



Analysis of transient stability in power systems with multiple shunt and series compensators

Çoklu seri ve paralel kompanzatorler ile güç sistemlerinde geçici kararlılık analizi

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Abstract

This study investigates the effect of multiple shunt and series compensators in transient stability case of a multi-machines power system. 22 bus multi machine real systems are modeled with Static Synchronous Compensator (STATCOM) and Static Synchronous Series Compensator (SSSC). The locations of the compensators are identified depending on the weak buses and transmission lines with highest voltage dip during transient cases. Transient stability cases are examined without STATCOM and SSSC, with STATCOM and SSSC multiple STATCOM and SSSC. Besides, Angular speeds of synchronous generators and variations voltage of buses are examined. Oscillations can decrease within short time with multiple STATCOM and SSSC in transient instability case.

Keywords: Transient stability, STATCOM, SSSC, Multi-Machines system

Öz

Bu çalışmada çok baralı bir güç sisteminin geçici kararlılık durumunda çoklu seri ve paralel kompanzatorlerin etkileri incelenmiştir. 22 bara çok makinalı gerçek sistemin Statik Senkron Kompazatör (STATCOM) ve Statik Senkron Seri Kompazatör (SSSC) ile modellemesi yapılmıştır. Kompanzatorlerin yerleşimi geçici durum esnasında hatlardaki en yüksek gerilim düşümüne ve zayıf baraya bağlı olarak belirlenmiştir. Geçici kararlılık durumu STATCOM and SSSC olmadığı durum, STATCOM and SSSC olduğu durum ve STATCOM and SSSC çoklu olduğu durumda incelenmiştir. Bunu yanısıra baraların gerilim değişimleri ve senkron generatorlerin açılma hız değişimleri incelenmiştir. Çoklu STATCOM and SSSC kullanımı ile geçici kararsızlık durumunda kısa zaman içerisinde salınımların azaldığı görülmüştür.

Anahtar kelimeler: Geçici kararlılık, STATCOM, SSSC, Çok-Makinalı sistem

1 Introduction

Power systems are very complex due to their interconnected structure. There may exist local, small scale problems in power systems as well as disruptive, system wide problems. System transients, inter-area oscillations and voltage collapses may be considered as examples of large scale problems. Flexible AC Transmission System (FACTS) controllers are developed and being utilized for a fast and flexible control to deal with those problems. With the advances in power electronics, voltage source inverter (VSI) based FACTS devices have shown better performance than other control devices. Primary VSI based controllers include shunt connected Static Synchronous Compensator (STATCOM), Static Synchronous Series Compensator (SSSC), and Unified Power Flow Controller (UPFC).

Many studies have been carried out on modeling and control schemes of FACTS controllers. Voltage regulation and rotor angle stability have been studied based on various critical clearing time and loading conditions [1-5]. Design and nonlinear coordinate controller for a STATCOM installed in infinite bus power system, and it shows that the proposed controller provides not only a coordinated control of ac-dc bus voltage but also good damping under transient conditions [6]. STATCOM modeling for voltage and angle stability studies has been given in [7]. The effect of control mode of SSSC, one of the inverter based FACTS, has been investigated in [8] and shown that SSSC operated in the permanent reactance control results in higher power oscillation damping, and synchronizing power limit than constant voltage mode. Similar results were

obtained in [9-10] in which the optimal control schemes are presented for dynamic series compensation and voltage regulation. It has been shown that SSSC is effective in improving rotor angle stability in infinite bus system and multi machine power systems [11]. Some of the studies dealing with series and shunt connected FACTS devices together are as follows: Dynamic operation of STATCOM and SSSC under various load excursions have been investigated in [12-13]. They are employed in analyzing steady-state and transient stability in an infinite bus system. While STATCOM provides voltage support, depending on the SSSC operation of control mode, they both are good at damping oscillations [14-19]. Application of STATCOM and SSSC on damping inter area oscillations are shown [20]. Optimal locations of various FACTS devices have been determined by using trajectory sensitivity analysis (TSA) [21]. A method is proposed to evaluate first swing stability of a large power system in the presence of FACTS [22]. A 20 machine system has been tested by observing machine angles and active reactive power changes. Another study conducted shows the impact of various FACTS devices on improving angle stability in the case of local and inter area oscillations [23].

This study examines the impact of multiple FACTS devices on a large power system. After a brief introduction of modeling of a multi-machine power system with FACTS devices, a procedure for transient stability analysis of a system with multiple FACTS devices is given. A multi-machine 22 bus system is used for this purpose. Various responses of the system against a three phase fault are analyzed and compared for cases with no device, single device and multi devices. The simulation studies show that the presence of multiple

STATCOM provides more damping for oscillations than multiple SSSC.

2 Modelling of multimachine power system

Before adding controllers to the system, n_g machine, n bus-power system is modeled where machines are represented by a conventional model. The swing equations are shown as follows ($i = n + 1, n + n_g$) [24].

$$\frac{d\delta_i}{dt} = w_s \Delta w_{r_i} \quad (1)$$

$$2H_i \frac{d\Delta w_{r_i}}{dt} = P_{m_i} - \sum_{j=1}^{n+n_g} |V_i| \times |V_j| \times \begin{bmatrix} G_{ij} \cos(\delta_i - \delta_j) \\ + B_{ij} \sin(\delta_i - \delta_j) \end{bmatrix} - KD_i \Delta w_{r_i} \quad (2)$$

The power flow equations are given depending on algebraic equations ($i = 1 \dots n$);

$$PL_i = \sum_{j=1}^n |V_i| \times |V_j| \times |Y_{ij}| \times \cos(\delta_i - \delta_j - \theta_{ij}) \quad (3)$$

$$2H_i \frac{d\Delta w_{r_i}}{dt} = P_{m_i} - \sum_{j=1}^{n+n_g} |V_i| \times |V_j| \times \begin{bmatrix} G_{ij} \cos(\delta_i - \delta_j) \\ + B_{ij} \sin(\delta_i - \delta_j) \end{bmatrix} - KD_i \Delta w_{r_i} \quad (4)$$

Where $Y_{ij} = |Y_{ij}| / \theta_{ij}$ obtained from the augmented Y_{BUS} matrix where the admittance corresponding to the transient reactance of the machines are included PL_i and QL_i are the real and reactive power loads, respectively, at the i^{th} bus [25-27].

3 Modelling of multiple STATCOM and SSSC

As shown in Figure 1, the STATCOM is connected in parallel with Bus i, while the SSSC is connected in series between Bus i and Bus j. They both consist of a voltage source converter connected by a coupling transformer to the system, therefore modelled as a controllable voltage source series with a leakage reactance excluding ohmic losses. By adjusting voltage, the reactive power can be controlled. The expressions for the current, reactive power injection, voltage and DC link voltage are given as,

$$I_s = \frac{V_s - V_{bus}}{jX_1} \quad (5)$$

$$Q_s = V_{bus}^2 \frac{V_s / V_{bus} - 1}{X_1} \quad (6)$$

$$V_{inj} = m \times k \times V_{dc} (\cos \delta - j \sin \delta) \quad (7)$$

$$I_s = I_d + jI_q \quad (8)$$

$$\frac{dV_{dc}}{dt} = \frac{m \times k}{C_{dc}} (I_d \cos \delta + I_q \sin \delta) \quad (9)$$

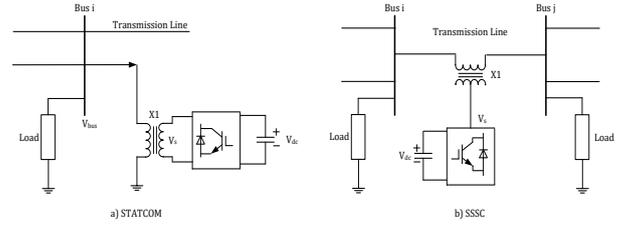


Figure 1: The STATCOM and SSSC circuit.

The active power equations with STATCOM connected to bus i can be given below:

$$P_i = P + \sum_{j=1}^N |V_i| \times |V_j| \times |Y_{kj}| \times \cos(\delta_k - \delta_j - \theta_{kj}) \quad (10)$$

$$Q_i = Q + \sum_{j=1}^N |V_i| \times |V_j| \times |Y_{kj}| \times \sin(\delta_k - \delta_j - \theta_{kj}) \quad (11)$$

Where active power (P) and reactive power (Q) are found to be:

$$P = G \times [V_k]^2 - [V_k] \times [E] \times [Y] \times \cos(\delta_k - \delta_j - \theta) \quad (12)$$

$$Q = -G \times [V_k]^2 - [V_k] \times [E] \times [Y] \times \sin(\delta_k - \delta_j - \theta) \quad (13)$$

Active and reactive power equations for SSSC can be stated as follows:

$$P_i = P_{ij} + \sum_{k=1}^N |V_i| \times |V_k| \times |Y_{ik}| \times \cos(\delta_i - \delta_k - \theta_{ik}) \quad (14)$$

$$Q_i = Q_{ij} + \sum_{k=1}^N |V_i| \times |V_k| \times |Y_{ik}| \times \sin(\delta_i - \delta_k - \theta_{ik}) \quad (15)$$

$$P_j = P_{ji} + \sum_{k=1}^N |V_j| \times |V_k| \times |Y_{jk}| \times \cos(\delta_j - \delta_k - \theta_{jk}) \quad (16)$$

$$Q_j = Q_{ji} + \sum_{k=1}^N |V_j| \times |V_k| \times |Y_{jk}| \times \sin(\delta_j - \delta_k - \theta_{jk}) \quad (17)$$

Dynamic equations for STATCOM and SSSC can be expressed as follows:

$$\frac{dI_d}{dt} = \frac{-R}{L} \times I_d + w \times I_p - \frac{1}{L} \times V_d + \frac{1}{L} \times E_d = 0 \quad (18)$$

$$\frac{dV_c}{dt} = \frac{-3}{2C_{dc}} (m_q \times I_q + m_d \times I_d) = 0 \quad (19)$$

$$\begin{bmatrix} I_q \\ I_d \end{bmatrix} = \begin{bmatrix} -R & \dots & -Lw \\ Lw & \dots & -R \end{bmatrix}^{-1} \times \begin{bmatrix} V_q \\ V_d \end{bmatrix} - \begin{bmatrix} -R & \dots & -Lw \\ Lw & \dots & -R \end{bmatrix}^{-1} \times \begin{bmatrix} E_q \\ E_d \end{bmatrix} \quad (20)$$

$$I_{qd} = Y_{qd} \times V_{qd} + I_{qd} \times E \quad (21)$$

Where, Δw_r per unit speed deviation, H inertia constant, w_s synchronous generator speed, P_m mechanical power input in per unit, δ_i the angular positions of the rotors, PL_i real power

loads, QL_i reactive power loads, X_1 leakage reactance of the coupling transformer, m modulation index, V_{dc} DC link voltage, I_d park transformation real line current, I_q park transformation reactive line current, Y admittance. Multiple STATCOM and SSSC are considered here as controllers. Admittance matrix (Y_t) given in equation 20 represents a general form of admittances having STATCOM connection in the first row, SSSC connection in the second row and n_g machine nodes in the last row.

$$Y_t = \begin{bmatrix} Y_{m2m1} & \dots & Y_{m2m2} & \dots & Y_{m2n} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ Y_{nm1} & \dots & Y_{nm2} & \dots & Y_{nn} \end{bmatrix} \quad (22)$$

where,

$$Y_{m1m1} = \begin{bmatrix} Y_{11} & \dots & Y_{12} & \dots & Y_{1m1} \\ Y_{21} & \dots & Y_{22} & \dots & Y_{2m1} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ Y_{m1} & \dots & Y_{1m1} & \dots & Y_{m1m1} \end{bmatrix} \quad (23)$$

$$Y_{m2m2} = \begin{bmatrix} Y_{(m1+1)(m1+2)} & \dots & Y_{(m1+1)(m1+4)} & \dots & Y_{(m1+1)(m1+m2)} \\ Y_{(m1+3)(m1+2)} & \dots & Y_{(m1+3)(m1+4)} & \dots & Y_{(m1+3)(m1+m2)} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ Y_{(m1+m2-1)(m1+2)} & \dots & Y_{(m1+m2-1)(m1+4)} & \dots & Y_{(m1+m2-1)(m1+m2)} \end{bmatrix} \quad (24)$$

As can be seen from the matrices, diagonal elements (Y_{m1m1} , Y_{m2m2}) are the elements affected by the installation of the FACTS devices [28]. For the stability analysis, in synchronous generator the sixth order model is used. The equations can be written as,

$$\delta = f_b(\omega - 1) \quad (25)$$

$$\omega = (P_m - P_e - D(\omega - 1)) / M \quad (26)$$

$$\dot{e}_q = -\dot{e}_q - \left(x_d - x_d' - \frac{T_{d0}^* x_d}{T_{d0} x_d'} (x_d - x_d') \right) i_d + \left(1 - \frac{T_{AA}}{T_{d0}} v_f^* \right) / T_{d0} \quad (27)$$

$$\dot{e}_d = (-f_s(e_d)) + \left(x_q - x_q' - \frac{T_{q0}^* x_q}{T_{q0} x_q'} (x_q - x_q') \right) i_q / T_{q0} \quad (28)$$

$$\dot{e}_q = (-\dot{e}_q + \dot{e}_q - \left(x_d - x_d' + \frac{T_{d0}^* x_d}{T_{d0} x_d'} (x_d - x_d') \right) i_d + \frac{T_{AA}}{T_{d0}} v_f^*) / T_{d0} \quad (29)$$

$$\dot{e}_d = (-\dot{e}_d + \dot{e}_d + \left(x_q - x_q' + \frac{T_{q0}^* x_q}{T_{q0} x_q'} (x_q - x_q') \right) i_q) / T_{q0} \quad (30)$$

Where f_b is the fundamental frequency base, P_m the mechanical power, M the mechanical starting time, D the damping coefficient, x_d and x_q the d-q axes synchronous

reactance, x_d' and x_q' the d-q axes transient reactance, x_d'' and x_q'' the d-q axes sub transient reactance, T_{d0}' and T_{q0}' the d-q axes open circuit transient time constant, T_{d0}'' and T_{q0}'' d-q axes open circuit sub transient time constant, T_{AA} d-axis additional leakage time constant, i_d and i_q d-q axes current, δ the rotor angle, w the rotor speed, v_f the field voltage, e_d' and e_q' d-q axes transient voltage, e_d'' and e_q'' d-q axes sub transient voltage [29].

4 Analysis approach

The load flow analysis is required for transient stability analyses. The results of the load flow are important for making decision in applying fault and determining the location of the compensators. The following steps are considered in analyzing transient stability effects of the system with multi compensators.

Level 1) Perform load flow,

Level 2) List the buses from the lowest voltage to the highest voltage based on the load flow results,

Level 3) List the lines according to their voltage drop, from the highest to the lowest based on the load flow results,

Level 4) Perform fault analysis by creating a three phase fault on the bus with the lowest voltage to show the severe impact,

Level 5) Locate a shunt compensator on the bus with the second lowest voltage,

Level 6) Locate a series compensator between the bus with the second lowest voltage and the neighboring bus, seeking that the highest voltage drop exists on the lines between those buses,

Level 7) Locate other shunt compensators on the buses according to the bus list determined in Level 2 and Level 5,

Level 8) Locate other series compensators between buses according to the line list given in Level 3 and Level 6.

5 Simulation study

The simulation study of a real based multi generator has been shown in Figure 2. In a real based multi generator 14 load buses and 7 generator buses take place [30].

Owing to continuous power flow, while Bus 8 was determined as the lowest voltage, the lines between buses 5-7 and 9-17 buses 9-17 were determined as highest two voltage dips. A three phase fault occurs between the time period of 0.2s and 0.35s. Breakers are placed between buses 7 and 8.

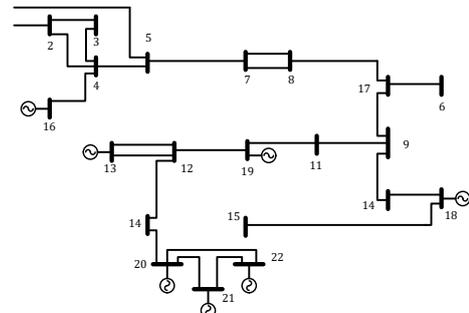


Figure 2: 7 machine 22 bus system.

Circuit breakers located at buses 7 and 8 have been set to open at 5 cycles.

Without STATCOM and SSSC, with STATCOM and SSSC, multiple STATCOM and SSSC in the faulted system are analyzed. Scenarios studied are given below:

1. A single shunt FACTS, A 100MVA STATCOM at bus 5,
2. A single series FACTS, A 100MVA SSSC between buses 5 and 7,
3. Multiple shunt FACTS, A 100MVA STATCOM at bus 5 and a 100MVA STATCOM at bus 7,
4. Multiple series FACTS, A 100MVA SSSC between buses 5-7 and a 100MVA SSSC between buses 9-17.

6 Simulation results

After the weakest bus is determined in the system, a three phase fault is created at that bus. The variation of angle, angular speed, active- reactive power of generators and load bus voltages are shown in Figure 3 and Figure 4, when there is no compensator connected to the system.

As can be seen from those figures, angular speed of some machines show unstable behavior without any controller. Bus voltages are not recovered after the fault is cleared. In order to recover the stability of the system, first single STATCOM and SSSC later, multi STATCOM and SSSC are integrated into the system as explained before. Results obtained from analyses of the system with single vs. multiple STATCOM and SSSC are given in Figure 3 to Figure12,

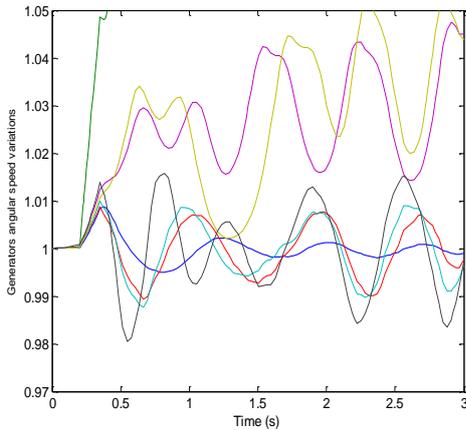


Figure 3: Variations of angular speed without FACTS.

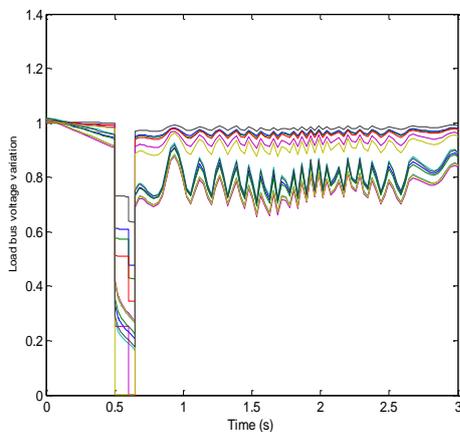


Figure 4: Variations of bus voltage without FACTS.

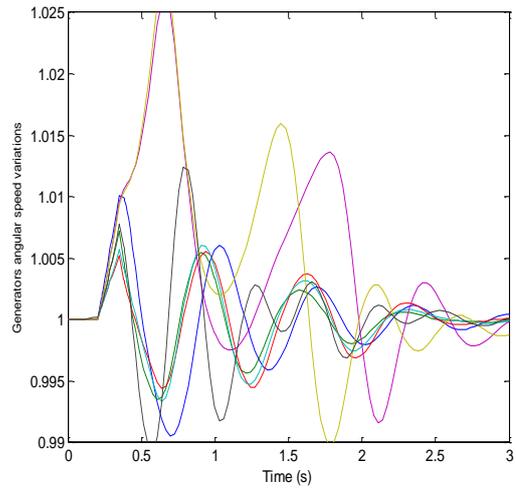


Figure 5: Variations of angular speed with single SSSC.

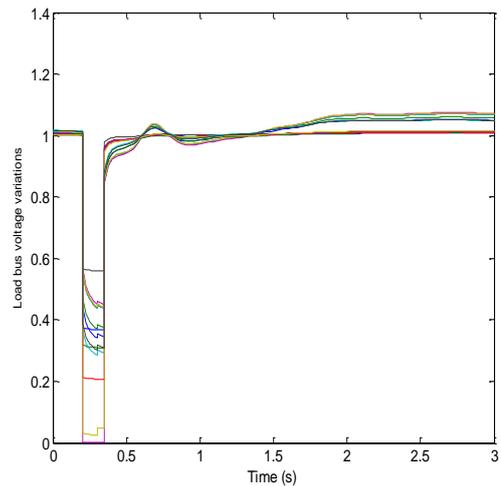


Figure 6: Variations of bus voltage with single SSSC.

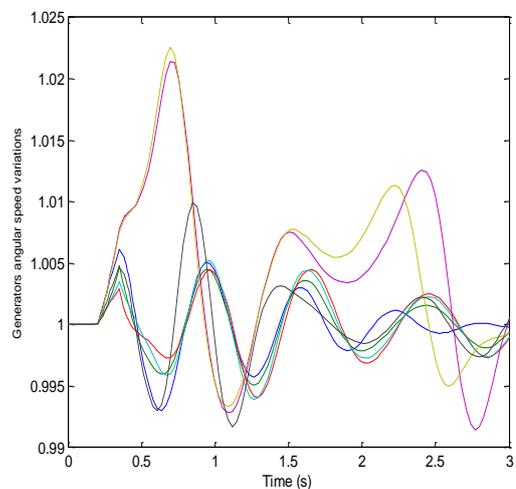


Figure 7: Variations of angular speed with single STATCOM.

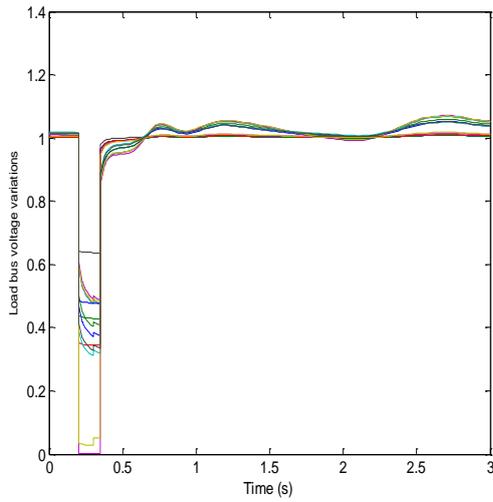


Figure 8: Variations of bus voltage with single STATCOM.

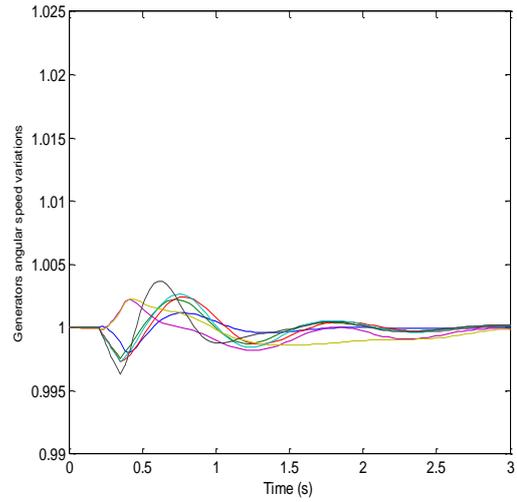


Figure 11: Variations of angular speed with multiple STATCOM.

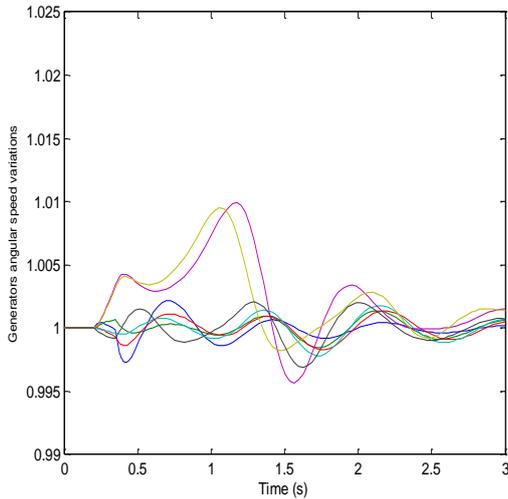


Figure 9: Variations of angular speed with multiple SSSC.

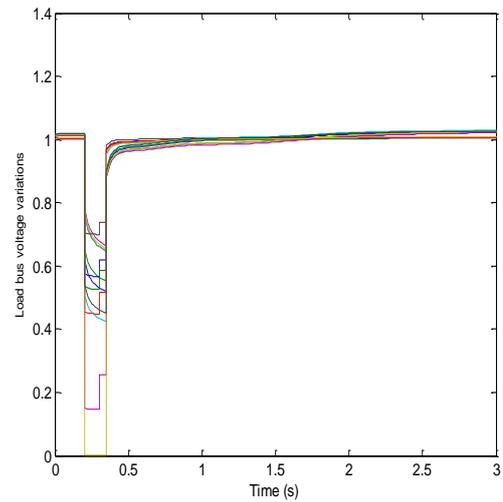


Figure 12: Variations of bus voltage with multiple STATCOM.
The following remarks can be drawn from the simulation results shown in Figure 5 to Figure 12.

1. Adding single compensators into the system can make the system more stable,
2. Oscillations in angular speed, angle and power variations are damped in the system with single STATCOM and SSSC,
3. A 100 MVA SSSC can improve the system stability, but its response is late when compared to a single STATCOM case,
4. Multi STATCOM case is more effective than the multi SSSC case in angle stability and in damping active power oscillations,
5. Having multi compensator integrated into the system has resulted in stability in a shorter time.

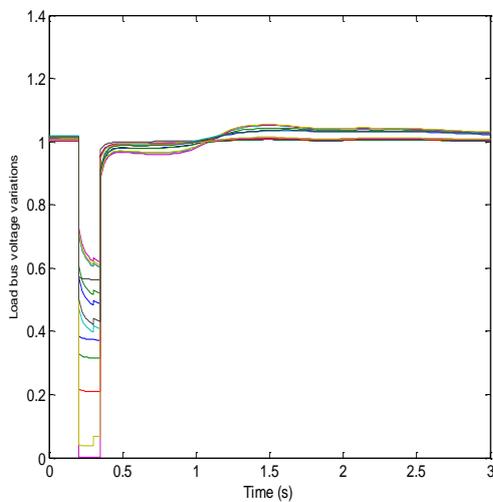


Figure 10: Variations of bus voltage with multiple SSSC.

Generator angular speed and bus voltage without STATCOM were stabilized in nearly 5 seconds and 3.4 seconds after 3 phase fault, respectively.

Generator angular speed and bus voltage with STATCOM were stabilized in nearly 3.1 seconds and 3 seconds after 3 phase fault, respectively. Generator angular speed and bus voltage with multi-STATCOM were stabilized in nearly 2.6 seconds and 1 second after 3 phase fault, respectively. Generator angular speed and bus voltage without SSSC were stabilized in nearly 5 seconds and 3.4 seconds after 3 phase fault, respectively.

Generator angular speed and bus voltage with SSSC were stabilized in nearly 3.2 seconds and 2.2 seconds after 3 phase fault, respectively. Generator angular speed and bus voltage with multi-SSSC were stabilized in nearly 2.9 seconds and 1.5 seconds after 3 phase fault, respectively.

While time responses of the variables are shown in Table 1, System parameter values are shown in Table 2. When there is no compensator in the system, the system reaches the stable mode in a long period of time depending on the excitation control of the machines. The best time response is achieved with the multiple STATCOM case.

Table 1: Time response of the variables.

Variables	Time response (s)				
	Without FACTS	With STATCOM	With SSSC	Multiple STATCOM	Multiple SSSC
Generator angular speed	5.00	3.10	3.20	2.60	2.90
Load bus voltage	3.40	3.00	2.20	1.00	1.50

Table 2: System parameter values.

Parameter value	Generator	STATCOM	SSSC
Power	500 MVA	Power (100 MVA)	Power (100 MVA)
Ra	0.0031 ohm	Current Control (Kp=50, Ki=0.1)	Operation Mod Constant voltage
Xa	0.2 ohm	Max.-Min Current (1.2 p.u.-0.8 p.u.)	Seri Compensation rate (%25)
Xd	1.05 ohm	-	Regulator Time Constant (0.025)
X'd	0.185 ohm	-	Max-Min Voltage (1.15-0.00 p.u.)
X''d	0.13 ohm		
Xq	0.98 ohm		
X'q	0.36 ohm		
X''q	0.13 ohm		
Inertia	13.08		
Damping	2 p.u.		

7 Conclusion

This study aims to examine the effect of multiple controllers on transient stability of a multi machine power system. Shunt and series controllers are connected to a real based 7 machine-22 bus system. A procedure for locating shunt and series compensators is explored in this study. Effects of those controllers on the system parameters are observed under transient conditions. System parameters are selected to be generator angular speed and bus voltages. While some machines in the system show unstable behavior with no compensator, the system stability is maintained with controllers' action. Oscillations are damped with the use of single STATCOM and SSSC easily, but it is achieved in a longer time of period causing unreliable energy usage. The utilization of multi compensators is, however, more effective in making the system stable in a shorter time. Another conclusion drawn from this study is that the system with multi STATCOM shows better time response than the system with multi SSSC in damping oscillations.

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