effect of change in position of fault with STATCOM at various locations

f. Effect of variation in generator loading with fault at different locations

A. *Effect of STATCOM at various locations*

After simulation of fault, it is found that the value of CCT changes for STATCOM at different locations.

Table 1: With STATCOM at various positions

Location of STATCOM	CCT (s)
Sending end	**0.209**
Centre point	0.187
Receiving end	0.119

The Table 1 shows that the best possible location of STATCOM for transient stability improvement is near sending end (faulted bus).

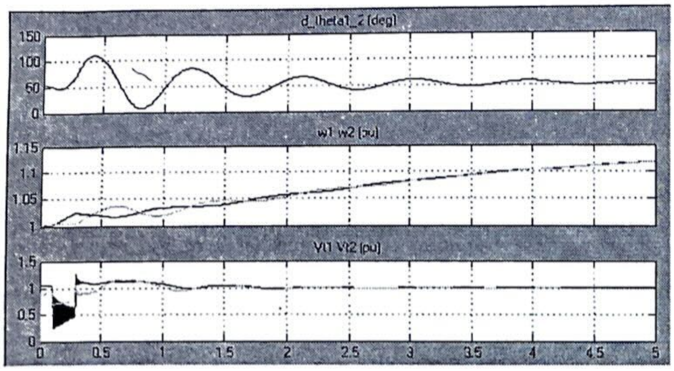

Fig. 4: Simulation results with STATCOM at sending end

The graph in Fig.4 shows the variation of different physical quantities such as load angle (δ), change in speeds (Δω), and terminal voltage (V_t) w.r.t. time in sec.

B. *Effect of variation in degree of Series Compensation at various locations without STATCOM*

Similar to previous case, three-phase ground fault is simulated and series compensation is provided at one of the various locations. It has been found that the value of CCT changes for different levels of compensation at different locations.

Table 2: Variation in degree of series compensation at various positions

Location of Series Compensation	% of Compensation	CCT (s)
Sending end	30	0.233
Sending end	50	0.257
Sending end	70	0.275
Centre point	30	**0.236**
Centre point	50	**0.264**
Centre point	70	**0.283**
Receiving end	30	0.224
Receiving end	50	0.244
Receiving end	70	0.259

The Table 2 shows that the value of CCT increases with increase in degree of compensation. And compensation gives better results when placed near centre.

The graphs in Fig.5, 6, 7 show variation of different physical quantities such as load angle (δ), change in speeds (Δω), and terminal voltages (V_t) w.r.t. time in sec.

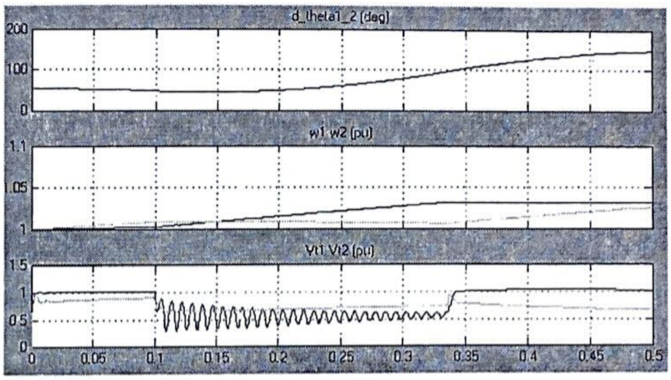

Fig. 5: Simulation results with 30% series compensation at centre

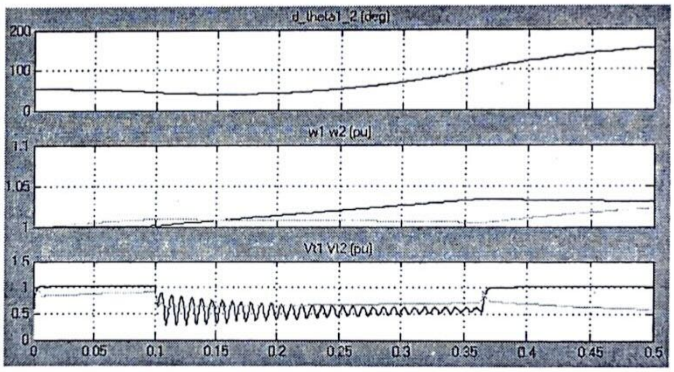

Fig. 6: Simulation results with 50% series compensation at centre

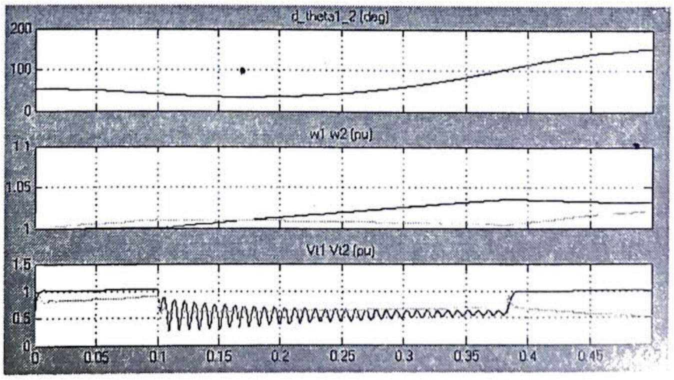

Fig.7: Simulation results with 70% series compensation at centre

C. *Effect of variation in degree of Series Compensation with STATCOM at various locations*

The value of CCT changes for different levels of compensation at different locations. The value also changes with varying the location of STATCOM. Therefore, study of transient stability margin at various locations with different combinations of degree of series compensation and STATCOM is done. Also the effect of placing both devices at same location is studied. The observed values of CCT in Table 3 provide an overall trend of system behaviour.

Table 3: Effect of variation in degree of series compensation with STATCOM at various positions

Location of Series Compen-sation	%age of Compen-sation	CCT (s) with STATCOM connected at		
		Sending end	Centre	Receiving end
Sending	30	0.224	0.250	0.168
Centre	30	**0.254**	0.249	0.171
Receiving	30	0.244	0.204	0.160
Sending	50	0.250	0.291	0.195
Centre	50	0.278	**0.294**	0.202
Receiving	50	0.263	0.215	0.181
Sending	70	0.283	0.313	0.224
Centre	70	0.295	**0.324**	0.233
Receiving	70	0.275	0.226	0.199

Following observation can be made from the results given in Table 3.

i. Best possible location of STATCOM varies:

Table 3 shows that the best possible location of STATCOM varies with the changes in degree of series compensation. For low compensation level at centre, STATCOM is best suited near sending end, while for moderate and high compensation level at centre, STATCOM is best suited near centre.

ii. When series compensation and STATCOM are applied at same end:

Table 3 also shows that the best possible location for using both at same position is centre. Also with increase in degree of compensation CCT increases.

iii. STATCOM may also cause deterioration of stability:

Arbitrary placement of the STATCOM is not always beneficial; it may cause system to become transiently unstable, like placing STATCOM at receiving end cause decrease in CCT and makes system unstable.

iv. Increase in compensation level improves stability:

It is quite clear from the table that increasing the degree of compensation helps in improving the transient stability.

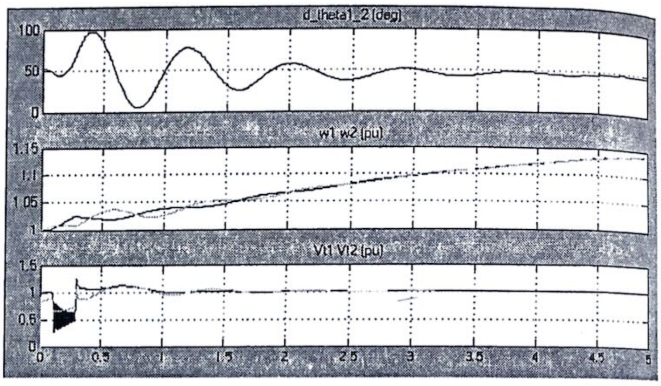

Fig. 8: Simulation results with 30% series compensation at centre with STATCOM at sending end

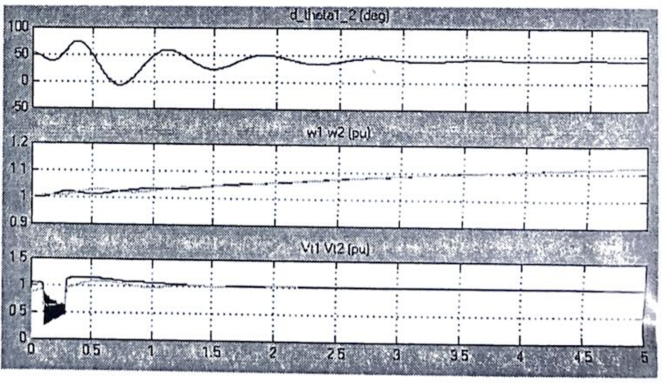

Fig. 9: Simulation results with 50% series compensation at centre with STATCOM connected at centre

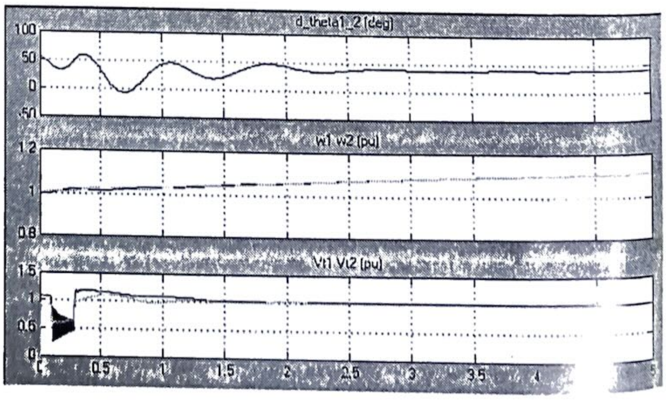

Fig. 10: Simulation results with 70% series comp ion at centre with STATCOM connected at cen

The graphs in Figs.8, 9, 10 show different physical quantities such as load angle (δ), change in speeds (Δω), and terminal voltages (V_t) w.r.t. time in sec.

D. *Effect of change in reference source voltage of STATCOM*

Variation in transient stability condition of system is studied with STATCOM placed at different location and shown in Table 4.

Table 4: Effect of change in reference voltage of STATCOM

Location of STATCOM	Vref	CCT (s)
Sending end	1.00	**0.209**
Sending end	1.05	**0.215**
Sending end	1.10	**0.221**
Sending end	1.15	**0.226**
Centre	1.00	0.187
Centre	1.05	0.187
Centre	1.10	0.187
Centre	1.15	0.187
Receiving end	1.00	0.119
Receiving end	1.05	0.119
Receiving end	1.10	0.119
Receiving end	1.15	0.119

Following observation can be made from the study:

i. Increase in Vref improves the system stability:

The value of CCT is found to be increasing with increase in reference source voltage (Vref) when STATCOM is placed at sending end (faulted bus). Thus stability margin improves with increase in Vref.

ii. Increase in Vref doesn't ensure improvement in stability:

Increase in reference source voltage (Vref) of STATCOM improves stability at some places like when placed at sending end (faulted bus), whereas it doesn't cause any changes in CCT when placed at other location.

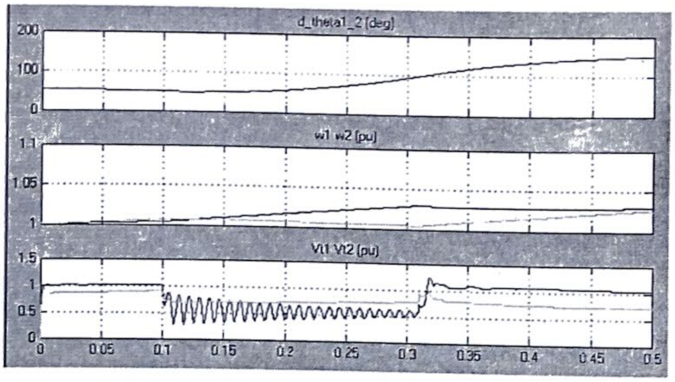

Fig.11: Simulation results with STATCOM (Vref = 1.00pu) connected at sending end

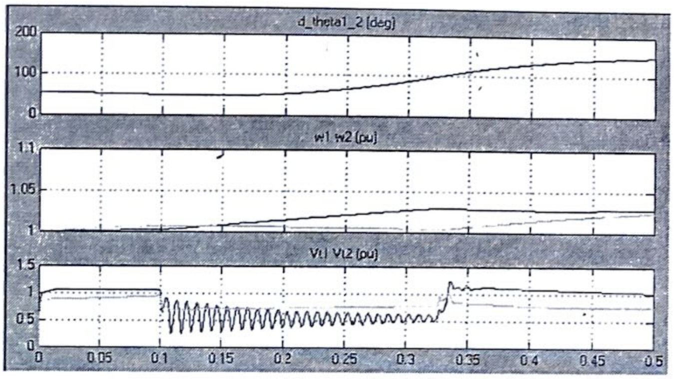

Fig.12: Simulation results with STATCOM (Vref = 1.15pu) connected at sending end

The graphs in Figs.11, 12 show different physical quantities such as load angle (δ), change in speeds (Δω), and terminal voltages (V_t) w.r.t. time in sec. So, it is quite clear that before compensating a power system with FACTS devices, we may need to assess the system stability conditions for different locations of fault, location of series and shunt compensation, degree of compensation and reference source voltage.

E. *Effect of change in position of fault with STATCOM at various locations*

The best location of STATCOM changes with position of fault. The value of CCT(s) also changes while varying the location of fault. Therefore, study of transient stability at various locations with different locations of fault is summarised and given in Table 5.

Table 5: Effect of change in position of fault

Location of Fault	Without STATCOM	CCT (s) with STATCOM connected at		
		Sending end	Centre	Receiving end
Sending	0.187	**0.209**	0.187	0.119
Receiving	0.422	0.365	0.405	**0.452**

Following observation can be made from the results given in Table 5.

i. Best possible location of STATCOM varies:

The Table shows that the best possible location of STATCOM for transient stability improvement varies with the location of fault. With fault at sending end, STATCOM is best suited near sending end, while with fault at receiving end, STATCOM is best suited near receiving end.

ii. STATCOM may also cause deterioration of stability:

Arbitrary placement of the STATCOM is not always beneficial; it may cause system to become transiently unstable. It is observed that placing STATCOM away from fault location makes system unstable.

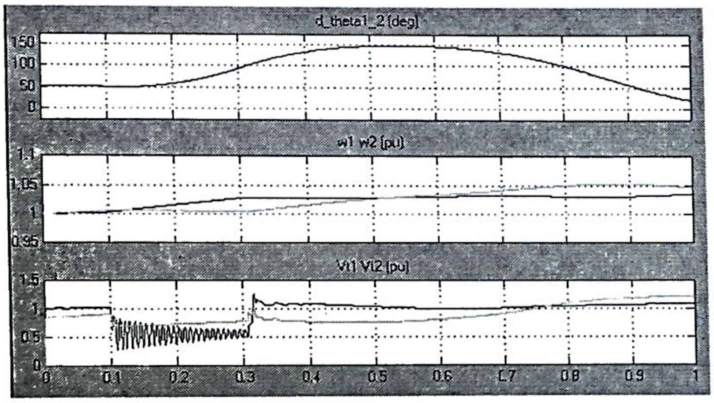

Fig. 13: Simulation results with fault and STATCOM connected at sending end

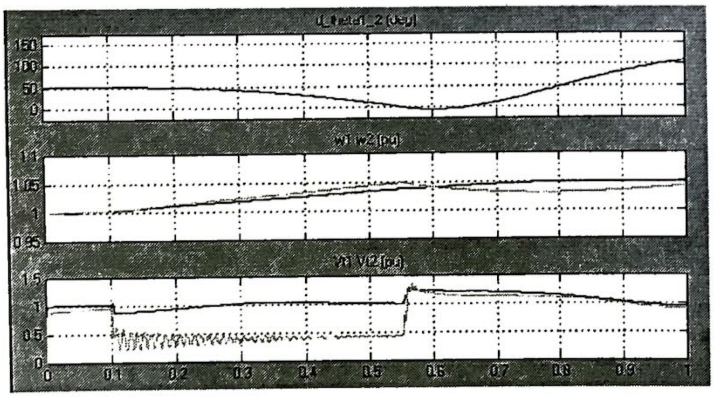

Fig.14: Simulation results with fault and STATCOM connected at receiving end

The graphs in Figs.13, 14 show different physical quantities such as load angle (δ), change in speeds (Δω), and terminal voltages (Vt) w.r.t. time in sec.

F. *Effect of variation in generator loading with fault at different locations*

The best location of STATCOM varies with location of fault. It can be observed that STATCOM gives best result when located near fault location. Also value of CCT varies with variation in generator loading (P1 and P2). The observations are given in Table 6.

Table 6: Effect of variation in generator loading with fault at different locations

P1	P2	CCT with STATCOM and Fault at sending end	CCT with STATCOM and Fault at receiving end
0.7	0.3	0.211	0.446
0.7	0.5	0.209	0.452
0.7	0.7	0.207	0.459
0.7	0.9	0.204	0.466
0.3	0.5	0.205	0.466
0.5	0.5	0.207	0.458
0.7	0.5	0.209	0.452
0.9	0.5	0.211	0.447

Following observation can be made from the results given in Table6.

i. Stability increases:

With increase in loading of generator near fault, the value of CCT increases with STATCOM near fault location.

ii. Stability decreases:

With increase in loading of generator far away from fault, the value of CCT decreases with STATCOM near fault location.

The analysis can be summarised as follows:

- It is found that the combined effect of the STATCOM and series compensation cannot be estimated from the individual effects only.
- The best possible combination of locations of two devices may differ for different levels of compensation.
- It is found that the best possible location of the FACTS devices (in terms of transient stability

improvement) is not fixed for a particular system; rather it depends on the location of fault.

- Though FACTS devices cause improves system stability margin in majority of cases, it may cause deterioration for some cases.
- Placement of STATCOM is not always helpful. It may cause reduction in stability margin in some cases. Placing STATCOM far away from the fault location, eg. STATCOM at receiving end when fault is at sending end gives similar results.
- Increase in the loading of generator near fault with STATCOM near fault location, stability margin increases, whereas reverse (i.e. increase in the loading of generator away from the fault) decreases stability margin.

4. CONCLUSION

In this paper, different simulations for analysis of transient stability condition of a power system are carried out in MATLAB/SIMULINK environment. The system is simulated by initiating a 3-phase fault in the line to study the various effects on transient stability condition, such as individual and combined effect of series compensation and STATCOM; variation of degree of compensation; variation of generator loading; variation of reference source voltage of STATCOM and location of fault. The transient stability condition is assessed by evaluating critical clearing time. Critical Clearing Time is in a range of hundred of milliseconds.

The best possible location of STATCOM is found to vary with degree of compensation level, fault location and operating criteria of the FACTS devices such as magnitude of voltage of STATCOM. It is shown that though STATCOM help in transient stability improvement of the system with proper placement, CCT is better in case of series compensation along with STATCOM. The effect of series compensation in a STATCOM connected system is different for different levels of series compensation. For a particular combination of location, increase in degree of compensation does not essentially ensure improvement in system stability. With low compensation, STATCOM is best suited near sending end, while with moderate and high compensation; STATCOM is best suited near centre. It is also found that STATCOM is best suited near fault location, and increase in the loading of generator near fault with STATCOM, increases the stability margin whereas increase in the loading of generator away from fault with STATCOM decreases the stability margin.

The placement of FACTS devices is beneficial for system stability in majority of cases. However, it may cause deterioration of stability for some combinations of location of fault and FACTS devices. Those locations can be found with the help of transient stability margin or CCT. Also, increase in reference source voltage of STATCOM does not ensure a better stability. Therefore evaluation of system stability condition is required for better and safer system operation.

All these observations underline the importance of finding transient stability assessment. For further work, we propose to use other approaches based to precisely find the optimal location of FACTS devices and to use these observations for transient stability enhancement of a power system.

APPENDIX

The data for various components used in the MATLAB model of Fig. 3. (All data are in pu unless specified otherwise; the notations used are as in Sim-Power-System toolbox):

Generator parameters: M1 =1400 MVA, M2 =700 MVA, V = 13.8 KV, f = 60 Hz, Xd=1.305, X'd = 0.296, X2 2 d = 0.255, Xq = 0.474, X2 2 q = 0.243, X1 = 0.18

Transformer parameters: T1=1400 MVA, T2=700 MVA, 13.8/500 KV, R2 =0.002, L2=0.12, Rm =500, Xm=500.

Transmission line parameters per km: R1 = 0.1755, R0 = 0.2758, L1 = 0.8737 mH, L0 = 3.22mH, C1 = 13.33 nF, C0 = 8.297 nF.

STATCOM parameters: 500 KV, ±100 MVAR, R = 0.071, L = 0.22, Vdc = 40 KV, Cdc = 375 ± ¼ F, Vref = 1.0, Kp = 50, Ki = 1000.

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