A PROCEDURE FOR TUNING STATCOM PARAMETERS FOR DAMPING POWER SYSTEM OSCILLATIONS

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Abstract: This work investigates the effects of the STATCOM (Static Synchronous Compensator), a FACTS (Flexible AC Transmission Systems) device, on small-signal power system angle stability. This investigation is carried out for a single machine connected to an infinite bus via a loss-less 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 tuning method of the STATCOM gains aiming the H2 norm minimization is briefly explained, and the presented simulations results enable an analysis of the effects of this controller for damping power systems low frequency electromechanical oscillations.

Keywords: Angle stability, bifurcations, FACTS, STATCOM, H2 norm.

1. 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 devices to damp low frequency electromechanical oscillation is being considered [Mithulananthan, 2003, Ying, 2000]. These devices allow the available transmission capacity increase as well as the control of the power flow over designed transmission routes [Gyugyi, 1998].

This work presents a study of the effects of a FACTS device, namely, STATCOM, on power system electromechanical oscillations damping. The investigation is carried out for a single machine infinite bus system with the inclusion of this device. A method of tuning of this FACTS device gains and an optimization process of these parameters are proposed in order to improve the oscillations damping.

2. POWER SYSTEM MODEL

The analysis of the STATCOM 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 STATCOM is connected, as shown in Fig. 1. This intermediate bus is located in the transmission line medium point, because this is the best place for reactive power compensation, since the voltage sag is deepest in this point in a non-compensated line [Hingorani & Gyugyi, 2000], [Kundur, 1993].

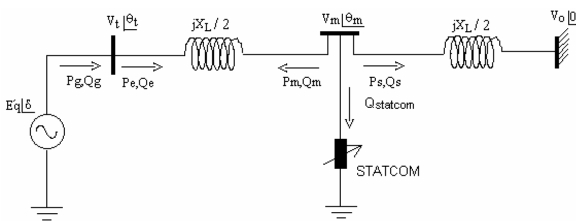

Fig. 1 – Single machine infinite bus system with STATCOM

The STATCOM integrates the reactive power compensation 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 (Thyristor Controlled Reactor) and TSC (Thyristor Switched Capacitor), shows a superior performance and best applicability to angle stability and harmonic control [Nassif, *et al,* 2003]. 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 storage system, and can supply to or absorb active power from the system [Chun, *et al,* 1998], [Gyugyi, 1998]. The functional model of the STATCOM is shown in Fig. 2. If the active power function is not explored, the STATCOM becomes a reactive power generator, and the supply energy source can be eliminated [Gyugyi, 1998].

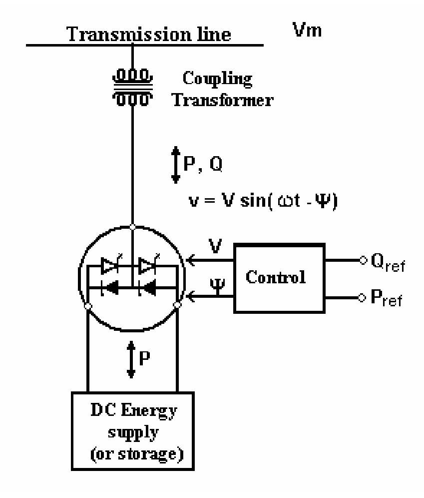

Fig. 2 – STATCOM functional model

The following equations describe the STATCOM model [Nassif, *et al,* 2003], [Chun, *et al,* 1998], and explains how it rapidly works to update its current in order to eliminate voltage deviations or to damp rotor oscillations on the synchronous machine:

$$Q_{STATCOM} = I_s V_m \quad (1)$$

$$I_S = -\frac{K_{STATCOM}.K_u}{(1+sT_{STATCOM})}\left(V_{mref} - V_m\right) + \frac{K_{STATCOM}.K_\omega}{(1+sT_{STATCOM})}\left(\omega_{ref} - \omega\right) \quad (2)$$

Equation (2) can be linearized, resulting in the following dynamic equation:

$$\Delta \dot{I}_s = \frac{1}{T_{STATCOM}}\left(-\Delta I_s + K_{STATCOM}\Delta u_s\right) \quad (3)$$

Let the output of the STATCOM controller be:

$$\Delta u_s = -K_u \Delta V_m + K_\omega \Delta\omega$$

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

An important remark is that the remote signal Δω 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 can be seen in Fig. 3.

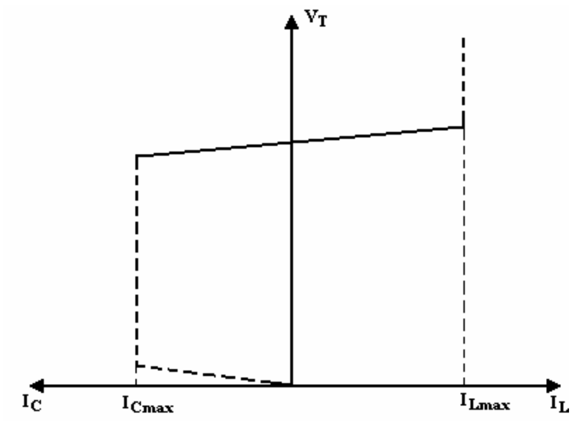

Fig. 3 – V x I characteristic of STATCOM

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

$$\begin{aligned} \dot{x} &= f(x, y, \mu) \\ 0 &= g(x, y, \mu) \end{aligned} \tag{4}$$

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 small enough so that the model can be linearized around some equilibrium point as,

$$\begin{aligned} \Delta\dot{x} &= J_1\Delta x + J_2\Delta y + B_w\Delta w \\ 0 &= J_3\Delta x + J_4\Delta y \end{aligned} \tag{5}$$

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_w is the perturbation matrix. For the system shown in Fig. 1, the following state equations can be formulated according to nodal power balance methodology [Deckmann & da Costa, 1994],[Nassif, *et al,*2003].

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

$$\begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} = \underbrace{\begin{bmatrix} 0 & A_{1g} & A_{2g} & 0 & 0 \\ 0 & R_{1g} & R_{2g} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -V_m \end{bmatrix}}_{J_3} . \begin{bmatrix} \Delta\omega \\ \Delta\delta \\ \Delta E_q^{'} \\ \Delta E_{FD} \\ \Delta I_S \end{bmatrix} + \underbrace{\begin{bmatrix} -A_{1g}-A_{1e} & A_{1e} & A_{3g}-A_{2e} & -A_{3e} \\ -R_{1g}-R_{1e} & R_{1e} & R_{3g}-R_{2e} & -R_{3e} \\ A_{1m} & -A_{1m}-A_{1s} & -A_{2m} & -A_{3m}-A_{2s} \\ R_{1m} & -R_{1m}-R_{1s} & -R_{2m} & -R_{3m}-R_{2s}-I_S \end{bmatrix}}_{J_4} . \begin{bmatrix} \Delta\theta_t \\ \Delta\theta_m \\ \Delta V_t \\ \Delta V_m \end{bmatrix} \tag{6}$$

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

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 [Deckmann & da Costa, 1994]. Eliminating the vector of algebraic variables, provided det $J_4 \neq 0$, the state-space system can be obtained as

$$\Delta\dot{x} = A\Delta x + B_w\Delta w \tag{7}$$

where

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

is the system state matrix.

3. THE OPTIMIZATION PROBLEM

To improve the damping performance of low frequency electromechanical oscillations, it can be suggested a tuning method to the voltage and rotor speed deviations feedback parameters for the STATCOM. This search for optimal parameters (K_u and K_ω values) improves the capacity of this FACTS device without introducing more controllers neither modifications in the power system model.

Putting the power system in the suitable form

$$\begin{aligned} \dot{x} &= A_1\Delta x + A_2\Delta y + B_u u + B_w\Delta w \\ 0 &= A_3\Delta x + A_4\Delta y \\ r &= C_1\Delta x + C_2\Delta y \end{aligned} \tag{8}$$

where u is the control law $u=K.r$ and the matrices above are defined like:

$$\begin{bmatrix} \Delta\dot{x} \\ \Delta\dot{x}_c \end{bmatrix} = \underbrace{\begin{bmatrix} J_1 & \Theta \\ \Theta & -\frac{1}{T_{STATCOM}} \end{bmatrix}}_{A_1} \begin{bmatrix} \Delta x \\ \Delta x_c \end{bmatrix} + \underbrace{\begin{bmatrix} J_2 \\ \Theta \end{bmatrix}}_{A_2} \Delta y + \underbrace{\begin{bmatrix} \Theta \\ \frac{1}{T_{STATCOM}} \end{bmatrix}}_{B_u} \underbrace{\begin{bmatrix} K_\omega & K_u \end{bmatrix}}_{K} r$$

$$0 = \underbrace{\begin{bmatrix} & 0 \\ & 0 \\ J_3 & 0 \\ & V_m \end{bmatrix}}_{A_3} \begin{bmatrix} \Delta x \\ \Delta x_c \end{bmatrix} + \underbrace{J_4}_{A_4} . \Delta y \tag{9}$$

$$r = \underbrace{\begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}}_{C_1} \begin{bmatrix} \Delta x \\ \Delta x_c \end{bmatrix} + \underbrace{\begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}}_{C_2} \Delta y$$

where the vector r is the vector containing the buses voltage and angles, and the state variable x_c is the STATCOM state variable $I_{statcom}$. This representation enables a well suitable form given by:

$$\begin{aligned} \Delta y &= -A_4^{-1} A_3 \Delta x \\ \Delta\dot{x} &= \underbrace{\left(A_1 - A_2 A_4^{-1} A_3\right)}_{A_x} \Delta x + B_u u \\ r &= \underbrace{\left(C_1 - C_2 A_4^{-1} A_3\right)}_{C_y} \Delta x \end{aligned} \tag{10}$$

As the gain K is varied, the following matrices can be utilized to investigate the problem:

$$\widetilde{A} = A_x + B_u K C_y$$
$$\widetilde{B} = B_\omega + B_u K D_{y\omega} \quad (11)$$
$$\widetilde{C} = C_z + D_{zu} K C_y$$

Considering the performance specifications, the square of the H_2 norm of the system can be expressed in terms of the symmetric and positive definite solution to a Lyapunov equation given in the form [Oliveira & Skelton, 2000]

$$trace\left[\widetilde{C}.P.\widetilde{C}^T\right] \quad (12)$$

The matrix P is the solution of the *Lyapunov* equation:

$$\widetilde{A}P + P\widetilde{A}^T + \widetilde{B}\widetilde{B}^T = \Theta \quad (13)$$

The method for choosing a suitable set of gains is thought in a way that for each operating point, as the gain (K_u or K_ω) is varied, the maximum value of the H_2 norm is stored. At the end of the process, the minimum value of this set is picked out. Repeating this procedure, the STATCOM gains can be chosen monitoring the norm H_2 so that the smallest values are being analyzed.

4. SIMULATIONS RESULTS

The system of Fig. 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. Fig. 4 illustrates the H_2 norm behavior over the variation of the K_u gain, and Fig. 5 illustrates a more insightfully view of this graphic, showing the points of minimal norm magnitude.

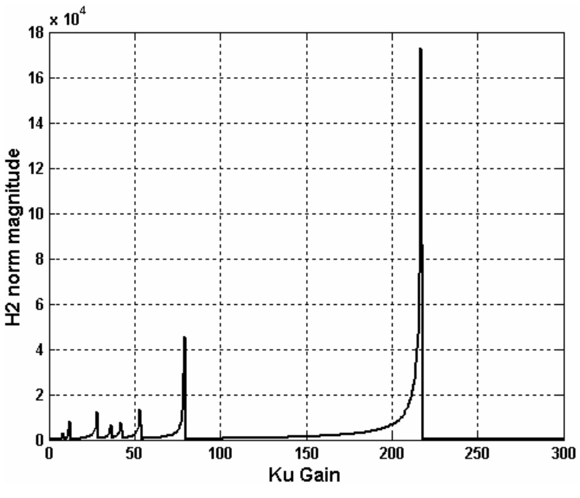

Fig. 4 – H_2 norm variation

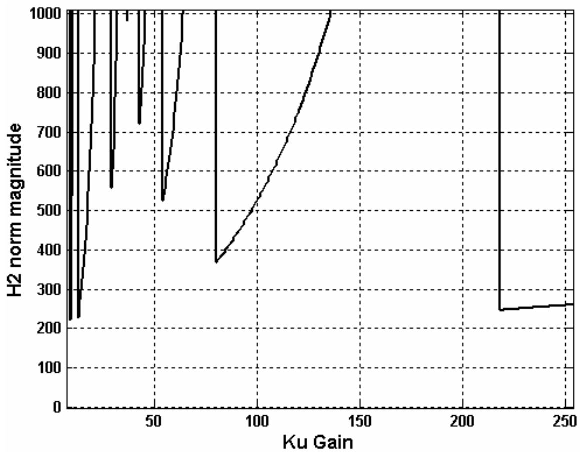

Fig. 5 – H_2 norm variation

The same procedure is also applied to the variation of the K_ω gain, and showed in Fig. 6, with a chosen K_u equals to 13.

Capturing the suitable value of K_ω, the procedure to get the K_u value is repeated, allowing the best selection for each gain.

With this analysis, it was possible to choose four situations to investigation. "Case 1" is the purely voltage deviation feedback in STATCOM, without any supplementary stabilizing signal. The second case, "Case 2", is the STACOM with a conventional parameters choice of K_u=K_ω=100 [Nassif, *et al,* 2003]. With the H_2 norm investigation it is possible to verify that among the cases analyzed in this work, a sub-optimal choice is K_u=13 and K_ω=95 ("Case 3"), and the optimal choice is K_u=220 and K_ω=1060 ("Case 4"). These four cases are pictured in Fig. 7, which shows the real part of critical eigenvalues for these four different tuning situations as the loading factor varies.

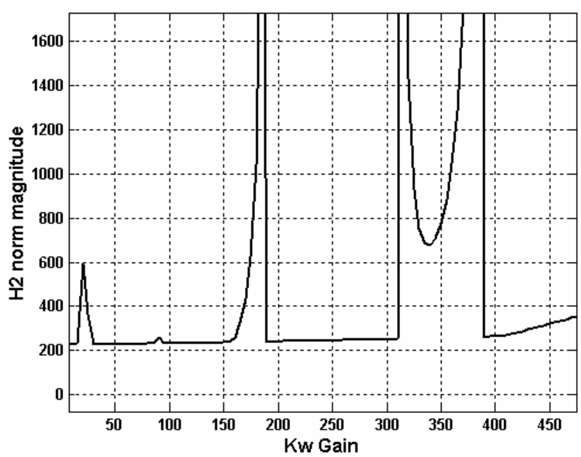

Fig. 6 – H_2 norm variation

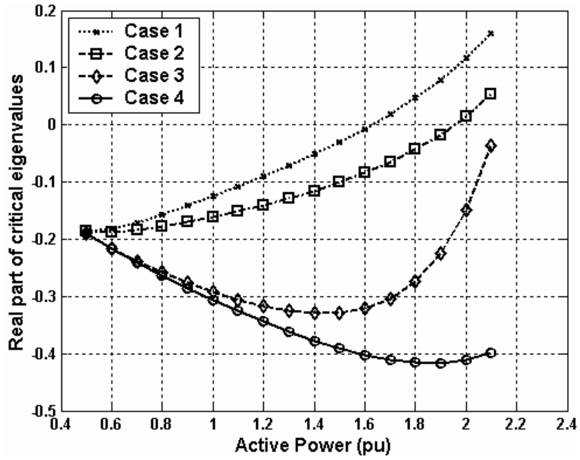

Fig. 7 – Real eigenvalues loci

Table 1 shows the exact instability limit for each case. Here, "Case 0" means the uncompensated system, without STATCOM. Per unit values are represented at the system basis of 100 MVA, and not at the generator basis, which justifies limit values larger than 1 pu.

Table 1: Instability limit (pu.)

Case 0	Case 1	Case 2	Case 3	Case 4
1,06	1.62	1.95	2.12	2.64

Figs. 8 and 9 show the step response for loading increase up to 2 p.u. and 2.2 p.u., respectively.

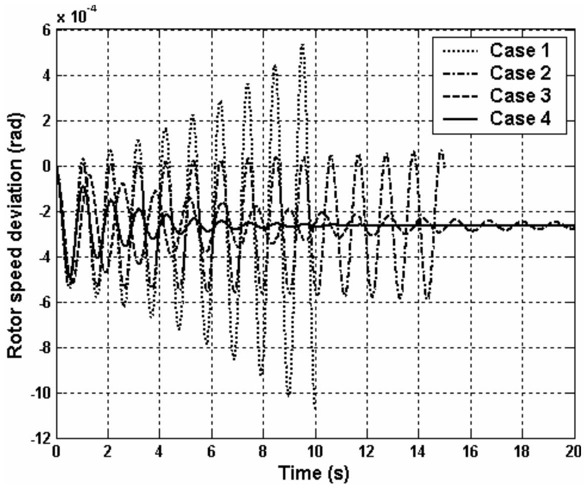

Fig. 8 – Step response

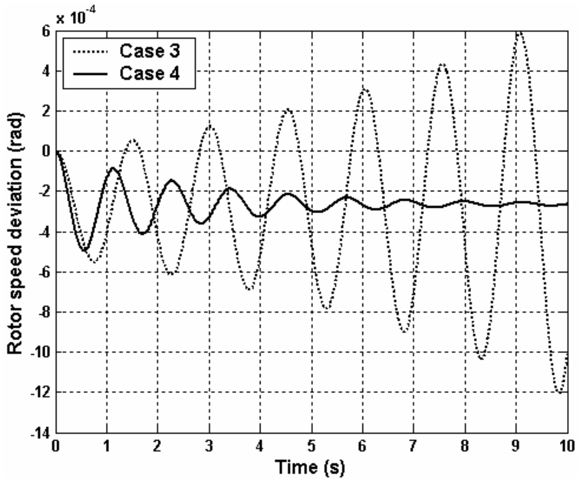

Fig. 9 – Step response

Fig. 10 shows the eigenvalues loci of Case 4 to illustrate the Hopf bifurcation, which occurs for all cases analyzed in this work. In this Fig., the loading factor was increased up to P_g = 3p.u.

The results presented in Fig.s 4 – 10 and in Table 1 show that the STATCOM exhibits a very good performance when used in damping power system oscillations. In addition, this performance can be greatly improved if the parameters of this FACTS device are coordinated in a well suitable form.

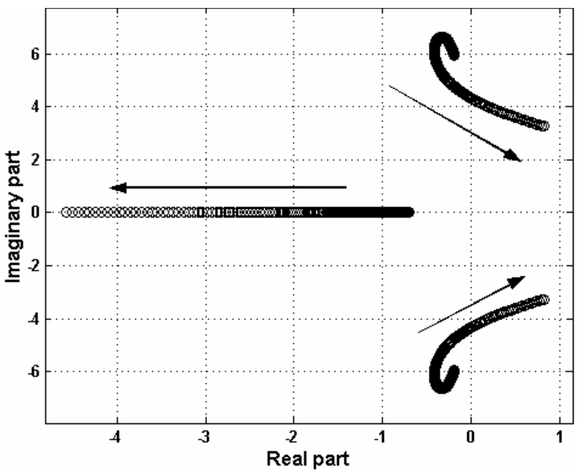

Fig. 10 – Eigenvalues loci

5. CONCLUSIONS

This work has examined the effects of different configurations of STATCOM on power systems low frequency electromechanical oscillations for electric power systems. The study of the linearized power system model with the inclusion of this FACTS device was conducted using eigenvalues analysis and bifurcation theory. The step response was used to add more illustrative behaviors of the complete system. The simulations results presented show that the STATCOM provides very good effectiveness in keeping small-signal angle stability, and the tuning based in the H_2 norm minimization of its gains is revealed as a great improvement in the compensating performance.

Our future research contains the application of this technique for multi-machine power systems, including the study of inter-area modes.

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APPENDIX A

Table 2 – Generator, AVR and transmission line parameters

M	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	1.6	0.32	1.55	6.0	12.5	0.05	0.1

Table 3 – STATCOM parameters

$K_{statcon}$	$T_{statcom}$
1.0	0.005 s

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