IMPROVEMENT OF FIRST SWING STABILITY LIMIT BY USING FACTS DEVICES

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ABSTRACT

In this paper, presents a control strategy of two shunt Flexible Ac Transmission System (FACTS) devices to improve the first swing stability limit of a power system. The two devices are Static VAR Compensator (SVC) and Static Synchronous Compensator (STATCOM.) The speed based control is unable to use the entire decelerating area in maintain stability. The control strategy presented improves the stability limit first by maximizing the decelerating area and then fully utilizing it in counter balancing the accelerating area. The control strategy is implemented on the FACTS devices connected to single machine infinite bus system. The same control strategy is also used for symmetrical faults in multimachine system. Results show that in both the systems, the control strategy implemented can provide high stability limit. It is found that among the two FACTS devices STATCOM can provide higher stability limit than SVC. The analysis is done by using MATLAB/simulink software.

Keywords- **Flexible ac transmission system (FACTS) devices, Single machine infinite bus (SMIB) system, Static VAR compensator (SVC), Static synchronous compensator (STATCOM).**

1. Introduction

A power system is a complex network comprising of numerous generators, transmission lines, variety of loads and transformers. As a consequence of increasing power demand, some transmission lines are more loaded than was planned when they were built. So, with increased power transfer, transient stability is increasingly important for secure operation. Transient stability is the main factor that limits the power transfer capability of long distance transmission lines. Power utilities are placing more emphasis on improving transient stability, especially first swing stability. A power system can be considered as first swing stable if the post-fault angle of all machines in center of angle reference frame increases (decreases) until a peak (valley) is reached when the angle starts returning [1],[2]. In general, a first swing stable system is considered as stable because system damping, governor, etc. usually help to damp oscillation in subsequent swings [3].

First swing stability limit of a single machine infinite bus (SMIB) system can be determined through equal area criterion (EAC) [4] which depends on the difference between input mechanical and output electrical power. During a fault electrical power reduced suddenly while the mechanical power remains constant, there by accelerating the rotor. The turbine delivers excess energy to the machine which can be represented by an area called accelerating area. To maintain the first swing stability, the generator must transfer the excess energy to the network once the fault is cleared. The excess energy transferring capability of the machine can be represented by an area called decelerating area. The stability limit can be improved by enlarging the decelerating area in early part of the post fault period. The network conditions cannot be controlled fast enough to enlarge the decelerating area dynamically. Recent development of power electronics introduces the use of flexible ac transmission system (FACTS) devices in power systems. FACTS devices [5],[6] are capable of controlling the network in a very fast manner hence improving the stability limit of a system.

Following a large disturbance, the FACTS controllers should first maximizes the first swing stability of a critical machine. This can be achieved by increasing the electrical power output of the machine as much as possible in early part of the post fault period. If the FACTS device is placed in the main power transfer path of the critical machine, the output power of the machine and hence its first swing stability limit can be increased by operating the FACTS devices at full capacitive rating. Such an operation should continue until the machine reaches a reasonable negative value during the first return journey. Afterwards, a continuous control, proportional to the speed of the machine, can be applied to improve the damping in subsequent swings.

For most of the faults in a multi-machine system, it was observed that only one machine (or a small group of machines) becomes severely disturbed and is called critical machine (or critical group). The critical machine (or critical group) is usually responsible to initiate instability for an unstable situation. In this paper the first swing stability limit of only the critical machine (or critical group) is improved with the help of FACTS devices.

2. Improvement of First Swing Stability Limit by Using Shunt FACTS Devices

Consider a lossless SMIB with shunt FACTS devices as shown in Fig 1(a). the equivalent circuit of the system is shown in Fig1(b) where E^I and V represents the machine internal bus voltage and infinite bus voltage respectively.X_1 is the reactance between bus m and machine internal bus and X_2 is the reactance between bus m and infinite bus.

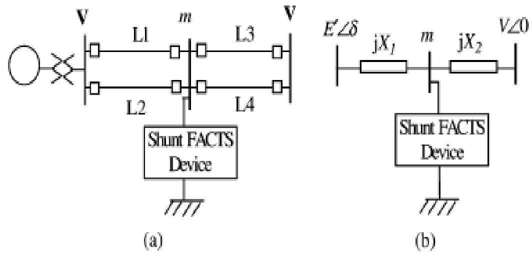

Fig.1.A SMIB system with a shunt FACTS device: (a) single line diagram and (b) equivalent circuit
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2.1 SVC

The static VAR compensator (SVC) is a shunt device of flexible ac transmission system (FACTS) family using power electronics to control power flow and improve transient stability on power grids. The SVC regulates voltage at its terminals by controlling the amount of reactive power injected into or absorbed from the power system. When system voltage is low, the SVC generates reactive power (SVC capacitive). When the system voltage is high, it absorbs reactive power (SVC inductive).

The equivalent susceptance B_{eq} is determined by the firing angle α of the thyristors. i.e., defined as the delay angle is measured from the peak of the capacitor voltage to the firing instant.

$$B_{eq} = B_l(\alpha) + B_c \qquad -(1)$$

Where $B_l(\alpha) = -\frac{1}{\omega l}\left(1 - \frac{2\alpha}{\pi} - \frac{\sin 2\alpha}{\pi}\right)$ - (2) ; $0^0 \leq \alpha \leq 90^0$

$$B_c = \omega c$$

If the real power consumed is assumed to zero then:

$$P_{SVC} = 0 \qquad -(3)$$

$$Q_{SVC} = -V^2 B_{SVC} \qquad -(4)$$

Where V is the bus voltage

As the reactive power demand at the bus varies, the susceptance is varied subjected to the limits. However, the reactive power is a function of square of the bus voltage. Hence the reactive power generated decreases as the bus voltage decreases.

The SVC can both absorb as well as supply reactive power at the bus it is connected to by control of the firing angle of the thyristor elements. By controlling the firing angle α of the thyristors (i.e., the angle with respect to the zero crossing of the phase voltage), the device is able to control the bus voltage magnitude. Changes in α results in changes on the currents and hence, the amount of reactive power consumed by the inductor. When $\alpha=90^0$, the inductor is fully activated but is deactivated when $\alpha=180^0$. The basic control strategy is typically to keep the transmission bus voltage within certain narrow limits defined by a control loop and the firing angle α ($90^0<\alpha<180^0$) limits.

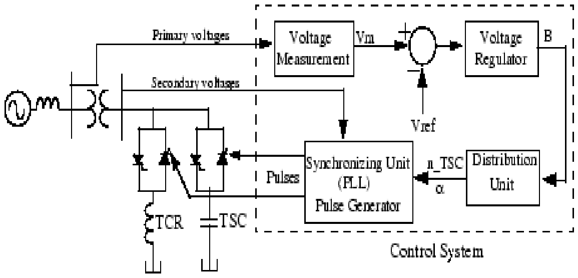


Fig.2: Single Line Diagram of SVC and its Control System Block Diagram

The control system consists of:

A measurement system: measuring the positive-sequence voltage to be controlled. A Fourier-based measurement system using a one-cycle running average is used. A voltage regulator: which uses the voltage error (difference between the measured voltage V_m and the reference voltage V_{ref}) to determine the SVC susceptance B needed to keep the system voltage constant. A distribution unit: which determines the TSCs (and eventually TSRs) that must be switched in and out, and computes the firing angle α of TCRs. A synchronizing system using a phase-locked loop (PLL) synchronized on the secondary voltages and a pulse generator that send appropriate pulses to the thyristors.

SVC can be modeled by a variable shunt susceptance B_{SVC} as shown in Fig:3(a).

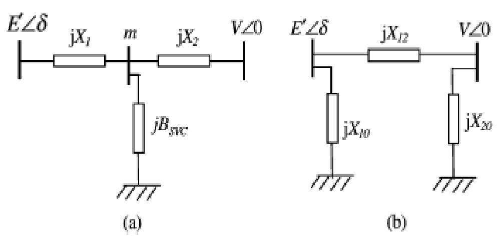


Fig.3. A SMIB system with a SVC

For given B_{SVC}, the transfer reactance X_{12} can be written as

$$X_{12} = X_1 + X_2 - B_{SVC} X_1 X_2 \qquad -(5)$$

The electrical output power P_e of the machine in Fig 3(b) is

$$P_e = \frac{E^I V}{X_{12}} \sin\delta \qquad -(6)$$

2.2 STATCOM

The power converter employed in the STATCOM can be either a voltage-source converter (VSC) or a current-source converter (CSC). In practice, however, the VSC is preferred because of the bidirectional voltage-blocking capability required by the power semiconductor devices used in CSCs.

The STATCOM regulates voltage at its terminals by controlling the amount of reactive power injected into or absorbed from the power system. When system voltage is low, the STATCOM generates reactive power (STATCOM capacitive). When the system voltage is high, it absorbs reactive power (STATCOM inductive).

The variation of reactive power is performed by means of a voltage sources converter (VSC) connected to the secondary of the coupling transformer. The VSC uses forced-commutated power electronic devices (GTOs or IGBTs) to synthesize a voltage V_2 from a DC voltage source.

The active and reactive power is transfer between a source V_1 and a source V_2. V_1 represents voltage to be controlled and V_2 is the voltage generated by the VSC

$$P = \frac{V_1 V_2 \sin\delta}{X} \qquad -(7)$$

$$Q = \frac{V_1(V_1 - V_2\cos\delta)}{X} \qquad -(8)$$

In steady state operation, the voltage V_2 generated by the VSC is in phase with V_1 (δ=0), so that only reactive power is flowing (P=0). If V_2 is lower than V_1, Q is flowing from V_1 to V_2 (STATCOM is absorbing reactive power). On the reverse, if V_2 is higher than V_1, Q is flowing from V_2 to V_1 (STATCOM is generating reactive power). The amount of reactive power is given by

$$Q = \frac{V_1(V_1 - V_2)}{X} \qquad -(9)$$

A capacitor connected on the DC side of the VSC acts as a Dc source. In steady state the voltage V_2 has to be phase shifted slightly behind V_1 in order to compensate for transformer and VSC losses and to keep the capacitor charged.

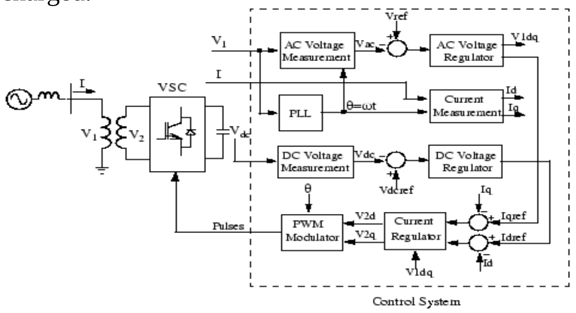
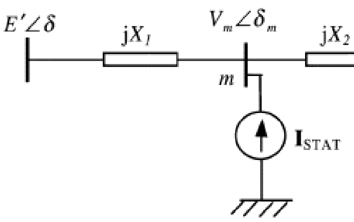


Fig.4: Single Line Diagram of STATCOM & its Control System Block Diagram

The control system consists of: A phase-locked loop (PLL): which synchronizes on the positive sequence component of the three-phase primary voltage V_1. The output of the PLL (angle θ=ωt) is used to compute the direct-axis and quadrature-axis components of the ac three-phase voltage and currents (labeled as V_d,V_q,I_d,I_q on the diagram). Measurement system: measuring the d and q components of AC sequence voltages and currents n to be controlled as well as the DC voltage V_{dc}. An outer regulation loop consisting of an AC voltage regulator and a DC voltage regulator. The output of the AC voltage regulator is the reference current I_{qref} for the current regulator (I_q= current in quadrature with voltage which controls reactive power flow). The output of the DC voltage regulator is the reference current I_{dref} for the current regulator (I_d=current in phase with voltage which controls active power flow). An inner regulation loop consisting of a current regulator. The output of the AC voltage regulator is the reference current I_{qref} for the current regulator (I_q=current in quadrature with voltage which controls reactive power flow). The output of the DC voltage regulator is the reference current I_{dref} for the current regulator (I_d=current in phase with voltage which controls real power flow).

A STATCOM can be represented by a shunt current source as shown in Fig :5.



(a)

Fig: 5. A SMIB system with a STATCOM

The STATCOM current is always in quadrature with its terminal voltage and can be written as (for capacitive mode of operation)

$$I_{STAT} = I_{STAT}\, e^{j(\delta_m - 90°)} \qquad -(10)$$

The voltage magnitude and angle of bus m are given by

$$V_m = \frac{E^I X_2 \cos(\delta-\delta_m) + V X_1 \cos\delta_m + X_1 X_2 I_{STAT}}{X_1+X_2} \qquad -(11)$$

$$\delta_m = \tan^{-1}\left(\frac{E^I X_2 \sin\delta}{V X_1 + E^I X_2 \cos\delta}\right) \qquad -(12)$$

For an inductive mode I_{STAT} can be replaced by $-I_{STAT}$.

The electrical output power P_e of the machine in Fig:4(a) can be written as

$$P_e = \frac{E^I X_2}{X_1+X_2}\sin(\delta-\delta_m) \qquad -(13)$$

3. Simulation Results

The control strategy of shunt FACTS devices is tested on both SVC and STATCOM placed in the SMIB system and 10-machine New England system. In all the cases, it is considered that the inductive rating of SVC is half of its capacitive rating. However, for STATCOM inductive and capacitive ratings are considered to be same.

TABLE-1
CCT FOR VARIOUS RATINGS OF SVC AND STATCOM

Results of SVC		Results of STATCOM	
B_{SVC}^{max} $(p.u)$	CCT(ms)	I_{STAT}^{max} $(p.u)$	CCT (ms)
0.00	67.7	0.00	67.7
0.25	96.9	0.25	104.5
0.50	119.2	0.50	130.4
0.75	137.9	0.75	151.1
1.00	154.5	1.0	168.4

3.1 Single Machine Infinite Bus System

The single line diagram of SMIB system shown in Fig: 1(a). A 3-phase fault on line L3 near bus m is considered and it is cleared by opening the line at both the ends. First the critical clearing time (CCT) of the fault is determined through equal area criterion for various ratings of shunt FACTS devices and results found are given in Table1. In determining the CCT, it is consider that the shunt FACTS devices are operating at full capacitive rating in early part of the post-fault period to maximize the decelerating area is used in counter balancing the accelerating area. Results of Table I indicate that the CCT of the fault without a shunt FACTS device is only 67.7ms and it is increases as the rating the device is increased. the reactive power associated with a SVC (STATCOM) can be represented by $V_m^2 B_{SVC}$ (V_m I_{STAT}). However, at a higher angle $V_{m,}$ decreases significantly and thus a STATCOM injects more reactive power (or transfer more accelerating power through the line) than that of SVC of similar rating. Hence STATCOM is capable of providing higher values of CCT than that of SVC.

Fig:6(a) shows the swing curve of the machine for critically stable (t_c (clearing time of fault) =119ms) and unstable (t_c=120ms) situations with a SVC of 0.5 pu. The variation of machine speed and SVC susceptance, for critically stable case is shown in Fig: 6(b). Unlike speed based control, the control strategy operates the SVC at its full capacitive rating beyond the zero speed to use the entire decelerating area. After wards, the control is switched to continuous type to improve the damping.

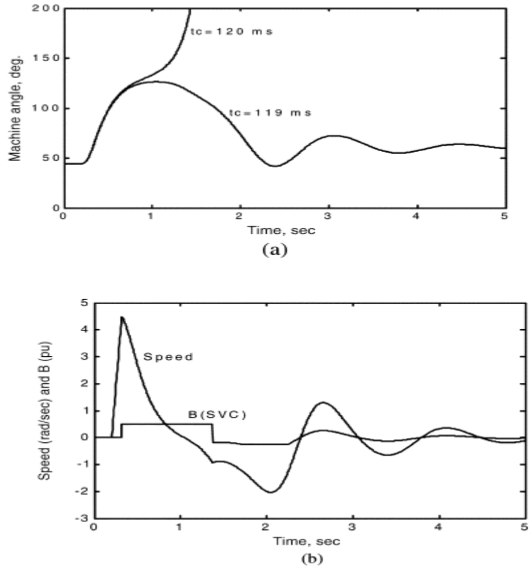


Fig.6. Results of SMIB system: (a) swing curves for critically stable and unstable situations; (b) variation of machine speed and SVC susceptance

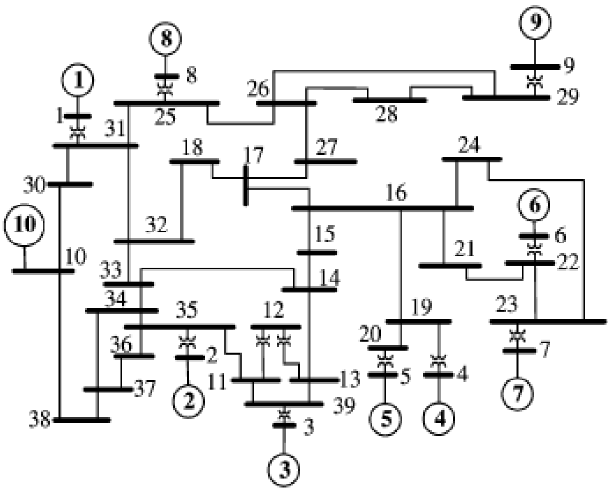


Fig.7. Single line diagram of the New England System

3.2. Multi-machine System

The control strategy of shunt FACTS devices is then applied to the 10-machine New England System. The single line diagram of the system is shown in Fig.7. In this system considering two symmetrical faults in two locations.

A 3-phase fault near bus 26 cleared by opening the line between buses 26 and 29 is considered. For this fault, machine-9 is found to be the most severely disturbed and is responsible to initiate the instability for an unstable situation. Shunt FACTS devices placed at bus 28 to improve the first swing stability of the system. The configuration of the system, for this fault case can be considered to be very similar to that of Fig:1 when the infinite bus is replaced by rest part of the system.

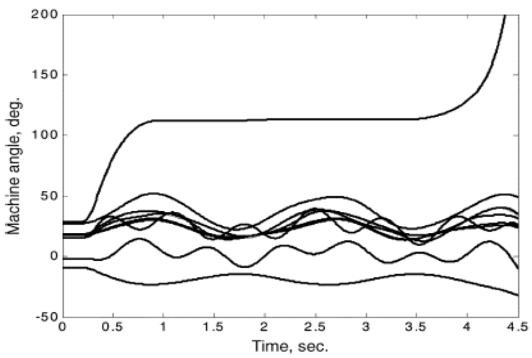


Fig:8 Swing curves of New England System without control

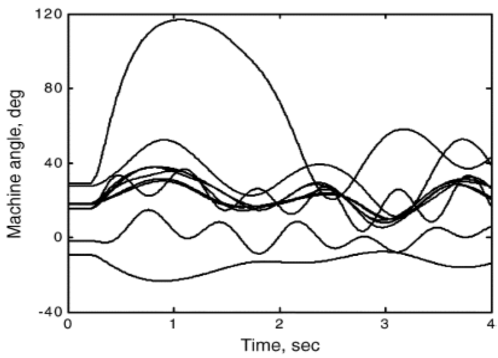


Fig:9 Swing curves of New England System with control

Fig:8 shows the swing curves of all the machines of the system for unstable situation and indicate that the machine 9 initially operates around the unequalibirium point for a long time ultimately the machine fails to remain in synchronism. Fig:9 shows the swing curves of all machines of the system for critically stable situation.

Another 3 phase fault at bus 18 cleared by opening the line between buses 18 and 32 is also studied. The first swing stability limit or CCT of the fault, without ant shunt FACTS device, is found as 235-236ms. Fig:10 Shows the swing curves of all machines of the system for t_c=235ms. And it indicates that machine 5 has the largest swing followed by machines 9 and 2 and other machines.

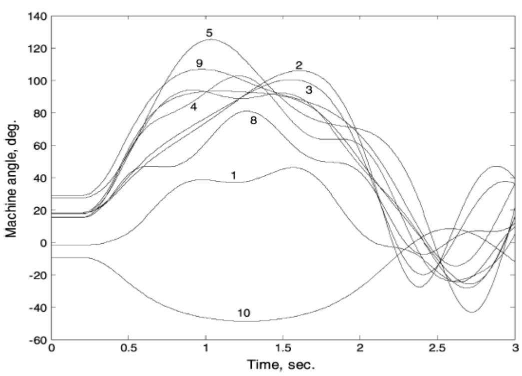


Fig:10 Swing curves of all machines for a 3 phase fault at bus 18

The first swing stability limit of the system with SVC placed at various locations and the results are summarized in Table II.

TABLE II
IMPROVEMENT OF FIRST SWING STABILITY LIMIT FOR A FAULT AT BUS 18

SVC at bus	CCT(ms)	Improvement of CCT(ms)
19	254-255	19
28	258-259	23
30	241-242	6
38	242-243	7

Result of Table II indicates that when the SVC is placed in the main power transfer path (buses 19 and 28) of the SDMs, it improves the first swing stability limit significantly. However, when the SVC is placed far away from the SDMs (buses 30 and 38), it may not improve the stability limit significantly.

4. CONCLUSION

The control strategy of shunt FACTS devices is tested on a single machine infinite bus (SMIB) system. The same control strategy is also applied to symmetrical faults in 10-machine 39-bus system. Simulation results indicated that the critical clearing time (CCT) obtained with the control is significantly higher than CCT without control. It was also observed that STATCOM can provide higher stability limit than that of a SVC of similar rating. In the 10-machine 39-bus system, the improvement of CCT is found to be very prominent when shunt FACTS device placed in a main power transfer path of severely disturbed machine.

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