COMPARATIVE ANALYSIS OF SVC AND STATCOM FOR DAMPING POWER SYSTEM LOW FREQUENCY ELECTROMECHANICAL OSCILLATIONS

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Abstract – **This work investigates the effects of two FACTS devices, namely SVC (Static VAR Compensator) and STATCOM (Static Synchronous Compensator), on small-signal power systems angle stability. This investigation is carried out for a single machine connected to an infinite bus via a reactive transmission line. The study is based on investigation of the eigenvalues of the linearized power system model in the framework of dynamic bifurcation theory. The presented simulations results enable a comparative analysis of the effects of these two controllers on power systems low frequency electromechanical oscillations damping.**

KEYWORDS

Angle stability, dynamic modes of instability, bifurcations, FACTS, SVC, STATCOM.

I. LOW FREQUENCY ELECTROMECHANICAL OSCILLATIONS

A phenomenon that is of great concern in the planning and operation of modern interconnected power systems is the low frequency electromechanical oscillations. These oscillations are consequences of the generators dynamical interactions when the system is subjected to disturbances. Common load fluctuations can lead to its appearing. These oscillations are more evident like synchronizing power flow oscillations and can be a direct consequence of the dynamical interactions between generators groups (one group oscillates against another), or between a generator (or group of generators) and the rest of the system. The first case establishes inter-area mode oscillations, and the second, local mode oscillations. The frequency range is 0.1 to 0.8 Hz for inter-area modes, and 1.0 to 2.0 Hz for local modes. These modes are worth paying attention because they have low natural damping, and it can be either very reduced or negative, mainly due to the voltage regulator action. This may have disastrous consequences to the interconnected systems stability, leading to partial or total collapses (black-outs).

The most common control action in use today to circumvent these problems employs Power Systems Stabilizers (PSS). The function of this device is to extend stability limits by modulating generator excitation to provide damping to the electromechanical oscillations. However, other effective solution such as the use of FACTS (Flexible AC Transmission Systems) devices to damp low frequency electromechanical oscillation is being considered. These devices allow the useable transmission capacity increase as well as the control of the power flow over designed transmission routes [4], [9].

This work presents a comparative study of the effects of two FACTS devices, namely, SVC and STATCOM, on power system electromechanical oscillations damping. The investigation is carried out for a single machine infinite bus system with the inclusion of these two FACTS devices.

II. FACTS DEVICES

Much attention has been paid to FACTS devices in the last years. The first applications of this technology have begun with the SVC utilization TCR – based (Thyristor- Controlled Reactor) with either fixed or switched capacitors thyristor-controlled (TSC – Thyristor-Capacitor Controlled). Nevertheless, more recent advances in the framework of power electronics have allowed the use of new generation FACTS devices, such as voltage source converter based (VSC – Voltage Source Converter) with the GTO (Gate-Turn-off) technology. In this technology are the STATCOM, SPFC (Static Power Flow Controller), SPS (Static Phase Shifter), UPFC (Unified Power Flow Controller), etc [5].

III. POWER SYSTEM MODEL

- **SVC**

A practical model of a SVC is a controllable reactor and a fixed capacitor. Throughout an adequate coordination of the capacitors and the reactor controller, the bus reactive power injected (or absorbed) by the SVC can be continually varied in order to control the voltage, to maintain the suitable power flow in the transmission network either over normal operating or disturbances conditions.

The analysis of the SVC influence on damping local mode oscillations in electrical power systems is accomplished for the single machine infinite bus system with an intermediate bus, in which the SVC is connected, as shown in Figure 1. This intermediate bus is located in the transmission line medium point, because this is the best place to reactive compensation, since the voltage sag is deepest in this point in a non-compensated line [5].

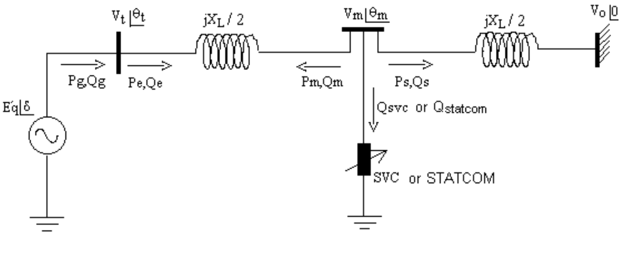

Figure 1 – Single machine infinite bus system with FACTS devices

The following equations describe the SVC model [1]:

$$Q_{SVC} = B_{svc} V_m^{\ 2}$$

$$B_{svc} = \frac{K_{SVC}}{(1 + sT_{SVC})} \left(V_{mref} - V_m \right) \tag{1}$$

The power system electromechanical stability problem can be represented by a set of differential and algebraic equations, as follows,

$$\dot{x} = f(x, y, \mu)$$

$$0 = g(x, y, \mu) \tag{2}$$

where x is a vector of dynamic state variables and y is a vector of algebraic variables, and μ is a parameter, which can be varied slowly, such as nodal powers. For small-signal stability analysis, we assume the system parameter variation is slow enough so that the model can be linearized around some equilibrium point as,

$$\Delta\dot{x} = J_1 \Delta x + J_2 \Delta y + B \Delta u$$

$$0 = J_3 \Delta x + J_4 \Delta y \tag{3}$$

where J_1, J_2, J_3 and J_4 are Jacobian matrices of f and g related to dynamic state and algebraic variables, respectively, and B is the perturbation matrix. For the system shown in Figure 2, the following state equations can be formulated according to nodal power balance methodology [3], [8]:

$$\begin{bmatrix} \Delta\dot{\omega} \\ \Delta\dot{\delta} \\ \Delta\dot{E}_q' \\ \Delta\dot{E}_{FD} \\ \Delta\dot{B}_{SVC} \end{bmatrix} = \underbrace{\begin{bmatrix} 0 & -\frac{A_{1g}}{M} & -\frac{A_{2g}}{M} & 0 & 0 \\ \omega_0 & 0 & 0 & 0 & 0 \\ 0 & -\frac{K_A}{T_{d0}'} & -\frac{x_d}{x_d' T_{d0}'} & \frac{1}{T_{d0}'} & 0 \\ 0 & 0 & 0 & -\frac{1}{T_e} & 0 \\ 0 & 0 & 0 & 0 & -\frac{1}{T_{SVC}} \end{bmatrix}}_{J_1} \cdot \begin{bmatrix} \Delta\omega \\ \Delta\delta \\ \Delta E_q' \\ \Delta E_{FD} \\ \Delta B_{SVC} \end{bmatrix} + \underbrace{\begin{bmatrix} \frac{A_{1g}}{M} & 0 & -\frac{A_{3g}}{M} & 0 \\ 0 & 0 & 0 & 0 \\ \frac{K_A}{T_{d0}'} & 0 & \frac{K_V}{T_{d0}'} & 0 \\ 0 & 0 & -\frac{K_e}{T_e} & 0 \\ 0 & 0 & 0 & -\frac{K_{SVC}}{T_{SVC}} \end{bmatrix}}_{J_2} \cdot \begin{bmatrix} \Delta\theta_t \\ \Delta\theta_m \\ \Delta V_t \\ \Delta V_m \end{bmatrix}$$

$$\begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} = \underbrace{\begin{bmatrix} 0 & A_{1g} & A_{2g} & 0 & 0 \\ 0 & R_{1g} & R_{2g} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -V_m^2 \end{bmatrix}}_{J_3} \cdot \begin{bmatrix} \Delta\omega \\ \Delta\delta \\ \Delta E_q' \\ \Delta E_{FD} \\ \Delta B_{SVC} \end{bmatrix} + \underbrace{\begin{bmatrix} -A_{1g} - A_{1e} & A_{1e} & A_{3g} - A_{2e} & -A_{3e} \\ -R_{1g} - R_{1e} & R_{1e} & R_{3g} - R_{2e} & -R_{3e} \\ A_{1m} & -A_{1m} - A_{1s} & -A_{2m} & -A_{3m} - A_{2s} \\ R_{1m} & -R_{1m} - R_{1s} & -R_{2m} & -R_{3m} - R_{2s} - 2B_{SVC} V_m \end{bmatrix}}_{J_4} \cdot \begin{bmatrix} \Delta\theta_t \\ \Delta\theta_m \\ \Delta V_t \\ \Delta V_m \end{bmatrix} \tag{4}$$

The coefficients A and R represent local sensitivity functions of active and reactive powers, respectively. They are related to the state variables and their expressions are presented in [8]. Eliminating the vector of algebraic variables, provided det $J_4 \neq 0$, the state-space system can be obtained as

$$\Delta\dot{x} = A \Delta x + B \Delta u \tag{5}$$

where

$$A = J_1 - J_2 J_4^{-1} J_3 \,.$$

is the system state matrix.

- **STATCOM**

The STATCOM integrates the SVC technique and the voltage source conversion, and is a novel concept to reactive power control. This novel technology, whether compared with conventional compensation methods using TCR and TSC (like SVC), shows a superior performance and best applicability to angle stability and harmonic control. The STATCOM considered here is analogous to an ideal rotating synchronous condenser operating under no load conditions, generating a balanced three-phase voltage, with controlled amplitude and angle. This ideal machine does not have inertia, and its response velocity is almost instantaneous, and does not affect the system impedance. Therefore, it can generate and absorb reactive power. Besides, it can exchange active power with the system if coupled to an appropriate energy source, and can supply to or absorb active power from the system [2], [4]. The functional model of the STATCOM is shown in Figure 2. If this function is not explored, the STATCOM becomes a reactive power generator, and the supply energy source can be eliminated [4].

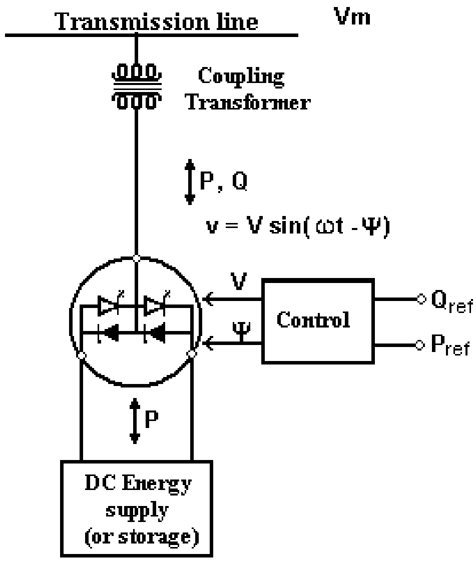

Figure 2 – STATCOM functional model

The STATCOM may be represented by the following set of equations [2]:

$$Q_{STATCOM} = I_s V_m \tag{6}$$

$$I_S = -\frac{K_{STATCOM} . K_u}{(1 + sT_{STATCOM})} \left(V_{mref} - V_m \right) + \frac{K_{STATCOM} . K_\omega}{(1 + sT_{STATCOM})} \left(\omega_{ref} - \omega \right) \tag{7}$$

Equation (7) can be linearized, resulting in the following dynamic equation:

$$\Delta \dot{I}_s = \frac{1}{T_{STATCOM}}\left(-\Delta I_s + K\Delta u\right) \tag{8}$$

Let the output of the STATCOM controller be:

$$\Delta u = -K_u \Delta V_m + K_\omega \Delta\omega \tag{9}$$

where K_u and K_ω are the gains of voltage and damping control loop, respectively.

An important remark is that the remote signal $\Delta\omega$ may not be readily available to the STATCOM, but it can be either synthesized from local measures or received from a communication system. The characteristic Voltage x Current of the STATCOM and SVC can be seen in Figure 3.

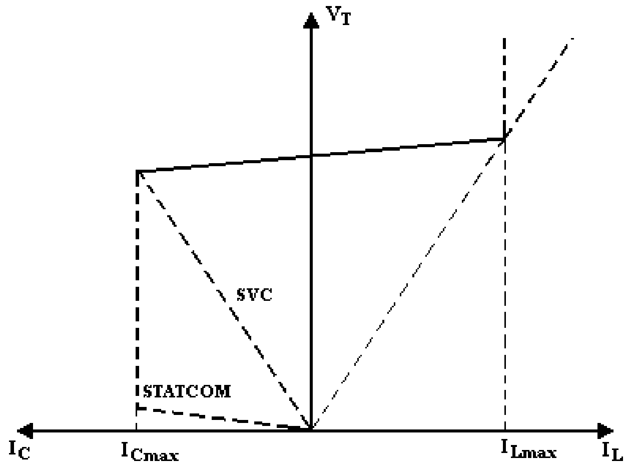

Figure 3 – V x I characteristics of SVC and STATCOM

For the STATCOM case, the following state representation can be obtained:

$$\begin{bmatrix} \Delta\dot{\omega} \\ \Delta\dot{\delta} \\ \Delta\dot{E}_q' \\ \Delta\dot{E}_{FD} \\ \Delta\dot{I}_S \end{bmatrix} = \underbrace{\begin{bmatrix} 0 & -\frac{A_{1g}}{M} & -\frac{A_{2g}}{M} & 0 & 0 \\ \omega_0 & 0 & 0 & 0 & 0 \\ 0 & -\frac{K_A}{T_{d0}'} & -\frac{x_d}{x_d' T_{d0}'} & \frac{1}{T_{d0}'} & 0 \\ 0 & 0 & 0 & -\frac{1}{T_e} & 0 \\ \frac{K_\omega . K_{STATCOM}}{T_{STATCOM}} & 0 & 0 & 0 & -\frac{1}{T_{STATCOM}} \end{bmatrix}}_{J_1} . \begin{bmatrix} \Delta\omega \\ \Delta\delta \\ \Delta E_q' \\ \Delta E_{FD} \\ \Delta I_S \end{bmatrix} + \underbrace{\begin{bmatrix} \frac{A_{1g}}{M} & 0 & -\frac{A_{3g}}{M} & 0 \\ 0 & 0 & 0 & 0 \\ \frac{K_A}{T_{d0}'} & 0 & \frac{K_V}{T_{d0}'} & 0 \\ 0 & 0 & -\frac{K_e}{T_e} & 0 \\ 0 & 0 & 0 & -\frac{K_{STATCOM} . K_u}{T_{STATCOM}} \end{bmatrix}}_{J_2} . \begin{bmatrix} \Delta\theta_t \\ \Delta\theta_m \\ \Delta V_t \\ \Delta V_m \end{bmatrix}$$

$$\begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} = \underbrace{\begin{bmatrix} 0 & A_{1g} & A_{2g} & 0 & 0 \\ 0 & R_{1g} & R_{2g} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -V_m \end{bmatrix}}_{J_3} . \begin{bmatrix} \Delta\omega \\ \Delta\delta \\ \Delta E_q' \\ \Delta E_{FD} \\ \Delta I_S \end{bmatrix} + \underbrace{\begin{bmatrix} -A_{1g} - A_{1e} & A_{1e} & A_{3g} - A_{2e} & -A_{3e} \\ -R_{1g} - R_{1e} & R_{1e} & R_{3g} - R_{2e} & -R_{3e} \\ A_{1m} & -A_{1m} - A_{1s} & -A_{2m} & -A_{3m} - A_{2s} \\ R_{1m} & -R_{1m} - R_{1s} & -R_{2m} & -R_{3m} - R_{2s} - I_S \end{bmatrix}}_{J_4} . \begin{bmatrix} \Delta\theta_t \\ \Delta\theta_m \\ \Delta V_t \\ \Delta V_m \end{bmatrix} \tag{10}$$

It is worth noting that the component of line 5 and column 1 of the matrix J_1 is equal to zero only if no supplementary stabilizing signal is used.

VI. SIMULATIONS AND RESULTS

The system of Figure 1 is simulated over a range of operating points. The parameters are found in appendix A. The small signal angle stability assessment is performed by monitoring the eigenvalues of matrix *A* as the system loading is increased. Figures 4 and 5 illustrate the critical eigenvalues loci of state matrix system without and with SVC for a loading increase up to 1.3 p.u. As can be seen, the Hopf bifurcation does not occur for the system with SVC.

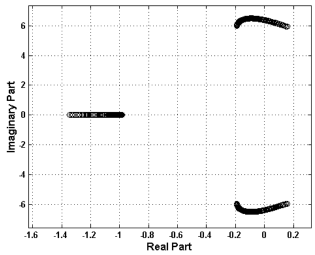

Figure 4 – Eigenvalues loci

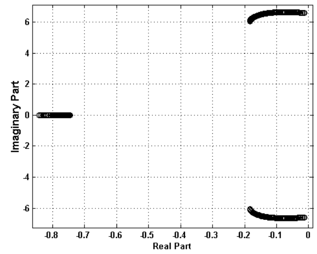

Figure 5 – Eigenvalues loci

Figures 6 and 7 show that for a loading increase up to 1.4 p.u., the Hopf bifurcation occurs for the system with SVC (Figure 6), but not for the system with STATCOM (Figure 7).

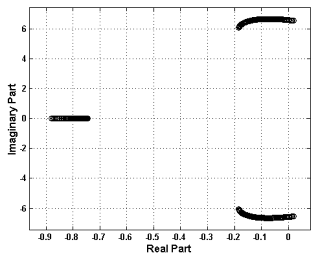

Figure 6 – Eigenvalues loci

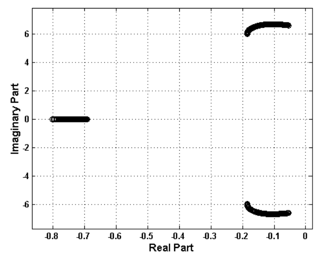

Figure 7 – Eigenvalues loci

At last, for the loading up to 1.7 p.u., Figures 8 and 9 illustrate that the Hopf bifurcation occurs for the system with STATCOM, but not for the system with speed deviation feedback.

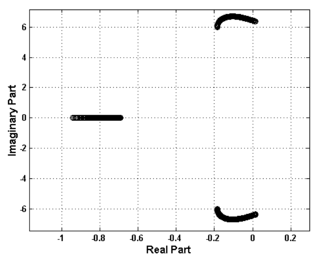

Figure 8 – Eigenvalues loci

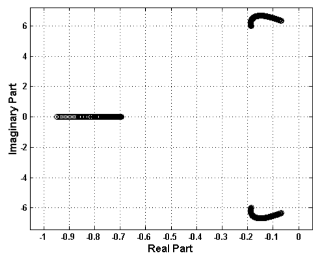

Figure 9 – Eigenvalues loci

Figures 10 and 11 show the real part of the critical eigenvalues as the system loading is increased. As can be seen, these Figures show that the STATCOM provides better effectiveness than the SVC in keeping system angular stability.

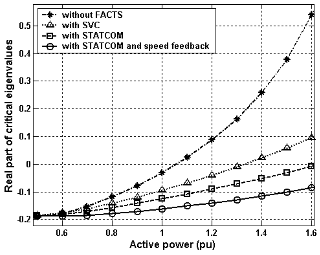

Figure 10 – Real eigenvalues loci

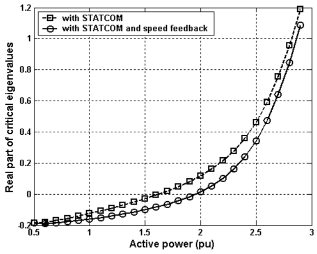

Figure 11 – Real eigenvalues loci

Table 1 shows the exact instability limit for each case.

Table 1: Instability limit (pu.)

without FACTS	with SVC	with STATCOM	with STATCOM
1.06	1.33	1.62	1.95*

* with supplementary speed deviation feedback control

Figures 12 and 13 show the step response for loading increase up to 1.4 p.u. and 1.5 p.u.

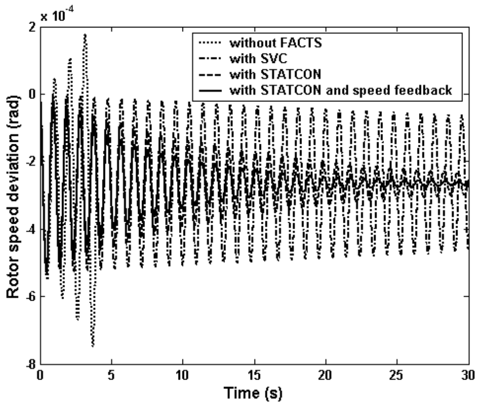

Figure 12 – Step response

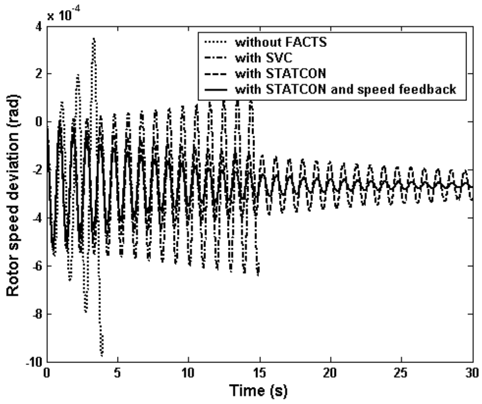

Figure 13 – Step response

The results presented in Figures 4-13 and in Table 1 show that the STATCOM exhibits a better performance than the SVC in damping power system oscillations.

VII. CONCLUSIONS

This work has examined the effects of the SVC and the STATCOM on power systems low frequency electromechanical oscillations. The studies of these two FACTS devices were conducted using eigenvalues analysis and bifurcation theory. The simulations results presented show that the STATCOM provides better effectiveness than the SVC in keeping small-signal angle stability.

VIII. APPENDIX A

Table 2 – Generator, AVR and transmission line parameters

M	D	R_e (pu)	x_d (pu)	x'_d (pu)	x_q (pu)	T'_{d0} (s)	K_e	T_e (s)	x_e (pu)
0.0	0.0	0.0	1.6	0.32	1.55	6.0	12.5	0.05	0.1

Table 3 – SVC and STATCOM parameters

k_{svc} (pu)	T_{svc} (s)	$K_{statcon}$	K_u	K_ω	$T_{statcom}$
20	0.05	1.0	100	100	0.005 s

IX. APPENDIX B

E generator voltage
δ generator rotor angle
ω generator rotor speed
E'_q quadrature axis winding voltage
E'_d direct axis winding voltage
E_{FD} field voltage
M Inertia constant
x_d direct axis reactance
x'_d transient direct axis reactance
x_q quadrature axis reactance
T'_{do} transient open-circuit direct axis time constant
K_e AVR gain
T_e AVR time constant
x_e transmission line reactance
V_m bus m voltage
V_t bus t voltage
θ_m bus m angle
θ_t bus t angle

X. REFERENCES

[1] Canizares, C. A., Faur, Z. T., "Analysis of SVC and TCSC controllers in Voltage Collapse", Power systems, IEEE Transactions on, Volume: 14 Issue:1, Feb 1999, Page(s): 158-165.

[2] Chun, L., Qirong, J., Xiarong, X., Zhonghong, W., "Rule-Based Control for STATCOM to Increase Power System Stability", Power System Technology, 1998. Proceedings. POWERCON '98. 1998 International Conference on, Volume 1, 18-21 Aug 1998. Page(s): 372-376.

[3] Deckmann, S. M. & da Costa, V. F., 1994, "A Power Sensitivity Model for Electromechanical Oscillation Studies", *IEEE Transactions on Power Systems*; Vol. 9, No. 2, pp. 965-971.

[4] Gyugyi, L., "Converter-Based FACTS Controlers", IEE Colloquium, 23 Nov. 1998, pp. 1-11.

[5] Hingorani, N. G. & Gyugyi, L. 2000, "Understanding FACTS: Concepts and Technology of Flexible AC Transmission Systems", Jon Wiley & Sons.

[6] Kimbark, E. W., 1956, "Power System Stability", John Wiley & Sons.

[7] Kundur, P., 1993, "Power System Stability and Control", Mc Graw – Hill, 1176p.

[8] Moreira, C. M., [1997], (in portuguese) "A Power Sensitivity Model for Voltage Stability Analysis", MSc Thesis, UNICAMP.