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Small Signal and First-Swing Stability Enhancement in Inter-Area Power System

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Abstract: *Generally, the Power systems are subjected to a wide range of disturbances, small and large. For small disturbances, load frequency and excitation voltage control problems are non interactive. In the large interconnected power system, it is also desirable to maintain the tie- line power flow at a given level irrespective of load changes in any area. Therefore there is a need to go for automatic controlling equipment (called Automatic Generation Control) which regulates the changes in frequency and the tie line power so as to meet the changing demands. The AGC system solely cannot control the disturbances, it need another controller like proportional integral (PI), proportional integral derivative (PID) controller. PI controller is simple for implementation but takes more time and gives large frequency deviations.*

Large disturbance is concerned with the ability of the power system to maintain synchronism when subjected to a severe disturbance, such as a short circuit on a transmission line. In general rotor angle stability is taken transient stability of power system, which is the function of operating condition and disturbances. In order to improve the Transient Stability margin, FACTS devices has been implemented. In this paper, the transient stability improvement is verified using Simulink, with different FACTS devices, namely Static Var Compensator (SVC) and Static Synchronous Compensator (STATCOM). It has been observed that the FACTS devices, when placed slightly off-centre towards sending-end, gives better performance in improving transient stability and the location depends on the amount of local/through load. The results are experimented and simulated on MATLAB/Simulink environment.

Keywords: *AGC, Conventional controller, Inter area power system, FACTS devices, SVC, STATCOM*

I. INTRODUCTION

The power system engineers have the end responsibility to satisfy the varying demands and deliver adequate power to load reliably and economically. In order to ensure this electrical energy system must be maintained at desired operating state represented by nominal frequency, voltage profile and load flow configuration. This is made possible by having a close control of real and reactive power generations of the system. The real and reactive powers are never steady, but continuously vary with the rising or falling trend. The real and reactive power generations must change accordingly to match the load per distributions. The control of an electrical energy system is in order to have an exact matching of the generation to load at nominal state, is quite a challenging problem. It is so because in a dynamic system the load continuously changes and system generation, responding to control impulses, changes the load with the transient unbalance of load and generation reflected in speed hence frequency variations.

For small perturbations, load frequency and excitation voltage control problems are non interactive hence treated as two independent 'decoupled control problems' for all practical purposes. In the large interconnected power system, it is also desirable to maintain the tie- line power flow at a given level irrespective of load changes in any area. To accomplish this, it becomes necessary to automatically regulate the operations of main stream valves or hydro gates in accordance with the suitable control strategy, which in turn controls the real power output of electric generators. But controlling the output of a power system manually is impossible as a power plant is huge area with combination of various electro-mechanical equipments like generators, transformers, turbines etc. Therefore there is a need to go for automatic controlling equipment which regulates the changes in frequency and the tie line power so as to meet the changing demands. The basic operating requirements of an ac power system are that the synchronous generators must remain in synchronism and the voltages must be kept close to their rated values [6]. The capability of a power system to meet these requirements in the face of possible disturbances (line faults, generator and line outages, load switchings, etc.) is characterized by its transient, dynamic, and voltage stability. The stability requirements usually determine the maximum transmittable power at a stipulated system security level. The development of the modern power system has led to an increasing complexity in the study of power systems, and also presents new challenges to power system stability, and in particular, to the aspects of transient stability and small-signal stability[9-12]. Transient stability control plays a significant role in ensuring the stable operation of power systems in the event of large disturbances and faults, and is thus a significant area of research. Recent break-throughs in power electronics technology have enabled the development of a variety of sophisticated controllers used to solve long-standing technical and economical problems found in electrical power systems at both the transmission and distribution levels. These emerging controllers are grouped under the headings FACTS and custom power technology respectively. The use FACTS devices in a power system can potentially overcome limitations of the present mechanically controlled transmission systems. By facilitating the bulk power transfers, these interconnected networks minimize the need to enlarge power plants and enable neighboring utilities and regions to exchange power. The stature of FACTS devices within bulk power system will continually increase as the industry moves toward a more competitive posture in which power as bought and sold as a commodity. This paper investigates the improvement of transient stability of a two-area power system, using FACTS devices like, SVC, STATCOM.

Literature Review: Recently network blackouts related to voltage collapse tend to occur from lack of reactive power support in heavily stressed conditions, which are usually triggered by system faults. Calvaer [2] stated that a system may undergo a voltage collapse if it includes at least one voltage collapse bus. Chebbo *et al.* [3] noted that the cause of the 1977 New York blackout was proved to have been a reactive power problem, and the 1987 Tokyo blackout was believed to have been due to a reactive power shortage and a voltage collapse during a summer peak load. However, reactive power has received less attention recently until the Great Blackout in August 2003 in the northeastern US, which showed that reactive power in US power systems was not very well planned and managed. Reactive power including its planning process has received tremendous interest after the 2003 Blackout from utilities, independent system operators (ISOs), researchers, and the government. Power electronics based equipment or Flexible AC Transmission Systems (FACTS), provide proven technical solutions to voltage stability problems. Especially, due to the increasing need for fast response for power quality and voltage stability, the shunt dynamic Var compensators such as Static Var Compensators (SVC) and Static Synchronous Compensators (STATCOM) have become feasible alternatives to a fixed reactive source, and therefore have received intensive interests. There are more than 50 SVCs installed in the United States, ranging from 30MVar to 650MVar each. STATCOMs are installed at several sites in the United States, ranging between 30MVar &100MVar each. FACTS make the application of a large amount of Var compensation more efficient, flexible, and attractive. Consequently, a series of questions have been raised frequently by utility planners and manufacturers: where is the right location and what is the right size for the installation of reactive power compensators considering technical and economic needs? Can the models, methods, and tools used for static Var planning be applied in dynamic Var planning? The answers to these questions are needed for utilities to make better use of these new power electronic controlled Var sources.

The mid-point sitting is most effective in reactive power control. The transmission line must be operating below the thermal limit and the transient stability limit. Tan, Y.L suggested a novel method for the analysis of the effectiveness of an SVC and a STATCOM of the same KVar rating for first-swing stability enhancement .The analysis shows that the STATCOM is superior to the SVC for first-swing stability enhancement [6]. Siddhartha Panda, Ramnarayan N. Patel investigated about the Shunt Flexible AC Transmission System (FACTS) devices, when placed at the mid -point of a long transmission line, play an important role in controlling the reactive power flow to the power network and hence both the system voltage fluctuations and transient stability.

II. DESCRIPTION OF SYSTEM MODEL

2.1 Case I: for Small Signal Analysis

An interconnected power system is divided into control areas connected by a tie line. In each control area, all generators are supposed to constitute a coherent group. Investigations have been carried out on a two equal area non-reheat thermal power system shown in fig 2.1. A step load perturbation of 1% of nominal loading has been considered in both areas. Here, the tie-line power deviations can be assumed as an additional power disturbance to any area. For the load frequency control, the proportional integral controller is implemented. The overall system can be modeled as a multi-variable system in the following form

$$x' = Ax(t) + Bu(t) + Dd(t) \text{ ------------------(1)}$$

Where A is the system matrix, B and D the input and disturbance distribution matrices, and $x(t)$, $u(t)$ and $d(t)$ are state, control signal and load change disturbance vectors.

$$x(t) = [\, \Delta f_1 \;\; \Delta P_{sg1} \;\; \Delta P_{t1} \;\; \Delta P_{tie} \;\; \Delta f_2 \;\; \Delta P_{sg2} \;\; \Delta P_{t2} \,]^T; \qquad u(t) = [\, u_1 \;\; u_2 \,]^T \quad and \quad d(t) = [\, \Delta P_{d1} \;\; \Delta P_{d2} \,]^T \text{ -----(2)}$$

where Δ denotes deviation from the nominal values and $u1$ and $u2$ are the control signals in area 1 and 2, respectively. The system output, which depends on area control error (ACE), is given as

$$y(t) = \begin{pmatrix} y_1(t) \\ y_2(t) \end{pmatrix} = \begin{pmatrix} ACE_1 \\ ACE_2 \end{pmatrix} = Cx(t)$$

and $ACEi = \Delta Ptie + bi\Delta fi \quad where \quad i = 1,2$ ------------- (3)

where bi is the frequency bias constant, Δf_i is the frequency deviation, $\Delta Ptie$ is the change in tie-line power for area i and C is the output matrix.

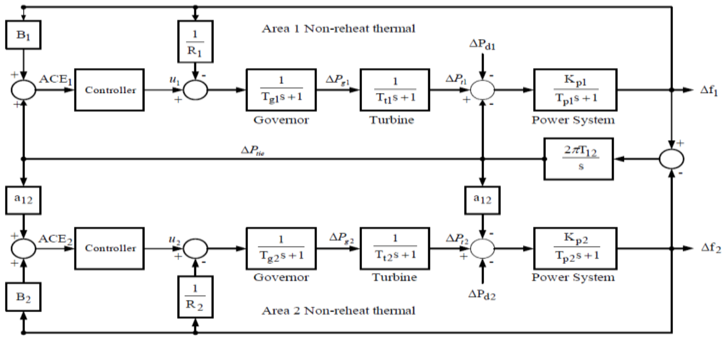


Fig.2.1 Two area interconnected power system with controller.

2.2 Case II: for Transient Analysis:

An extended power system can be divide into a number of load frequency control areas inter connected by means of tie-lines. Without loss of generality we shall consider a two area case connected by a single tie-line as illustrated in fig.2.2. The two area system as proposed is modeled with two hydraulic generating units of 1400 MVA and 700 MVA, respectively, in each area, connected via a 600 km long transmission line as shown in Fig. 1 for our study [5, 7]. The two machines are equipped with a hydraulic turbine and governor (HTG), excitation system and power system stabilizer (PSS). The FACTS devices used for this model have the same rating of ±100 MVA and the reference voltage is set to 1.0 pu. Initial power outputs of the generators are $P_1 = 0.7$ pu and $P_2 = 0.5$ pu and the Sending End Power (SEP) and Receiving End Power (REP) without the FACTS device are 894 MW and 864 MW respectively. A three phase fault occurs at sending end bus at time t = 0.1s. The original system is restored upon the clearance of the fault.

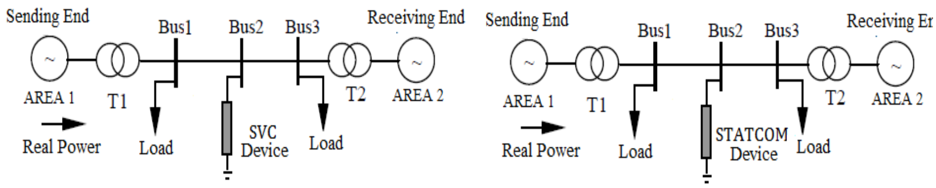


Fig.2.2: Two-area power system with SVC and STATCOM devices

The transient following a system perturbation is oscillatory in nature, but if the system is stable, these oscillations will be damped toward a new quiescent conditions. These oscillations however are reflected as fluctuations in the power flow over the transmission lines. If a certain line connecting the two groups of machines undergoes excessive power fluctuations, it may be tripped out by its protective equipment there by disconnecting the two groups of machines. This problem is termed the stability of the tie line, even though in reality it reflects the stability of the two groups of the machines. The shunt converter is able to generate or absorb controllable reactive power in both operating modes (i.e., rectifier and inverter). The independently controlled shunt reactive compensation can be used to maintain the shunt converter terminal AC voltage magnitude at a specified value.

III. Design Of Pi Controller

The well designed integral controller alone can bring the steady state error to zero but the speed of the response of the system becomes slow resulting high overshoot and settling time. The overshoot is reduced and the speed of the response improves by using only proportional controller. It is obvious that the presence of the proportion-al controller is highly required at transient to make faster system response thus reducing the overshoot. But only the proportional controller fails to bring the steady state error to zero. So there is need to present both the integral and proportional controller. The task of load frequency controller is to generate a control signal *ui* that maintains system frequency and tie- line interchange power at predetermined values. The control signal for the conventional PI controller can be given in the following equation.

$$u_i(t) = -k_P ACE_i - \int k_I (ACE_i)dt = -k_P (\Delta P_{tie} + b_i \Delta f_i) - \int k_I (\Delta P_{tie} + b_i \Delta f_i)\, dt \text{ ------------------ } (5)$$

Where, k_P and k_I are proportional and integral gains respectively, ACE is area control error which defines "a quantity reflecting the deficiency or excess of power within a control area" and u_i is controlled output of the i^{th} area. *bi* is area *i* frequency bias constant, *Δfi* is area *i* frequency change, *ΔPtie*, is the change in tie-line power.

IV. FACTS DEVICES

FACTS controllers may be based on thyristor devices with no gate turn-off or power devices with gate turn-off capability. FACTS controllers are used for the dynamic control of voltage, impedance and phase angle of high voltage AC transmission lines. The basic principles of the following FACTS controllers, which are used in the two-area power system under study, are discussed briefly [1-4].

4.1 Static Var Compensator (SVC)

Static var systems are applied by utilities in transmission applications for several purposes. The primary purpose is usually for rapid control of voltage at weak points in a network. Installations may be at the midpoint of transmission interconnections or at the line ends. Static Var Compensators are shunt connected static generators / absorbers whose outputs are varied so as to control voltage of the electric power systems. In its simple form, SVC is connected as Fixed Capacitor-Thyristor Controlled Reactor (FC-TCR) configuration as shown in Fig. 4.1. The SVC is connected to a coupling transformer that is connected directly to the ac bus whose voltage is to be regulated. The effective reactance of the FC-TCR is varied by firing angle control of the anti-parallel thyristors. The firing angle can be controlled through a PI (Proportional + Integral) controller in such a way that the voltage of the bus, where the SVC is connected, is maintained at the reference value[4].

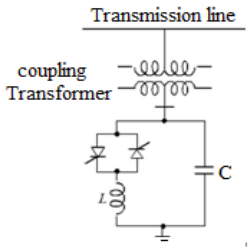


Fig. 4.1. Static VAR Compensator (SVC)

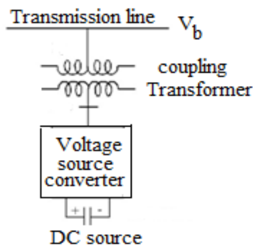


Fig. 4.2. STATCOM

4.2 Static Synchronous Compensator (STATCOM)

A STATCOM, controlled to regulate the terminal voltage, can increase the transient stability by maintaining the transmission voltage at the midpoint or some appropriate intermediate point in face of the increased power flow encountered immediately after fault clearing. However, the transient stability can be increased further by temporarily increasing the voltage above the regulation reference for the duration of the first acceleration period of the machine. The voltage increased above its nominal value will increase the electric power transmitted and thus will increase also the deceleration of the machine. This is illustrated in fig. 4.1, where the *P* versus δ plots of a simple two-machine system with different midpoint compensations represents the *P* versus δ is shown [5, 7]. The plot marked $P = 2V^2 \sin(\delta/2)/X$ plot obtained with an ideal compensator holding the midpoint voltage constant. The plots marked with STATCOM and SVC represents these compensators with a given rating insufficient to maintain constant midpoint voltage over the total range of δ. Thus, the *P* versus δ plots are identical to that of the ideal compensator up to a specific δ ($\delta = \delta_i$) at which the SVC becomes a fixed capacitor and the STATCOM a constant current source. In the interval between δ_i and δ, the *P* versus δ plots is those which correspond to a fixed midpoint capacitor and a constant reactive current source. The continuations of these plots in the δ_i to zero interval show the *P* versus δ characteristic of the two-machine system with the maximum capacitive admittance of the SVC and with the maximum capacitive output current of the STATCOM. That is angles smaller than δ_i the transmission line is overcompensated and for angles greater, it is undercompensated. This overcompensation capability of the compensator can be exploited to enhance the transient stability by increasing the var output to the maximum value after fault clearing. Depending on the rating of the compensator, and the allowed voltage increase, the attainable increase in transient stability margin can be significant.

4.3 Location of Shunt FACTS devices in Inter-area Power System:

Previous works on the topic prove that shunt FACTS devices give maximum benefit from their stabilized voltage support when sited at the mid-point of the transmission line. The proof of maximum increase in power transfer capability is based on the simplified model of the line neglecting line resistance and capacitance. Based on the simplified line model it has been proved that the centre or midpoint of a transmission line is the optimal location for shunt FACTS devices. When the actual model of the line is considered, it is found that the FACTS device needs to be placed slightly off-centre to get the highest possible benefit.

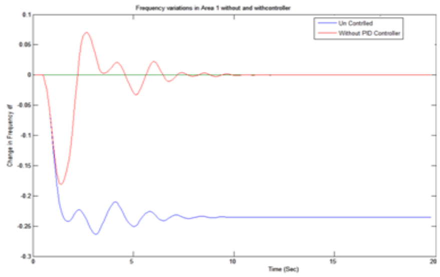
The mid-point sitting is most effective in reactive power control. The transmission line must be operating below the thermal limit and the transient stability limit. Tan, Y.L suggested a novel method for the analysis of the effectiveness of an SVC and a STATCOM of the same KVar rating for first-swing stability enhancement .The analysis shows that the STATCOM is superior to the SVC for first-swing stability enhancement [4]. Siddhartha Panda, Ramnarayan N. Patel investigated about the Shunt Flexible AC

Transmission System (FACTS) devices, when placed at the mid -point of a long transmission line, play an important role in controlling the reactive power flow to the power network and hence both the system voltage fluctuations and transient stability. This paper deals also with the location of a shunt FACTS device to improve transient stability in a long transmission line with predefined direction of real power flow. It has been observed that the FACTS devices, when placed slightly off-centre towards sending-end, give better performance in improving transient stability and the location.

V. SIMULATION RESULTS

Case Study I:Samll Signal Analysis

The two area interconnected system using PI controller in each area is shown in above Fig.4 after including the nominal parameters. The mathematical model is created and simulation is carried out for 20sec. Figs. 5.1 and 5.2 shows the responses of change in frequency (Δf) and change in tie line power (ΔP_{tie}) of a two area Non-reheat thermal system of Uncontrolled, Conventional PI controller for 1% step load perturbation (ΔP_L) inarea1[4].



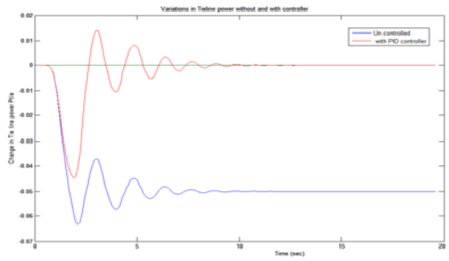


Fig.5.1: Frequency deviation in Area-1 without and with without and with PID controller

Fig.5.2 Tie-line power deviation PID controller

From the above two figures (i.e Fig.5.1 & Fig.5.2) the oscillations in frequency and tie line power are damped out and the steady state error zero with the PI controller.

Case Study II: Transient stability Analysis

The two area system as proposed in Section 2 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. 5.1 for our study. The two machines are equipped with a hydraulic turbine and governor (HTG), excitation system and power system stabilizer (PSS). Both SVC and STATCOM used for this model have the same rating of ±100 MVA and the reference voltage is set to 1 pu for both SVC and STATCOM. Initial power outputs of the generators are P_1 = 0.7 pu and P_2 = 0.5 pu and the SEP and REP without the FACTS device are 894 MW and 864 MW respectively. A three phase fault occurs at sending end bus at time t = 0.1s. In order to maintain system stability after faults, the transmission line is shunt compensated at its center by a ±100 MVA SVC and STATCOM.

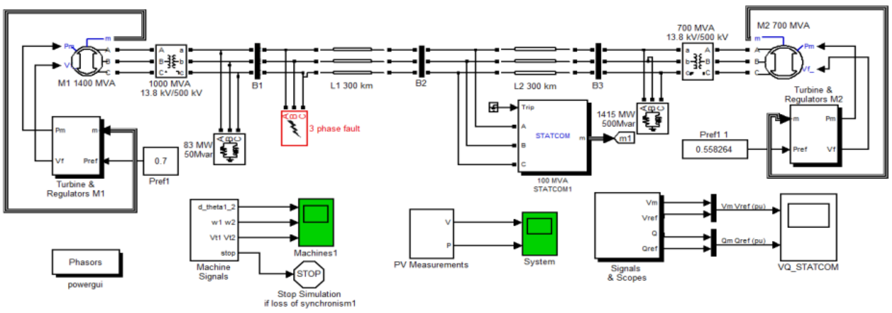


Fig. 5.1. Simulation of Two-area power system with STATCOM

5.1 With Static Var Compensator (SVC):

When a 3-ph fault [9] is occurs at the proper location in the transmission line then the system will be at out of synchronism and looses its stability.

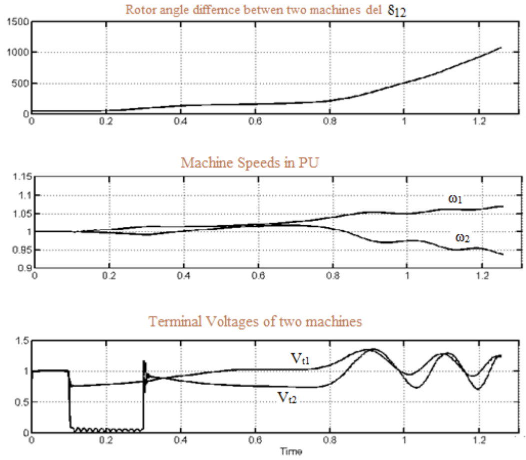


Fig.5.2. waveforms for Rotor angle, Speed & voltages with 3-ph fault

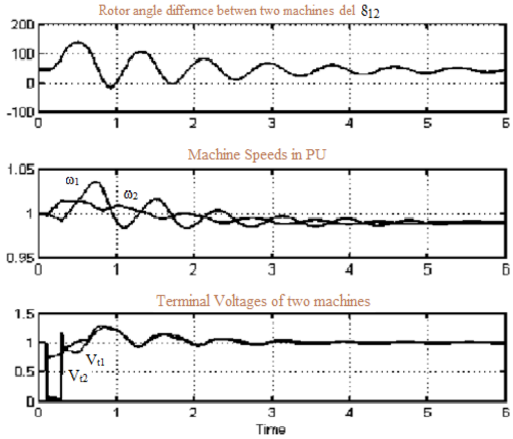


Fig.5.3.waveforms for Rotor angle, Speed & voltages with fault wne SVC placed at middle of Tr.line

On placing the SVC in the transmission line at the distance of L1=300km & L2=300km i.e. absolutely at the mid point of the transmission line,we can get the stabilised waveform at fault clearing time t=0.19 sec only. If we place the SVC in the transmission line at the distance of L1=300km & L2=300km i.e. absolutely at the mid point of the transmission line, system is unstable at FCT t = 0.2 sec

5.2 With Static Synchronous Compensators (STATCOM):

On placing the STATCOM at the exactly at middle of Transmission line length distances (i.e L1=300Km & L2=300km), the system is stable with the fault clearing time of 0.2 sec.

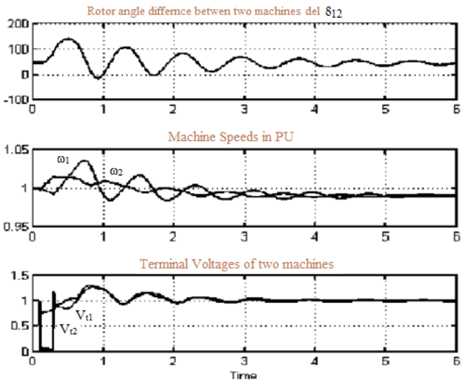


Fig.5.3. Rotor angle, Speed & voltages with fault by with fault by palcing STATCOM at middle of Tr. line at FCT of 0.2 sec.

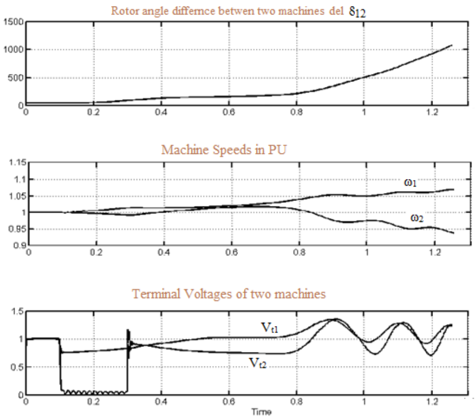


Fig.5.4. waveform for Rotor angle, Speed & voltages with fault by palcing STATCOM at middle of Tr. line at FCT of 0.21 sec

Similarly by changing the fault clearing time in the same distances as the fault clearing time of t=0.21sec, we can't get the stabilized system. The summary of above analysis with shunt FACTS devices is expalined by the following table

.

Length of Transmission line	With Shunt FACTS devices	
	SVC	*STATCOM*
L1=300KM, L2=300KM & T=0.19 sec	Stable	Stable
L1=300KM, L2=300KM & T=0.2sec	Unstable	Stable
L1=240KM, L2=360KM & T=0.2 sec	Stable	Stable
L1=300KM, L2=300KM & T=0.21 sec	Unstable	Unstable
L1=240KM, L2=360KM & T=0.21 sec	Unstable	Stable

Table 1: Comparison between SVC & STATCOM

For a Fault Clear Time of 0.19 sec, the system is working satisfactorily when the SVC is placed at mid-point of the transmission line (for L1=300Km & L2=300Km.) But when FCT is changed to 0.2 Sec, the system loses synchronism. The same system is not losing synchronism if the location of SVC is changed slightly (i.e when L1=240Km & L2 = 360Km) . Also the same system is sustaining its stability with STATCOM even for a FCT 0f 0.21sec. We observed STATCOM shows better performance than SVC.

VI. CONCLUSION

Different simulations are carried out in MATLAB/Simulink environment. The effectiveness of the proposed controller in increasing the damping of local and inter area modes of oscillation is demonstrated using Two area Non-reheat thermal Power System. Also the simulation results for AGC and PID controller are compared. The shunt FACTS devices (like SVC and STATCOM) are simulated for the Transient Stability Enhancement on a Two-area Power System. The system is simulated by initiating a three-phase fault near the first machine in the absence of shunt FACTS devices. In this case, the difference between the rotor angles of the two machines is increased tremendously and ultimately loses its synchronism. But, when the same fault is simulated in the presence of SVC and STATCOM, the system becomes stable. The SVC and STATCOM provides voltage support at the bus where it is connected. From the result analysis it is observed that the STATCOM shows better performance than SVC.

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