

IMPACT OF INTERACTIONS AMONG POWER SYSTEM CONTROLS

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PRESENTATION CONTENTS

- **Adverse effects on intra-plant modes caused by improperly designed power system stabilizers**
- **Using zeros to understand the adverse terminal voltage transients induced by the presence of PSSs**
- **Hopf bifurcations in the control parameters space**
- **Simultaneous partial pole placement for power system oscillation damping control**
- **Secondary voltage regulation: preliminary study in the Rio Area**

IMPACT OF INTERACTIONS AMONG POWER SYSTEM CONTROLS

ADVERSE EFFECTS ON INTRA-PLANT MODES CAUSED BY IMPROPERLY DESIGNED POWER SYSTEM STABILIZERS

ADVERSE EFFECTS ON INTRA-PLANT MODES CAUSED BY PSS

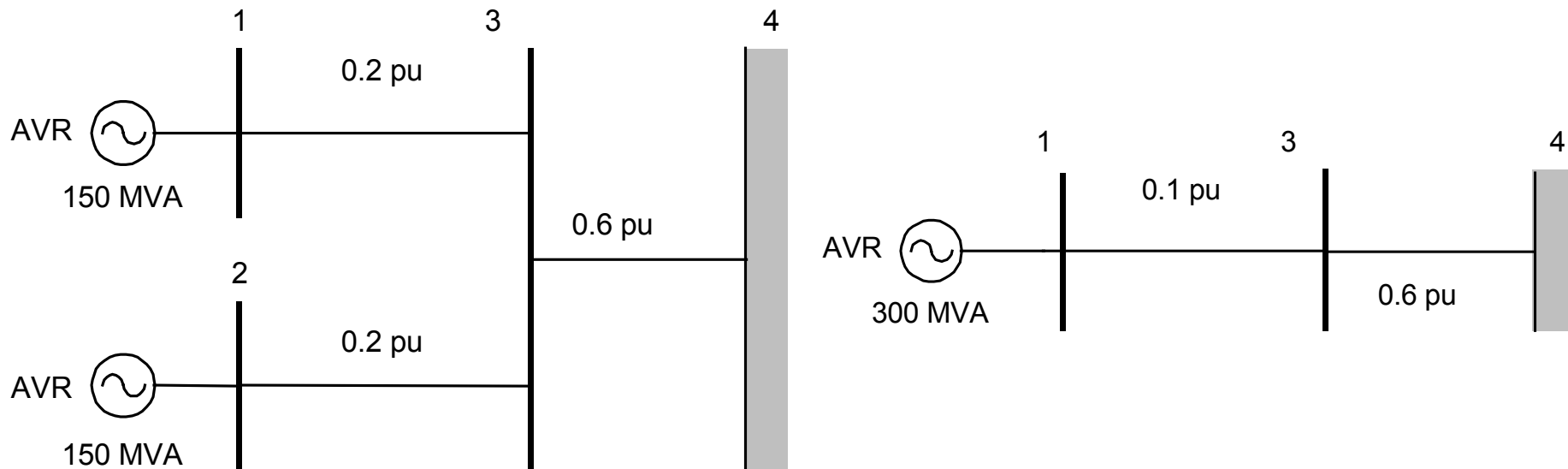
- **Large systems \Rightarrow most multi-unit power plants are usually modeled as single equivalent machines**
 - ➔ **Reduces the number of system states, but...**
 - ➔ **Does not capture the intra-plant dynamics**
- **When improperly designed, PSSs may cause adverse interactions and intra-plant mode instability**

ADVERSE EFFECTS ON INTRA-PLANT MODES CAUSED BY PSS

➤ Two-unit power plant connected through a high impedance to the infinite bus

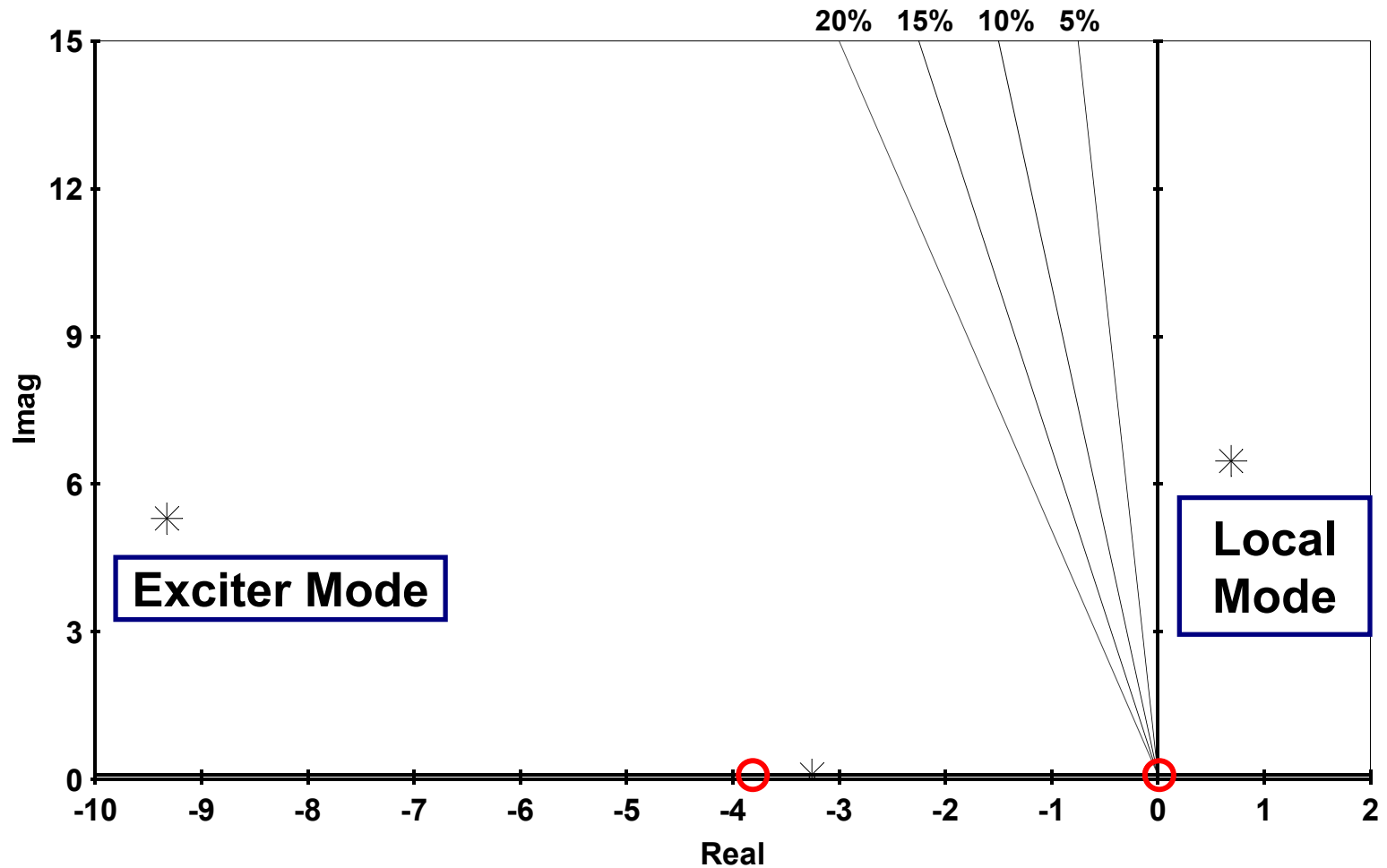
→ 2-Machine system

→ Equivalent SMIB representation



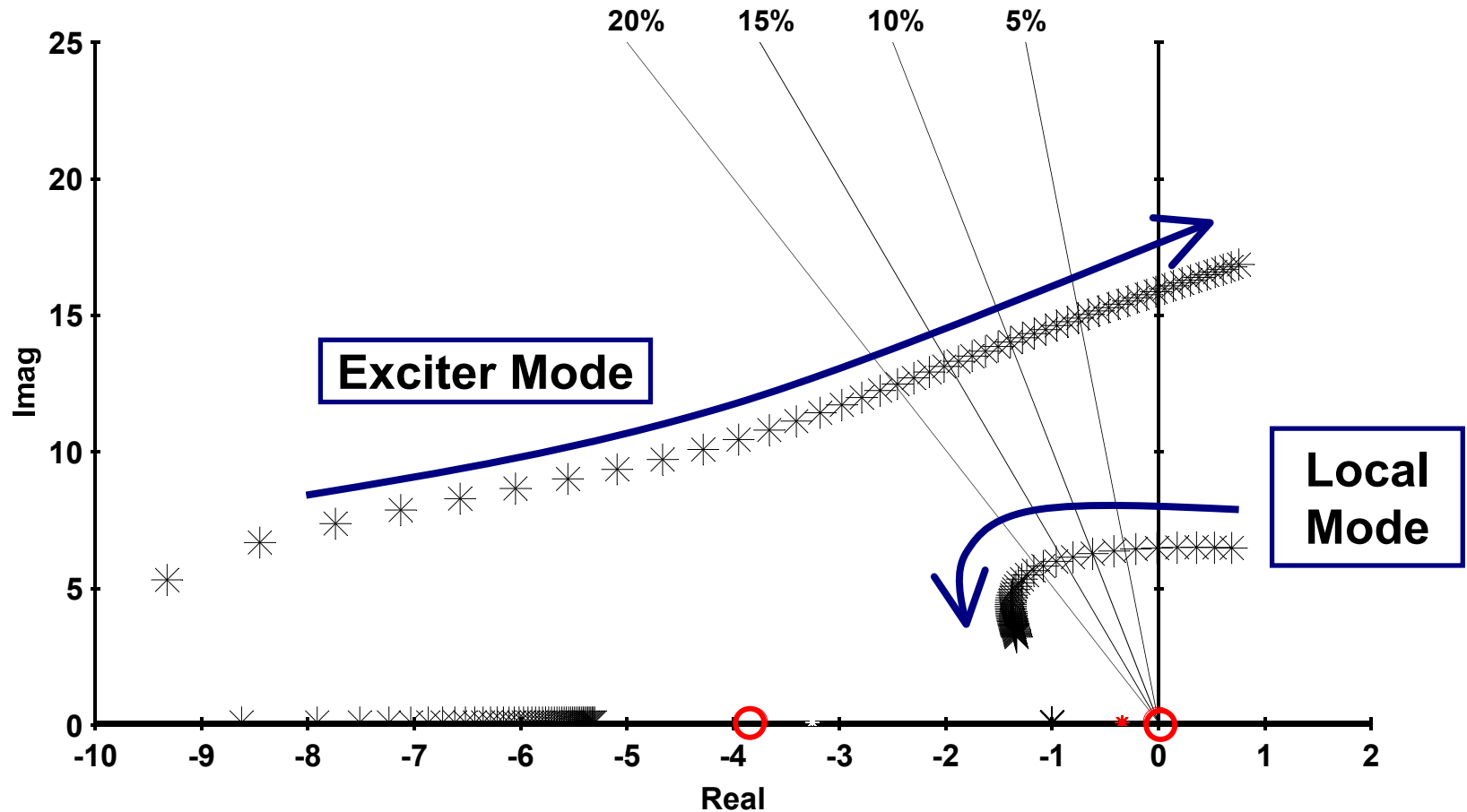
ADVERSE EFFECTS ON INTRA-PLANT MODES CAUSED BY PSS

➤ SMIB, pole-zero map of $[\Delta\omega_1/\Delta V_{REF1}]$



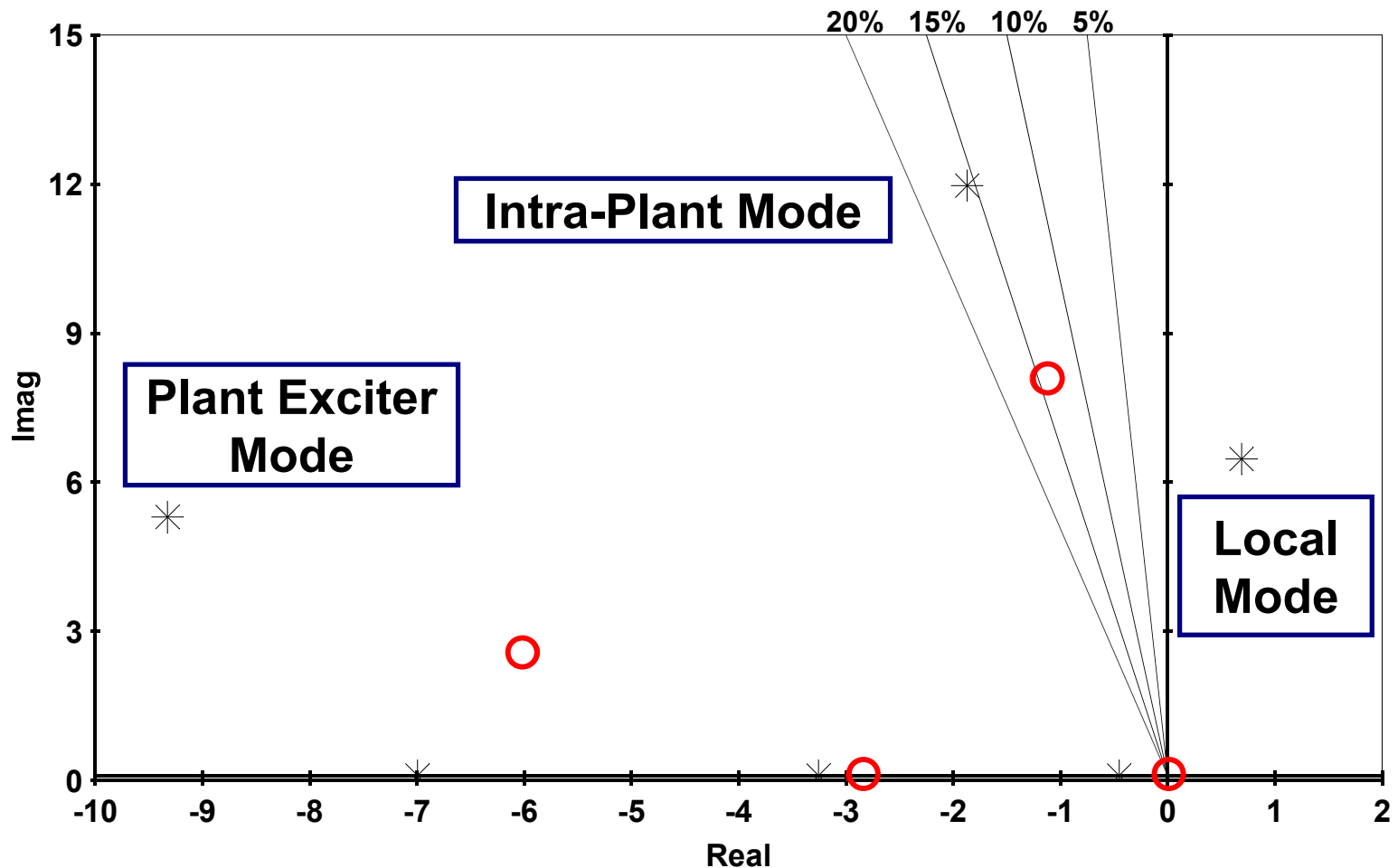
ADVERSE EFFECTS ON INTRA-PLANT MODES CAUSED BY PSS

➤ SMIB system – PSS (center frequency = 1.0 Hz)



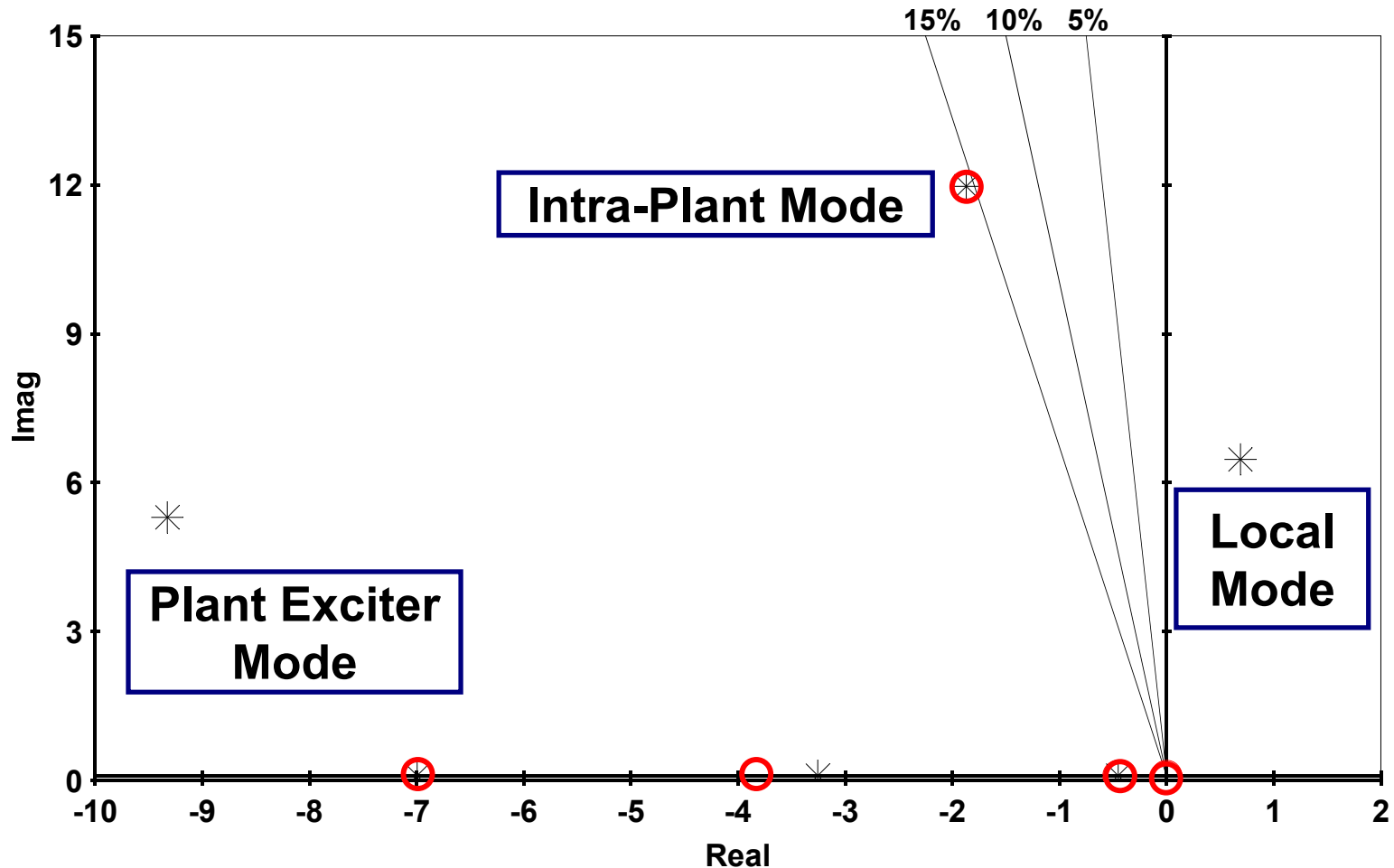
ADVERSE EFFECTS ON INTRA-PLANT MODES CAUSED BY PSS

➤ 2-machine system, pole-zero map of $[\Delta\omega_1/\Delta V_{REF1}]$



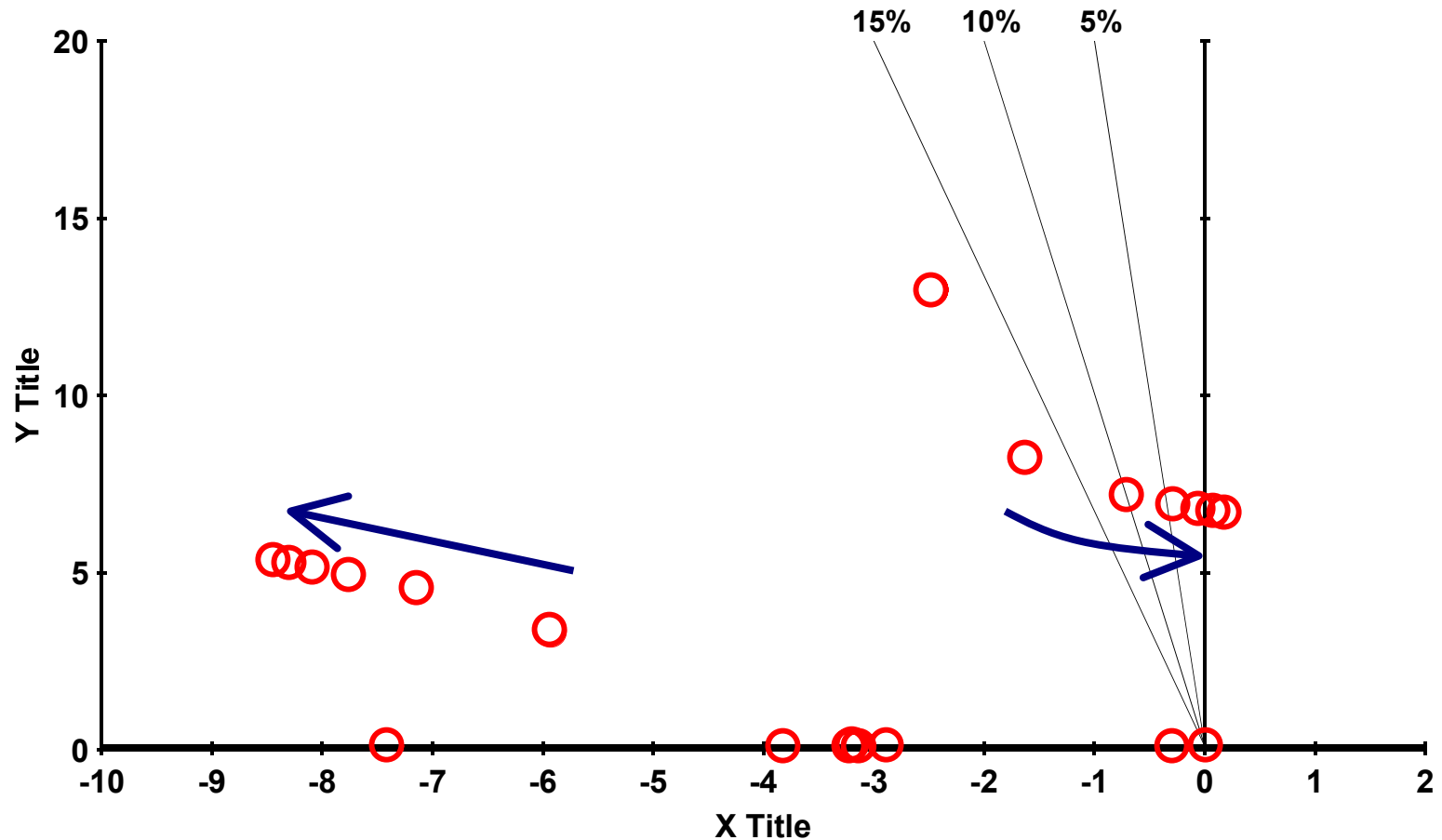
ADVERSE EFFECTS ON INTRA-PLANT MODES CAUSED BY PSS

➤ 2-machine system, pole-zero map of $[(\Delta\omega_1 + \Delta\omega_2)/\Delta V_{REF1}]$



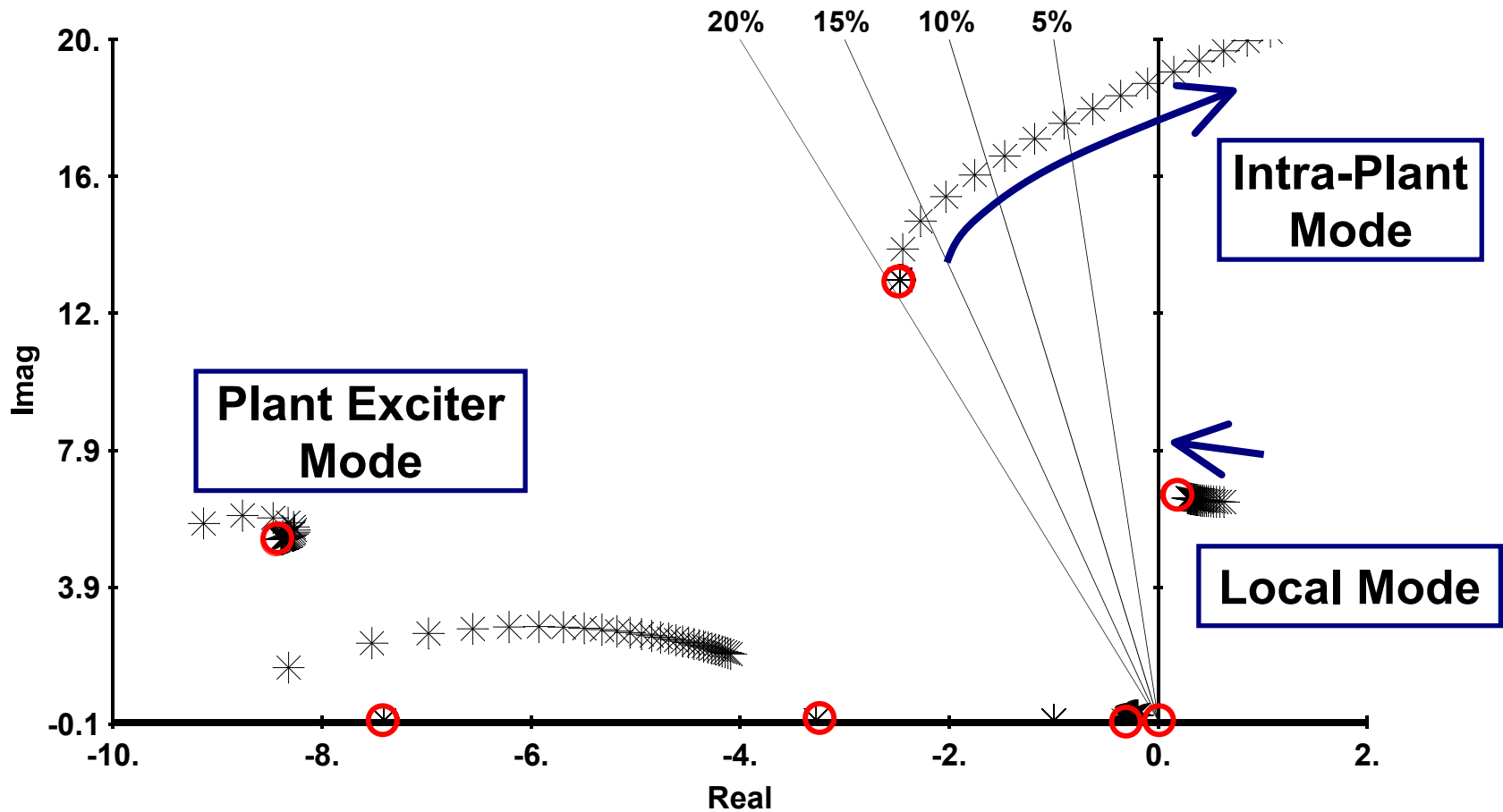
ADVERSE EFFECTS ON INTRA-PLANT MODES CAUSED BY PSS

- Map of zeros for different number of modeled machines (from 1 to 7)



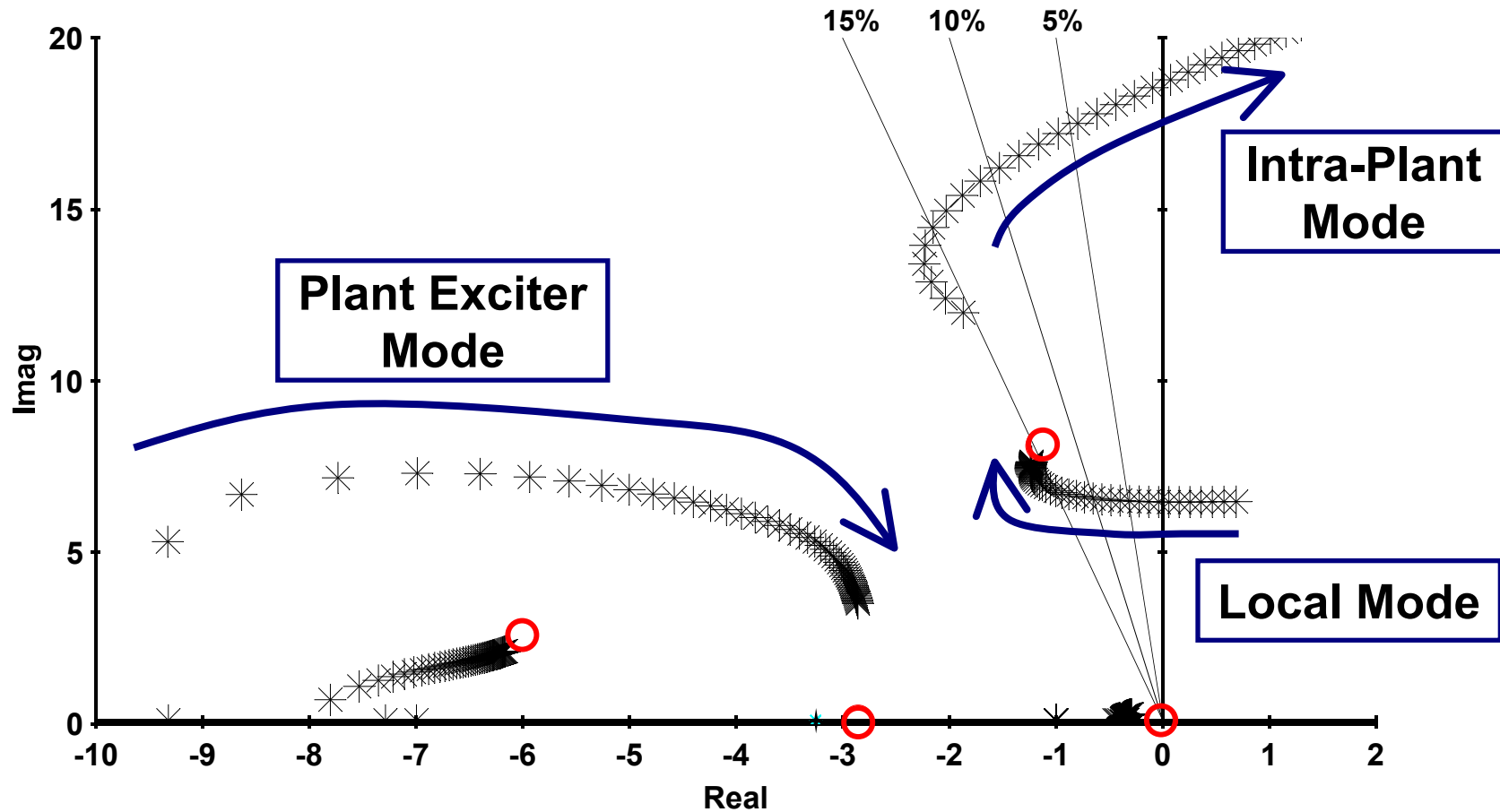
ADVERSE EFFECTS ON INTRA-PLANT MODES CAUSED BY PSS

➤ 7 Machines, 1 PSS



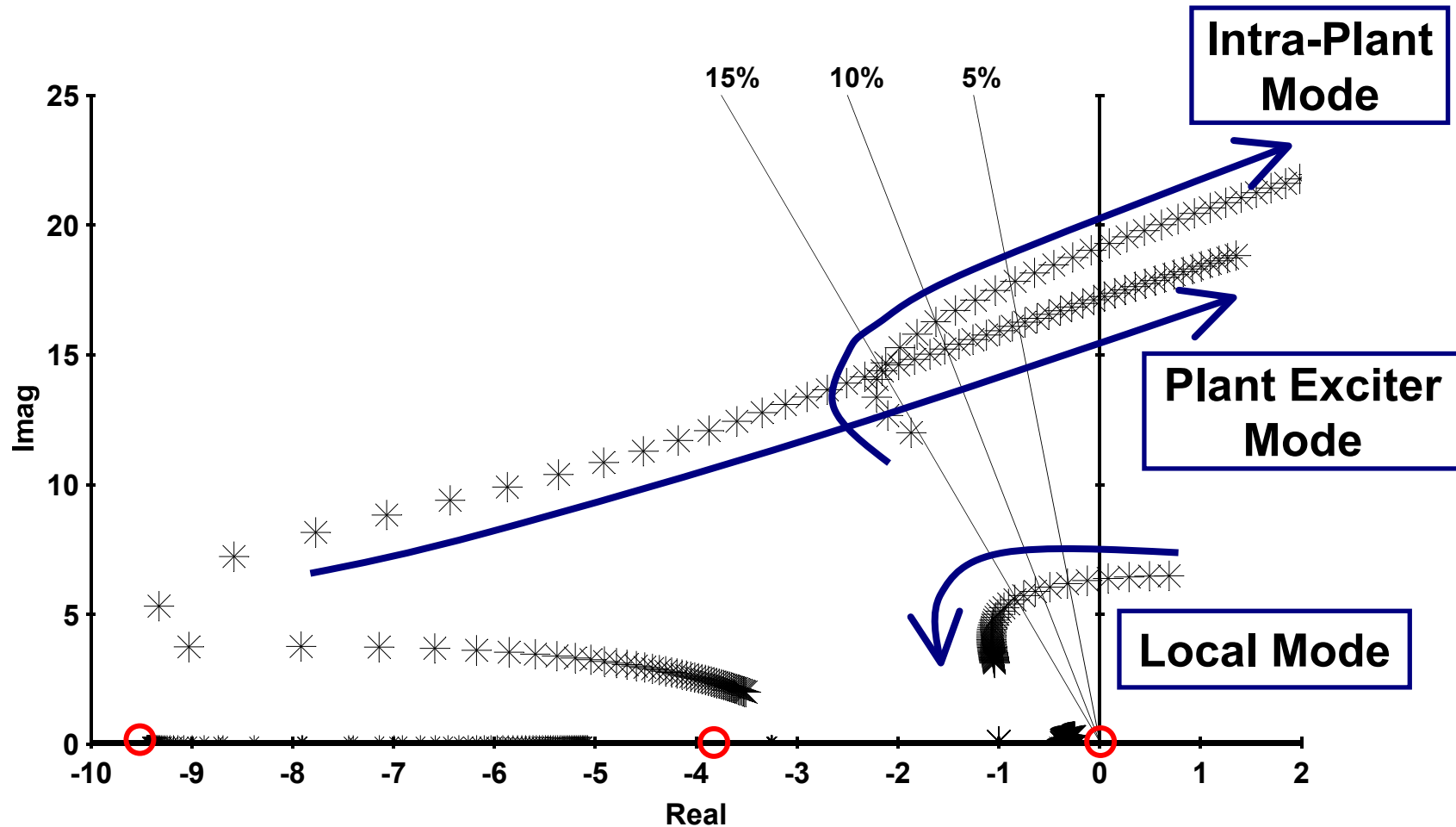
ADVERSE EFFECTS ON INTRA-PLANT MODES CAUSED BY PSS

➤ 2-Machine system – 1 PSS (center frequency = 1.0 Hz)



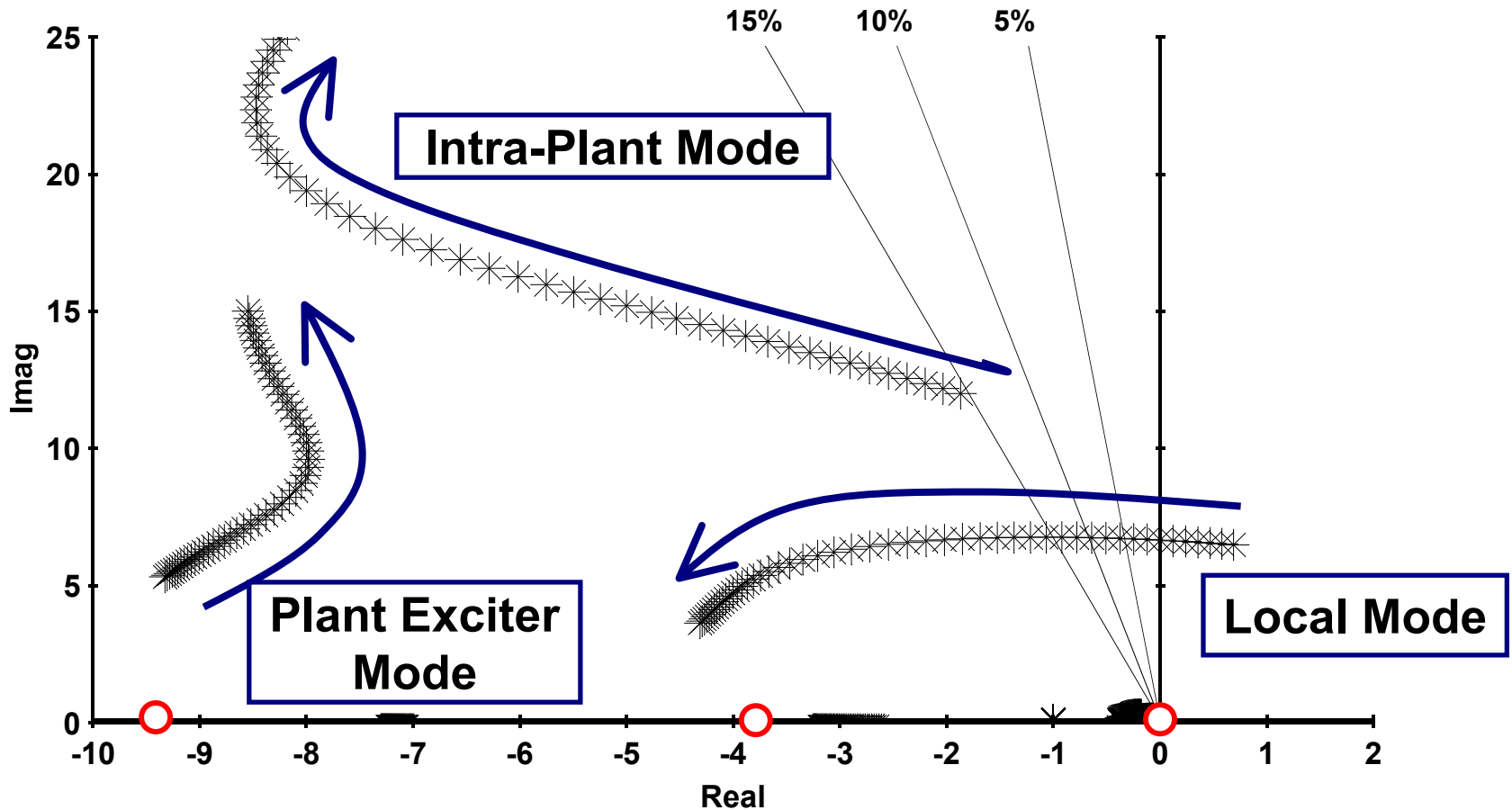
ADVERSE EFFECTS ON INTRA-PLANT MODES CAUSED BY PSS

➤ 2-Machine system – 2 PSSs (center frequency = 1.0 Hz)



ADVERSE EFFECTS ON INTRA-PLANT MODES CAUSED BY PSS

➤ 2-Machine system – 2 PSSs (center frequency 5.0 Hz)



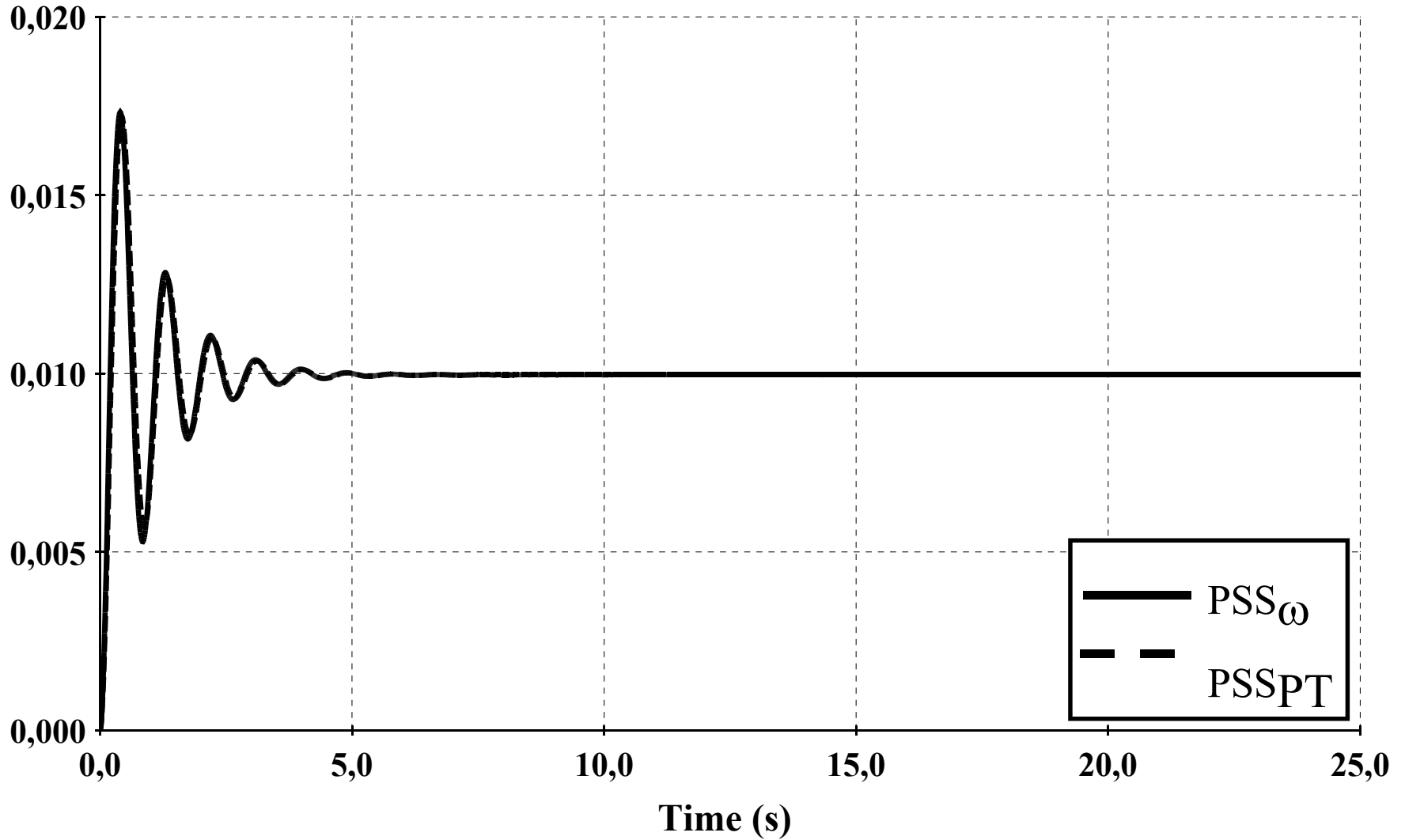
IMPACT OF INTERACTIONS AMONG POWER SYSTEM CONTROLS

USING ZEROS TO UNDERSTAND THE ADVERSE TERMINAL VOLTAGE TRANSIENTS INDUCED BY THE PRESENCE OF PSSs

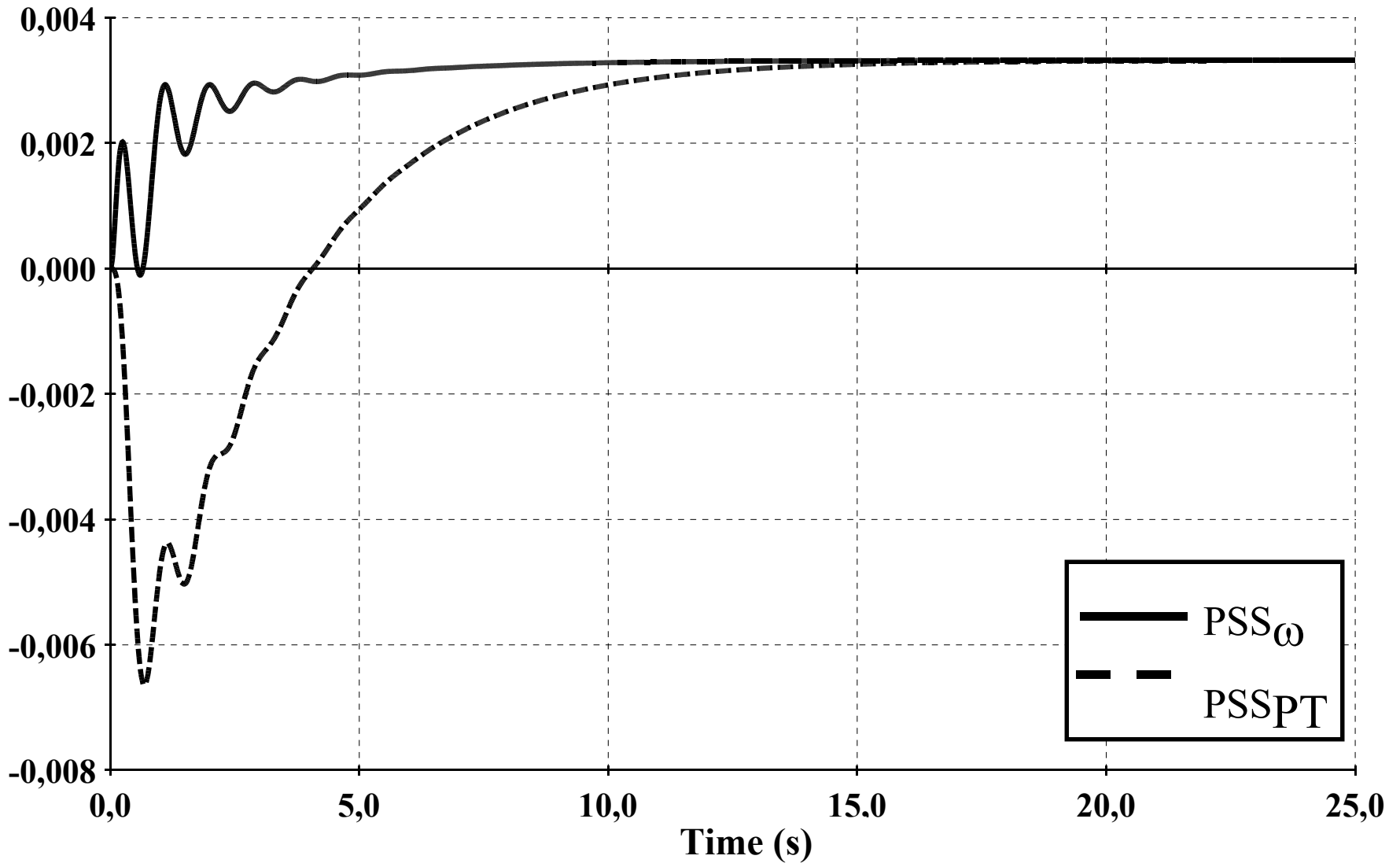
ADVERSE IMPACTS ON TERMINAL VOLTAGE DUE TO PSSs

- **Studying zeros to understand the adverse voltage transients induced by the presence of PSSs**
- **Comparing the performances of PSSs derived from either rotor speed or terminal power signals**

ACTIVE POWER CHANGES FOLLOWING ΔP_{MEC} IN SMIB

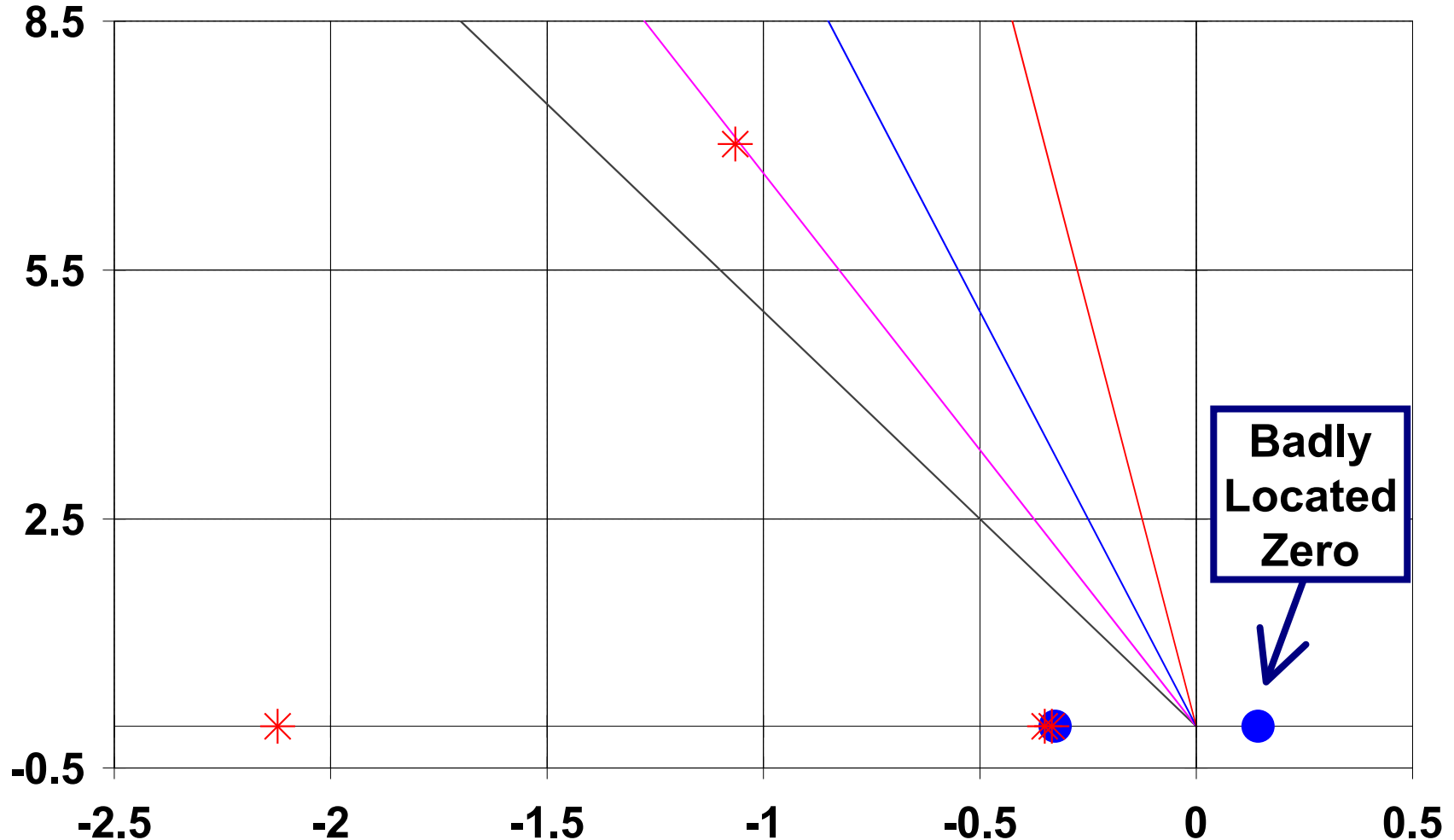


REACTIVE POWER CHANGES FOLLOWING ΔP_{MEC} IN SMIB

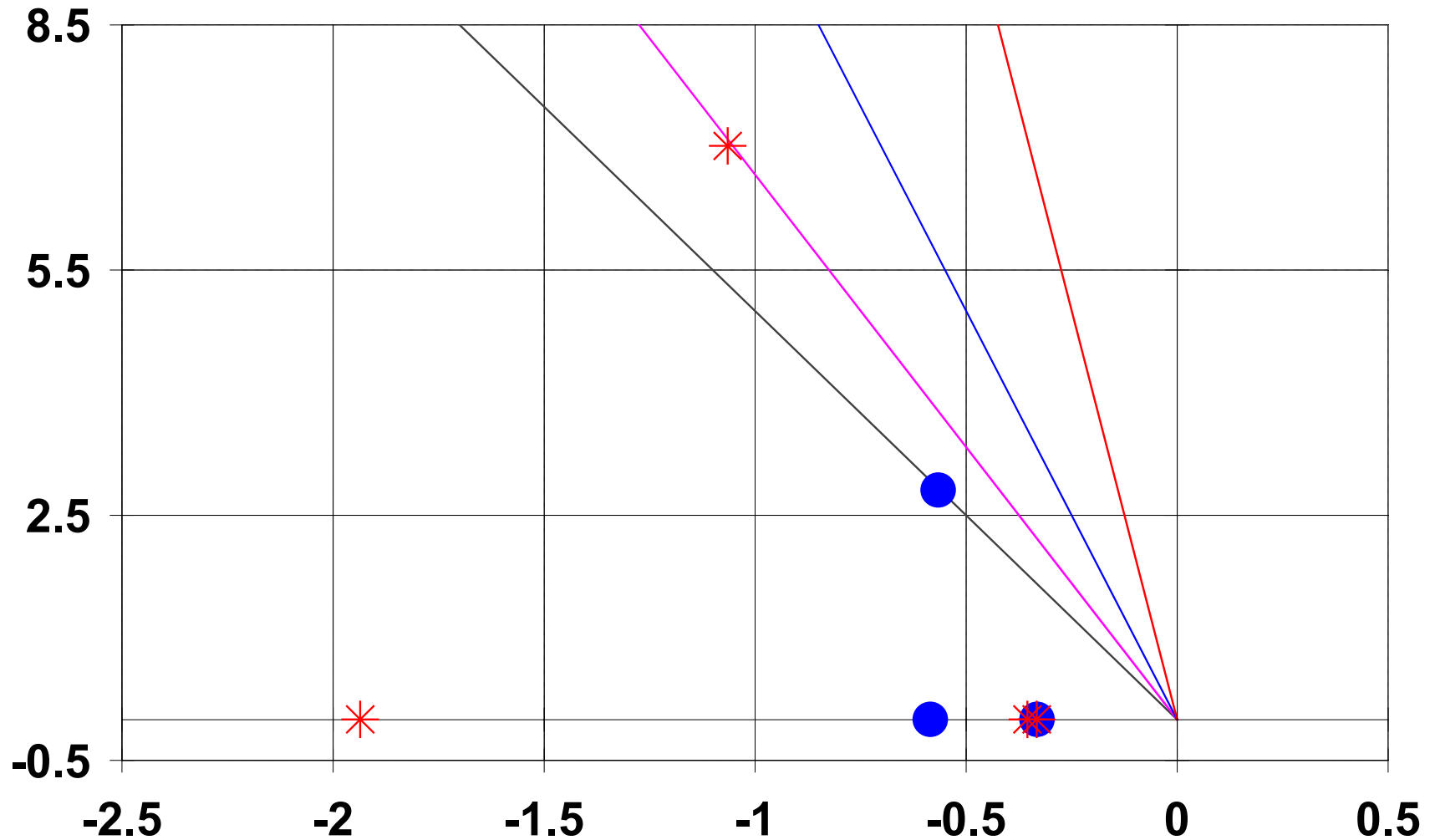


POLE-ZERO MAP FOR $\Delta Q_T / \Delta P_{MEC}$ (PSSPT)

- Zero near the origin causes bigger overshoot in the step response



POLE-ZERO MAP FOR $\Delta Q_T / \Delta P_{MEC}$ (PSS ω)



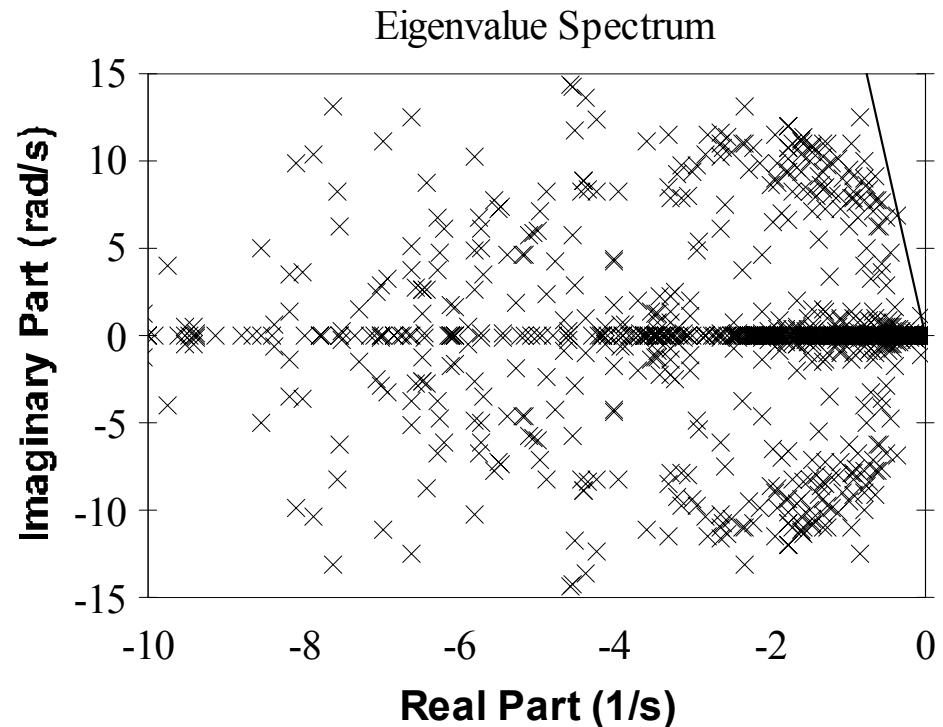
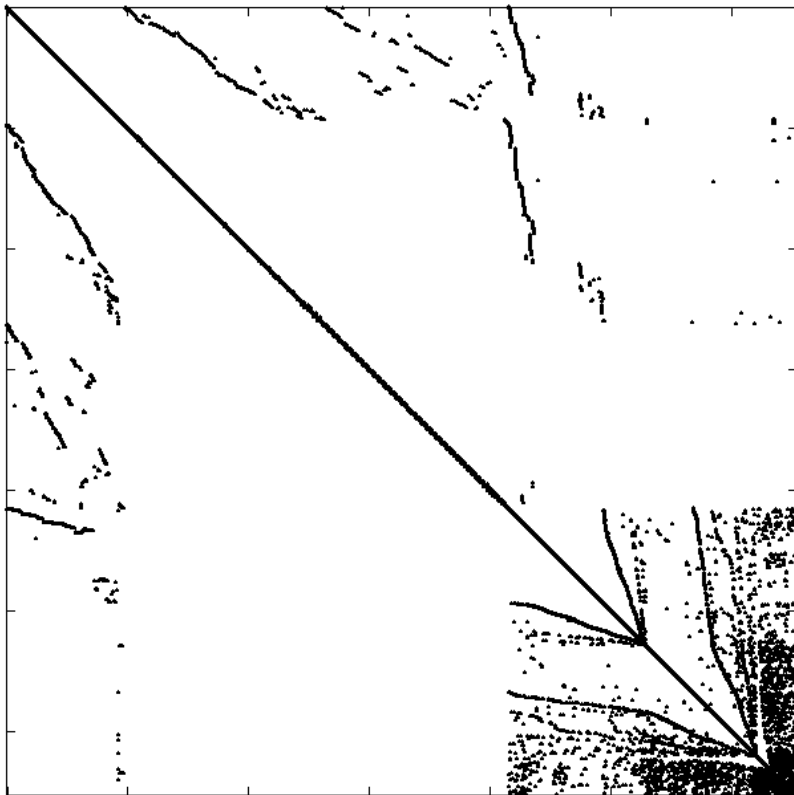
**HOPF BIFURCATIONS IN THE
CONTROL PARAMETERS SPACE**

HOPF BIFURCATION ALGORITHMS

- **Compute parameter values that cause crossings of the small-signal stability boundary by critical eigenvalues**
- **Hopf bifurcations are computed for:**
 - **Single-parameter changes**
 - **Multiple-parameter changes (minimum distance in the parameter space)**

HOPF BIFURCATIONS – TEST SYSTEM UTILIZED

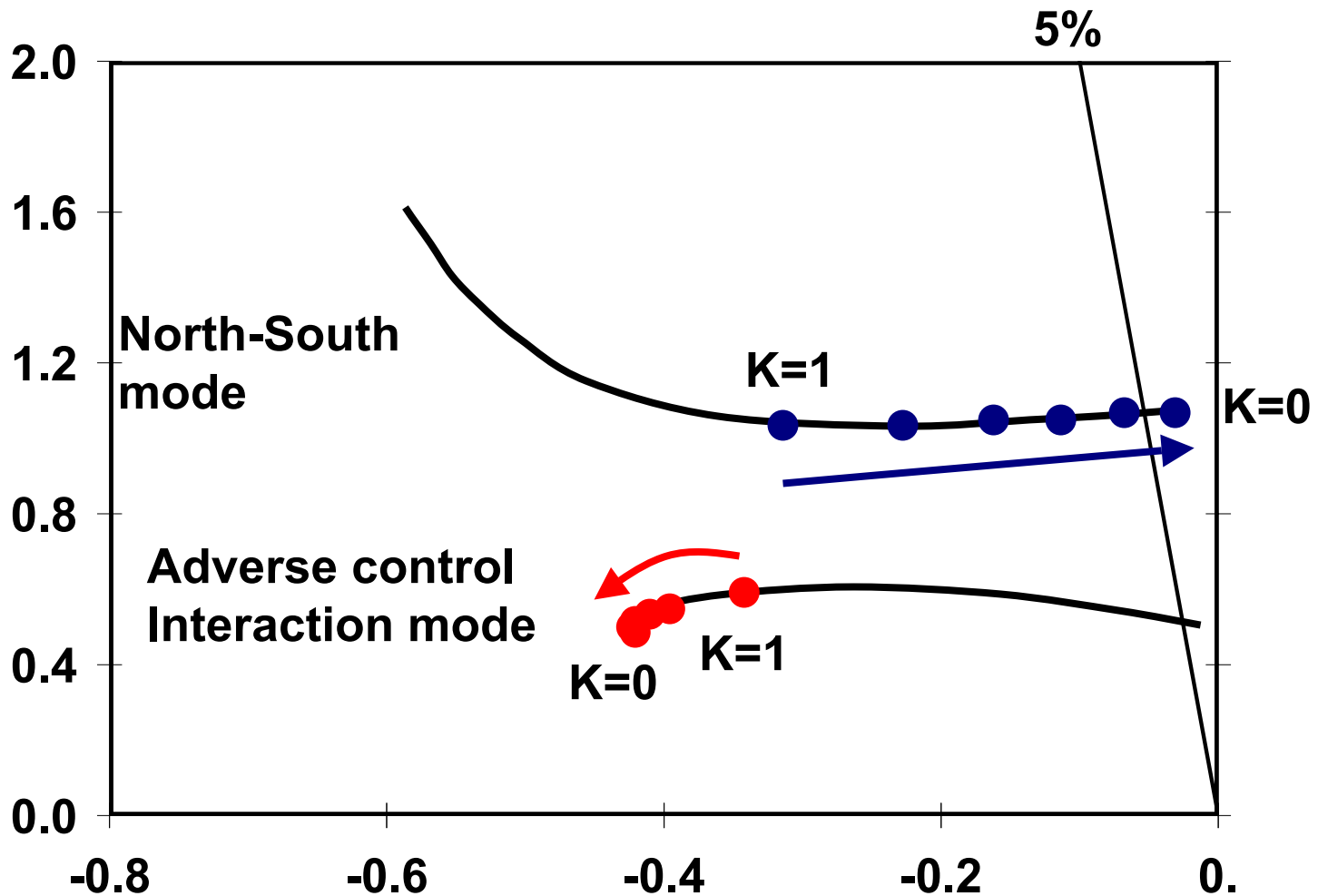
- **Brazilian North-South Interconnection: 2,400 buses, 3,400 lines, 120 generators and associated AVRs, 46 stabilizers, 100 speed-governors, 4 SVCs, 2 TCSCs, 1 HVDC link**
- **Matrix dimension is 13,062 with 48,521 nonzeros and 1,676 states**



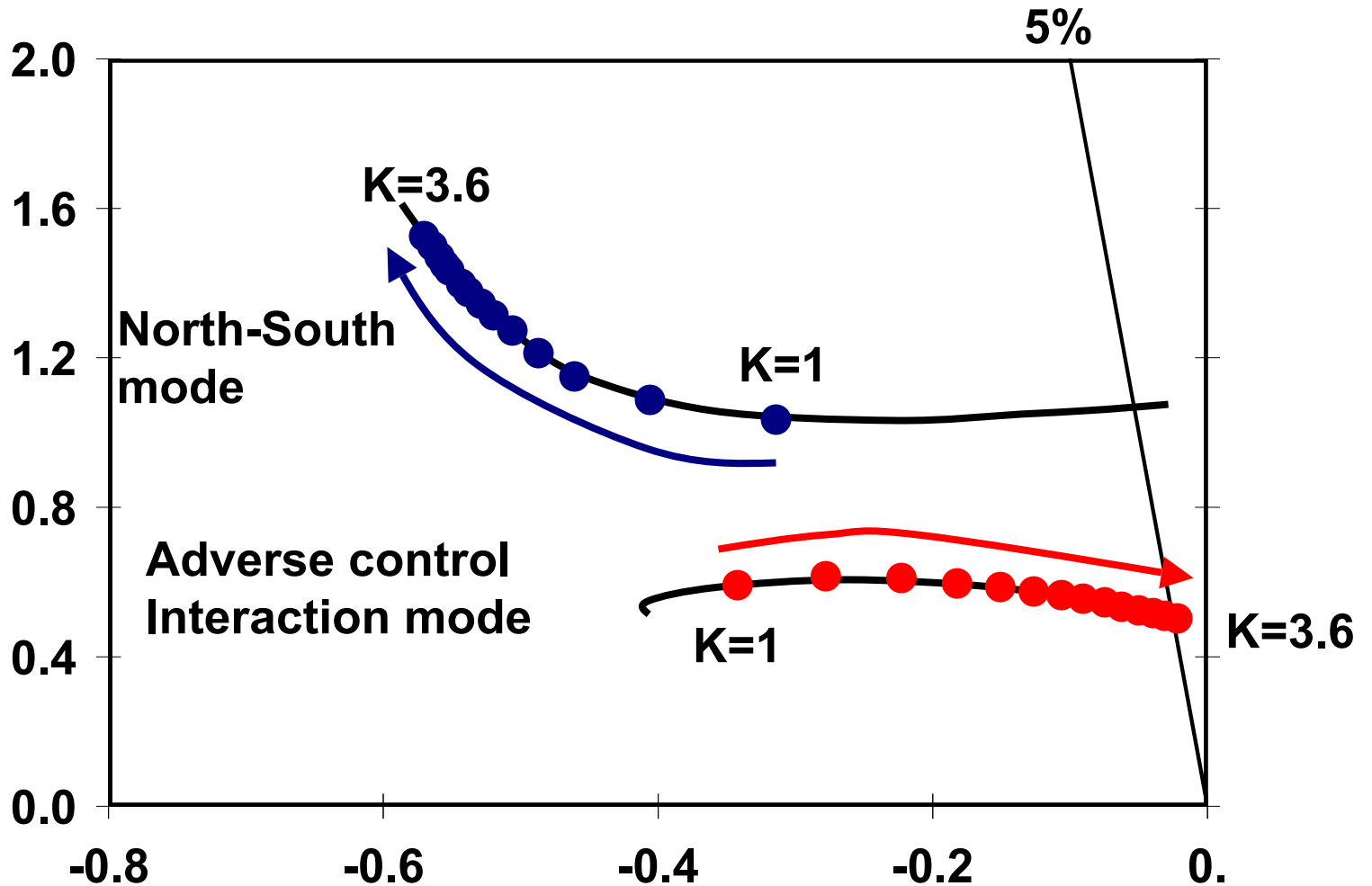
HOPF BIFURCATIONS – TEST SYSTEM PROBLEM

- **Two TCSCs located at each end of the North-South intertie, equipped with PODs to damp the 0.17 Hz mode**
- **The Hopf bifurcation algorithms were applied to compute eigenvalue crossings of the security boundary (5% damping ratio) for gain changes in the two PODs**

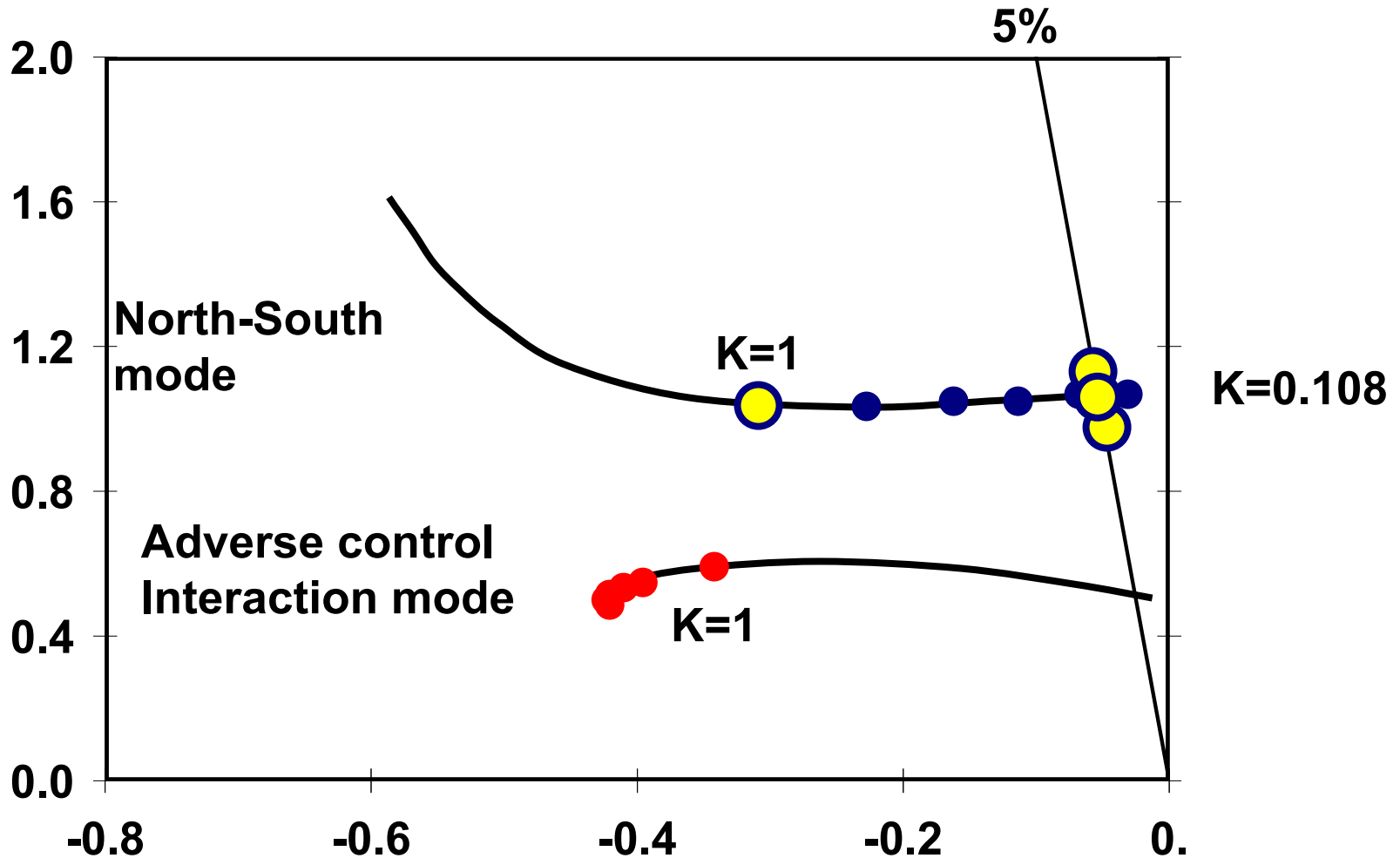
ROOT CONTOUR WHEN REDUCING THE GAINS OF THE 2 TCSCs



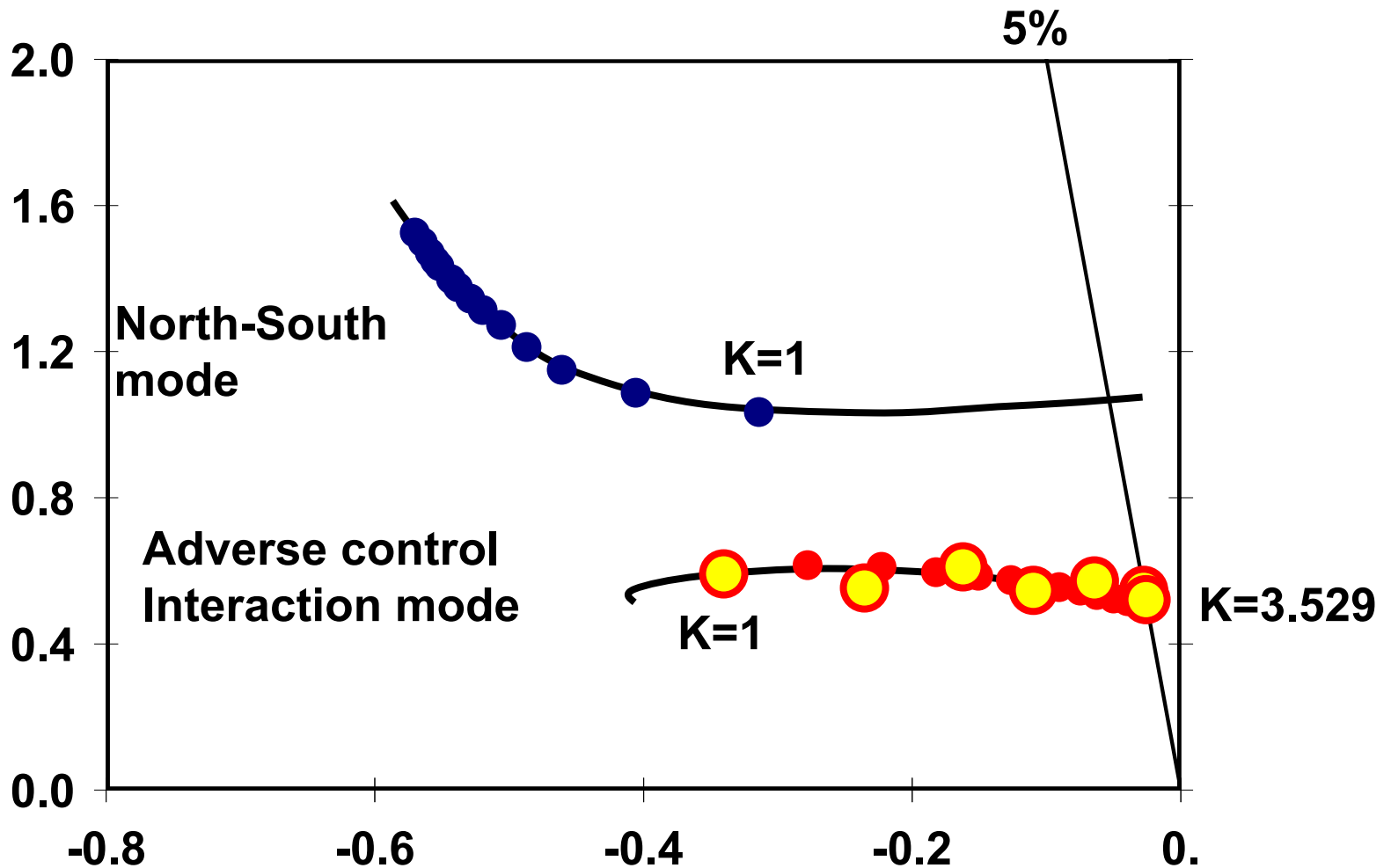
ROOT CONTOUR WHEN INCREASING THE GAINS OF THE 2 TCSCs



DETERMINING SECURITY BOUNDARIES THROUGH HOPF (5%)



DETERMINING SECURITY BOUNDARIES THROUGH HOPF (5%)



HOPF BIFURCATIONS - CONCLUSIONS

- **Two crossings of the security boundary were found, both being related to POD gains far away from the nominal values(1 pu):**

$$3.529 > K > 0.108$$

- **Computational cost of Hopf bifurcation algorithm**
 - ➔ **Single-parameter changes : 0.16 s (per iteration)**
 - ➔ **Multiple-parameter changes : 0.35 s (per iteration)**

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SIMULTANEOUS PARTIAL POLE PLACEMENT

FOR

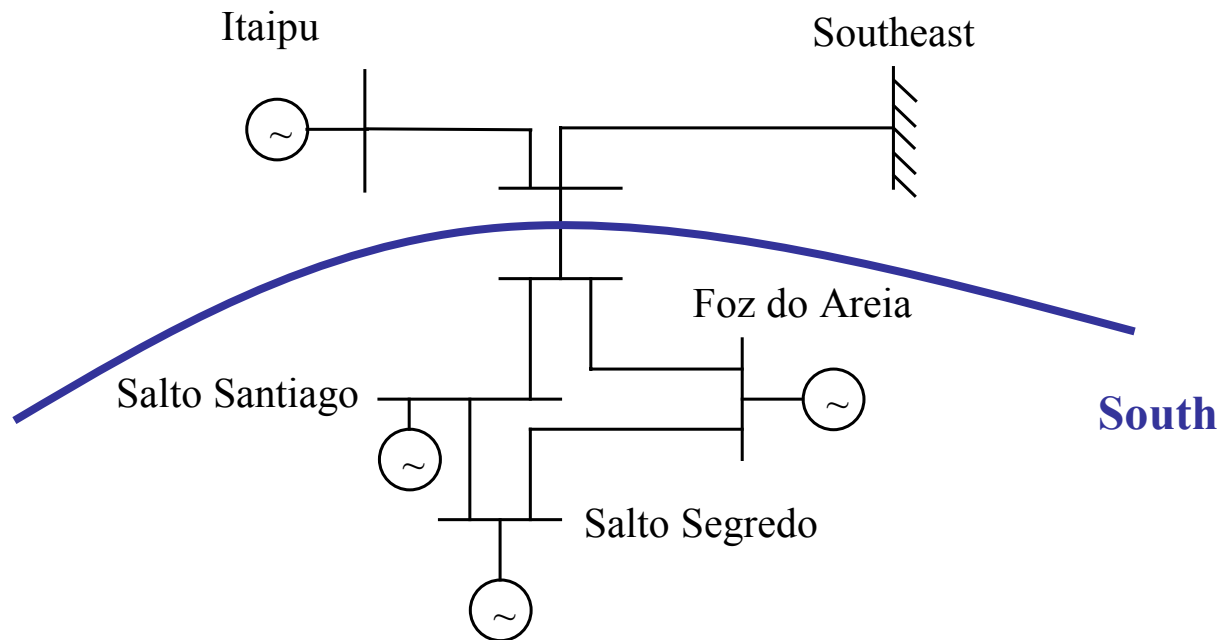
POWER SYSTEM OSCILLATION DAMPING CONTROL

INTRODUCTION

- **Purpose \Rightarrow choose adequate gains for the Power System Stabilizers (PSSs) installed on generators of a test system**
- **PSSs \Rightarrow used to improve the damping factor of electromechanical modes of oscillation**
- **Stabilization procedure:**
 - ➔ **Determine the system critical modes**
 - ➔ **Determine the machines where the installation of PSSs would be more effective**
 - ➔ **Assess each PSS contribution to the control effort**
 - ➔ **Tune the gains of the PSSs using transfer function residues associated with other information**

TEST SYSTEM

- Simplified representation of the Brazilian Southern system
- Characteristics:
 - Southeastern region represented by an infinite bus
 - Static exciters with high gain ($K_a = 100$, $T_a = 0.05$ s)



CRITICAL OSCILLATORY MODES

Critical electromechanical modes of oscillation

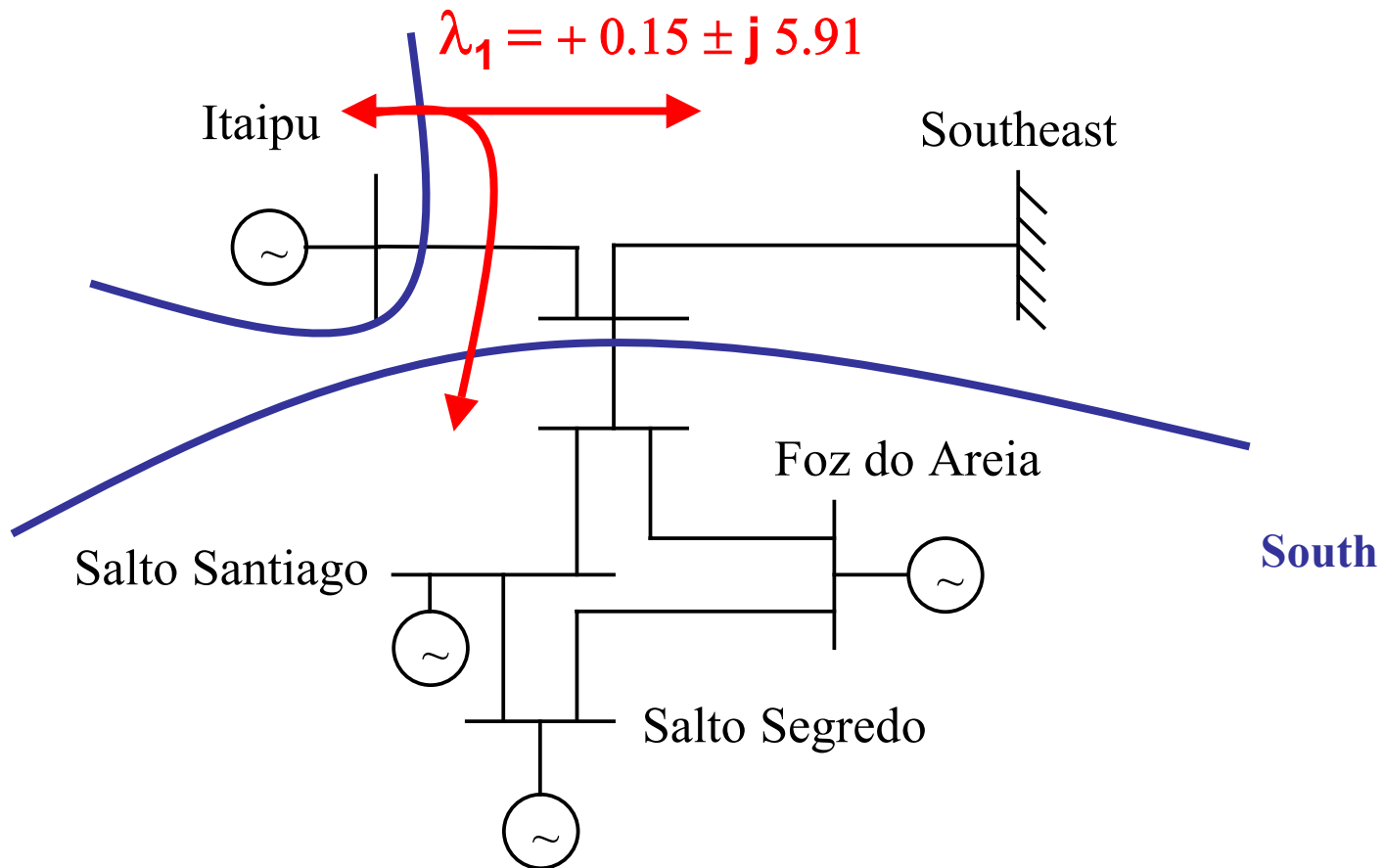
	Real	Imag.	Freq. (Hz)	Damping
λ_1	+0.15309	± 5.9138	0.94121	-2.59%
λ_2	+0.17408	± 4.6435	0.73904	-3.75%

Parameters related to the phase tuning of the PSSs

Number of lead blocks	T_w (s)	T_n (s)	T_d (s)
2	3	0.100	0.010

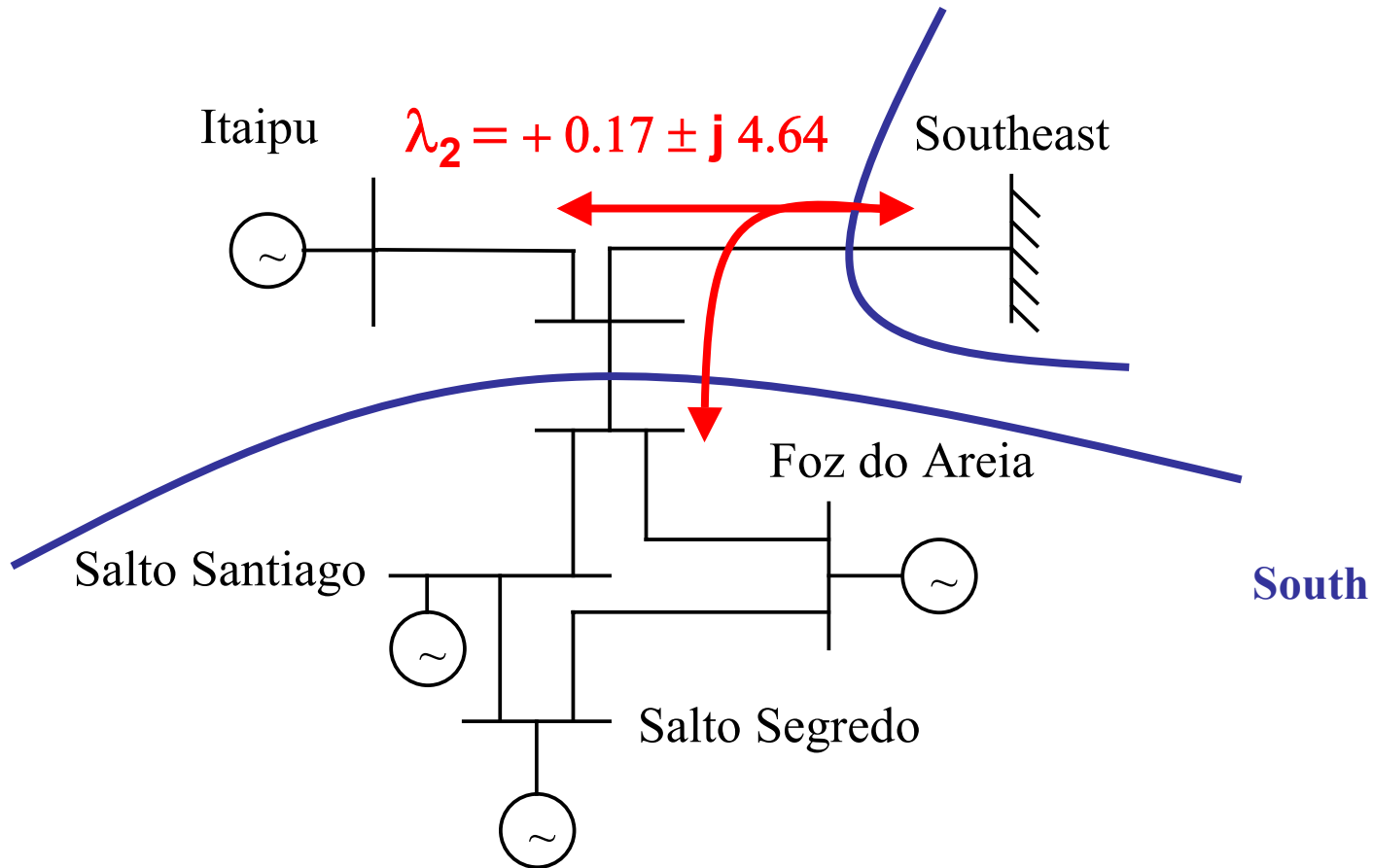
CRITICAL OSCILLATORY MODES

λ_1 : Itaipu x (South + Southeast)



CRITICAL OSCILLATORY MODES

λ_2 : Southeast x (Itaipu + South)



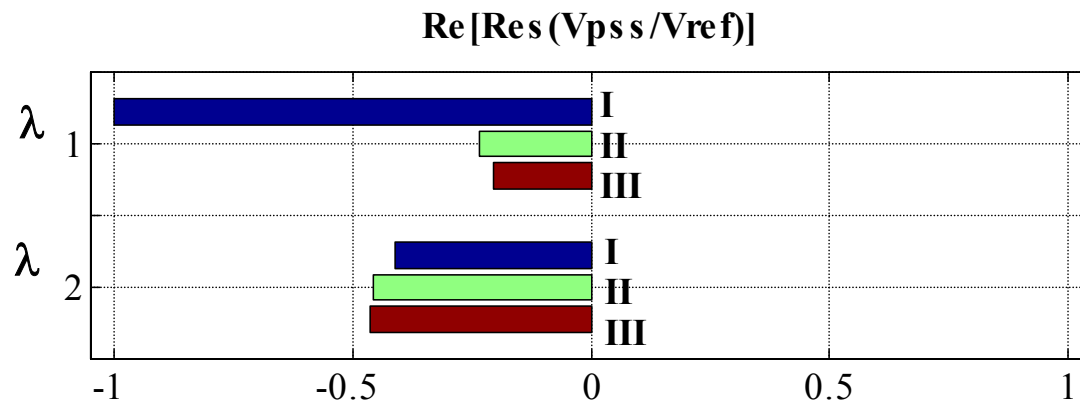
CONTRIBUTION OF EACH PSS TO THE λ SHIFT

- A change in the gain vector $\underline{\Delta K}$ will produce shifts in both the real and imaginary parts of the eigenvalues
- The contribution of each PSS to these shifts can be estimated using the matrix of transfer function residues
- For λ_1 and three PSSs:

$$\begin{bmatrix} \text{Re}[\Delta\lambda_1] \\ \text{Im}[\Delta\lambda_1] \end{bmatrix} = \begin{bmatrix} \text{Re} \left[R \left(\frac{\Delta V_{PSS1}}{\Delta V_{REF1}}, \lambda_1 \right) \right] & R \left(\frac{\Delta V_{PSS2}}{\Delta V_{REF2}}, \lambda_1 \right) & R \left(\frac{\Delta V_{PSS3}}{\Delta V_{REF3}}, \lambda_1 \right) \\ \text{Im} \left[R \left(\frac{\Delta V_{PSS1}}{\Delta V_{REF1}}, \lambda_1 \right) \right] & R \left(\frac{\Delta V_{PSS2}}{\Delta V_{REF2}}, \lambda_1 \right) & R \left(\frac{\Delta V_{PSS3}}{\Delta V_{REF3}}, \lambda_1 \right) \end{bmatrix} \begin{bmatrix} \Delta K_1 \\ \Delta K_2 \\ \Delta K_3 \end{bmatrix}$$

CONTRIBUTION OF EACH PSS TO THE λ SHIFT

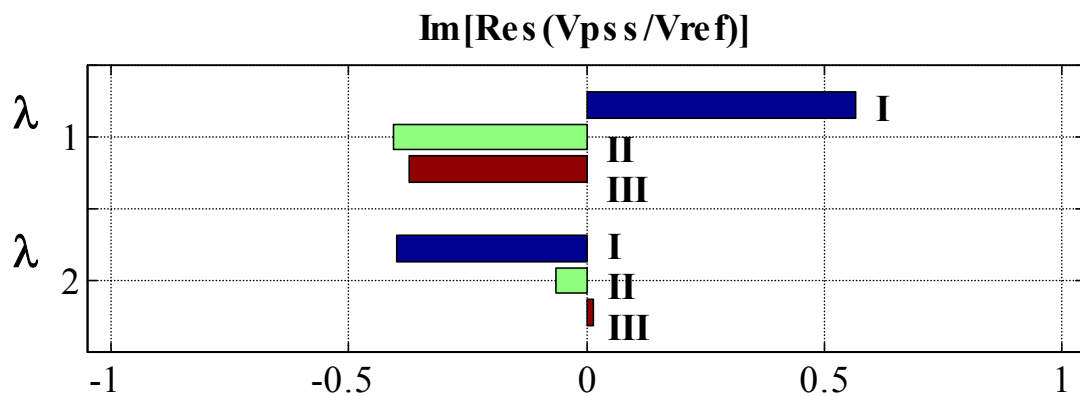
- Normalized contribution of each PSS in the shifts of the real and imaginary parts of the two critical eigenvalues



Oscillatory Modes

λ_1 – Itaipu mode

λ_2 – Southern mode



PSS Location

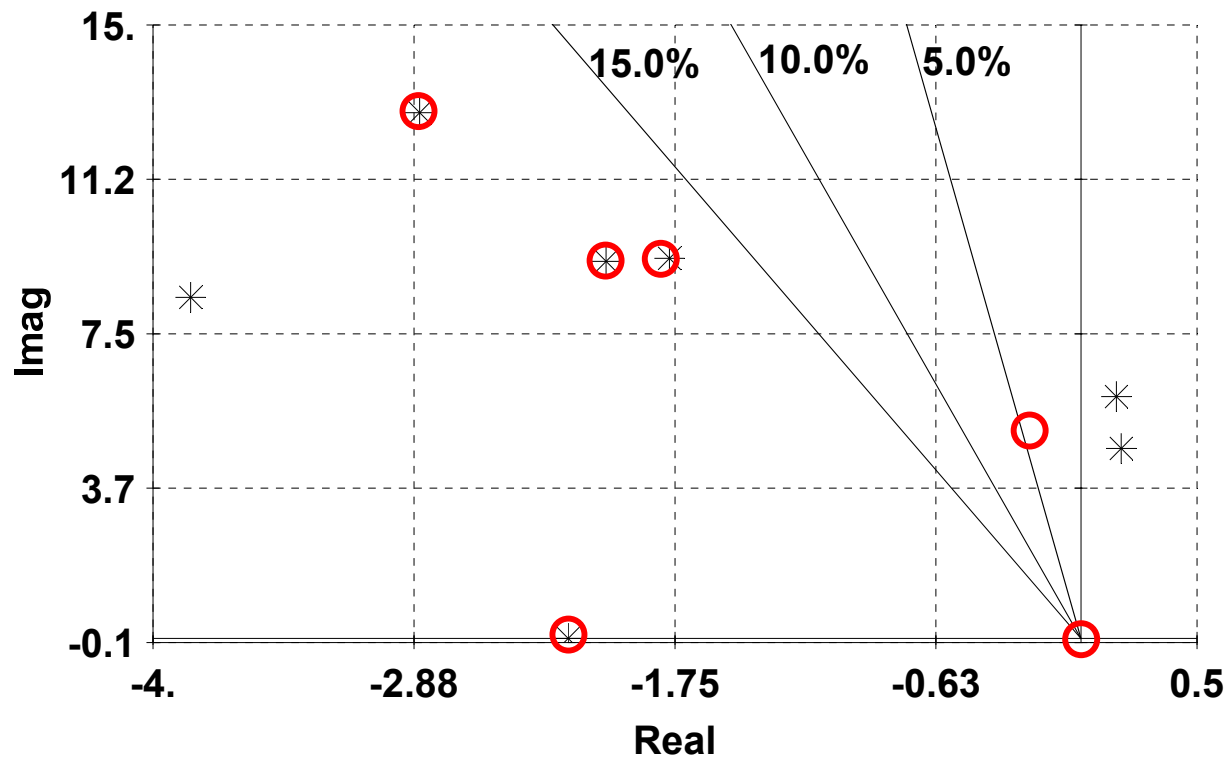
I – Itaipu

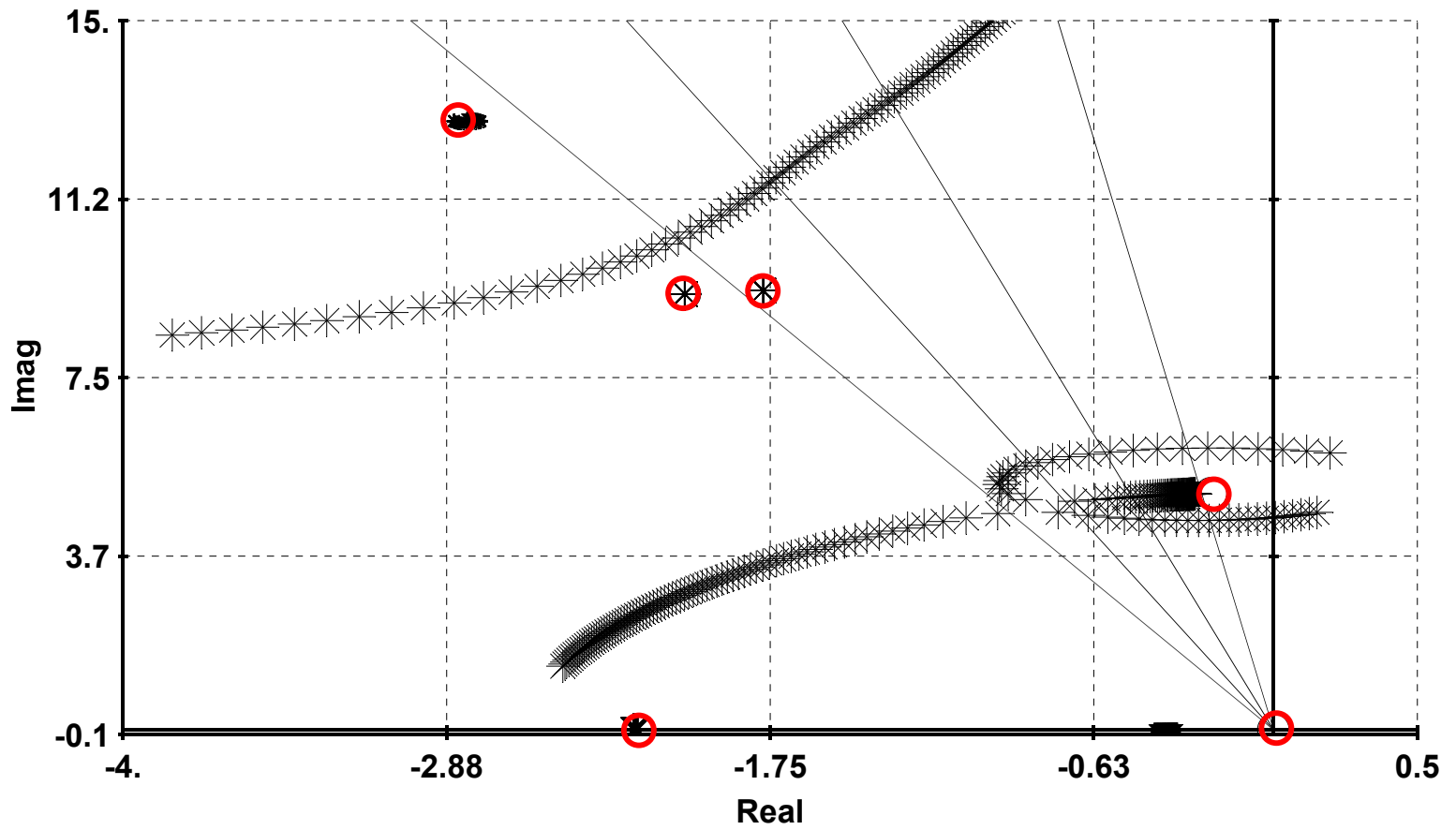
II – S. Segredo

III – Foz do Areia

POLE-ZERO MAP OF $[\Delta\omega/\Delta V_{REF}]$

- Map of poles and zeros for the matrix transfer function $[\Delta\omega/\Delta V_{REF}]$ with PSS in Itaipu





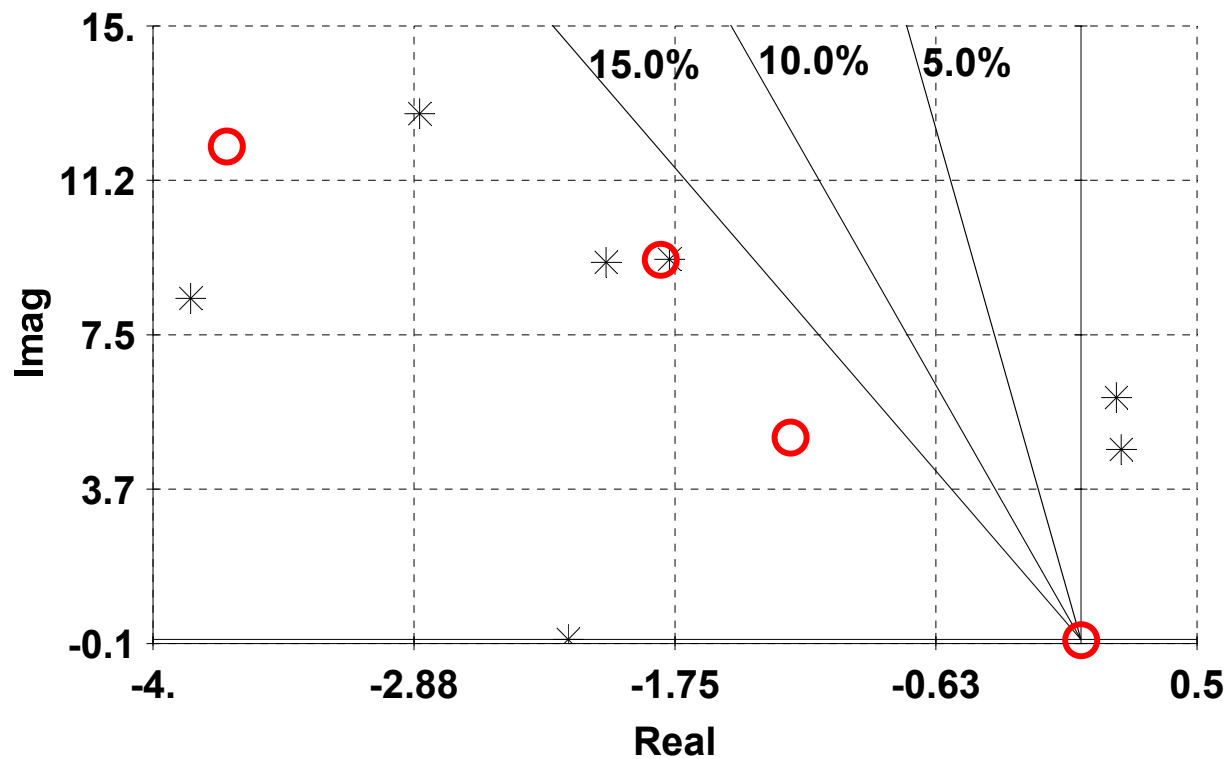
POLE PLACEMENT – 2 MODES AND 2 PSSs

- Improve the damping factors of two critical oscillatory modes by the use of two PSSs installed in:
 - Itaipu and Salto Segredo
- The gains of the PSSs are computed for a desired shift in the real part of the eigenvalues
- Gain vector $\underline{\Delta K}$ will be calculated at each Newton iteration using the following relation:

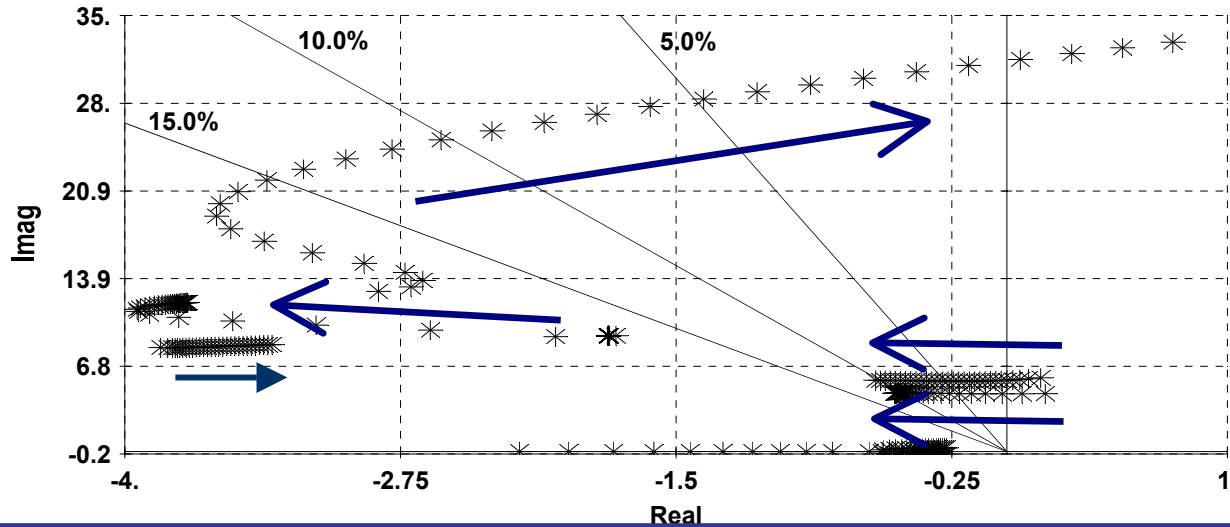
$$\begin{bmatrix} \Delta K_1 \\ \Delta K_2 \end{bmatrix} = \begin{bmatrix} \operatorname{Re} \left[R \left(\frac{\Delta V_{PSS1}}{\Delta V_{REF1}}, \lambda_1 \right) \right] & R \left(\frac{\Delta V_{PSS2}}{\Delta V_{REF2}}, \lambda_1 \right) \\ \operatorname{Re} \left[R \left(\frac{\Delta V_{PSS1}}{\Delta V_{REF1}}, \lambda_2 \right) \right] & R \left(\frac{\Delta V_{PSS2}}{\Delta V_{REF2}}, \lambda_2 \right) \end{bmatrix}^{-1} \begin{bmatrix} \operatorname{Re} \left[\Delta \lambda_1 \right] \\ \operatorname{Re} \left[\Delta \lambda_2 \right] \end{bmatrix}$$

POLE-ZERO MAP OF $[\Delta\omega/\Delta V_{REF}]_{2 \times 2}$

- Map of poles and zeros for the matrix transfer function $[\Delta\omega/\Delta V_{REF}]_{2 \times 2}$ with PSSs in Itaipu and S. Segredo



POLE PLACEMENT – 2 MODES AND 2 PSSs

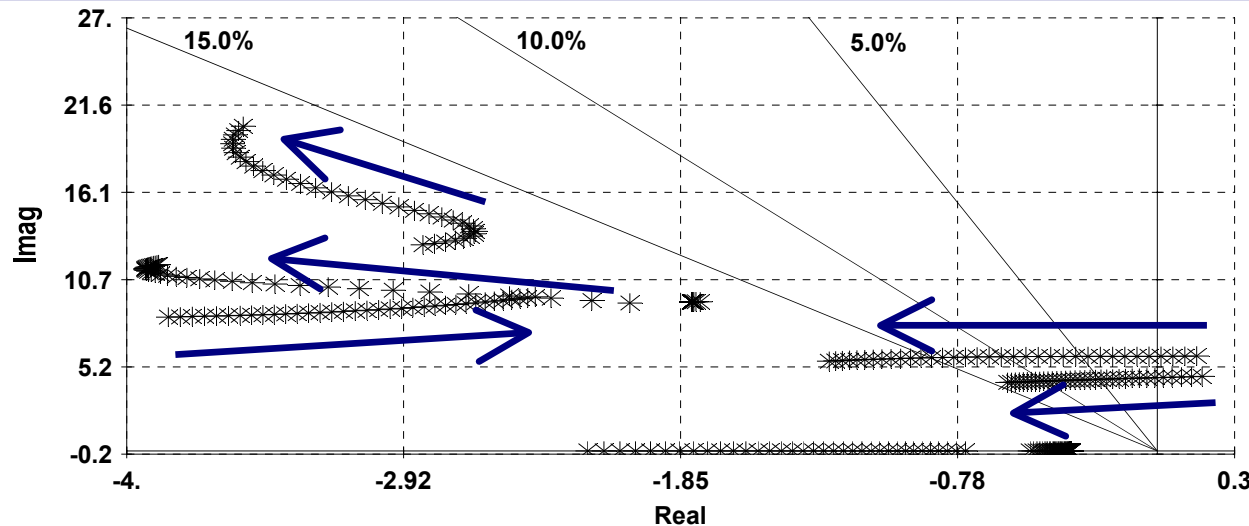


$$K_{I\text{taipu}} = 5$$

$$K_{S.\text{Segredo}} = 91$$

$$\zeta_{\lambda_1} = 10.4\%$$

$$\zeta_{\lambda_2} = 10.9\%$$



$$K_{I\text{taipu}} = 14$$

$$K_{S.\text{Segredo}} = 29$$

$$\zeta_{\lambda_1} = 22.0\%$$

$$\zeta_{\lambda_2} = 13.5\%$$

POLE PLACEMENT – 2 MODES AND 2 PSSs

- **The pole location must be carefully chosen**
 - ➔ **Some specified pole locations may require high PSS gains and cause exciter mode instability**
- **Comments on the installation of a third PSS**
 - ➔ **Facilitates the pole placement \Rightarrow more convenient pole-zero map**
 - ➔ **Number of PSSs differs from the number of poles to be placed \Rightarrow pseudo-inverse of a non-square matrix must be computed**
 - ➔ **Algorithm must be modified**

PSEUDO-INVERSE ALGORITHM

- **Problems without unique solution \Rightarrow pseudo-inverse algorithm**

$$\text{Re}[R]_{m \times n} \underline{\Delta K}_{n \times 1} = \text{Re}[\Delta \lambda]_{m \times 1} \quad \begin{array}{l} m = \text{number of modes} \\ n = \text{number of PSSs} \end{array}$$

- **If $m < n$ \Rightarrow the algorithm will produce gain values that ensure a minimum norm for the gain vector**

$$\min \|\underline{\Delta K}\|$$

- **If $m > n$ \Rightarrow the algorithm will produce gain values that ensure a minimum norm for the error vector (solution of the least square problem)**

$$\min \|\text{Re}[R] \underline{\Delta K} - \text{Re}[\Delta \lambda]\|$$

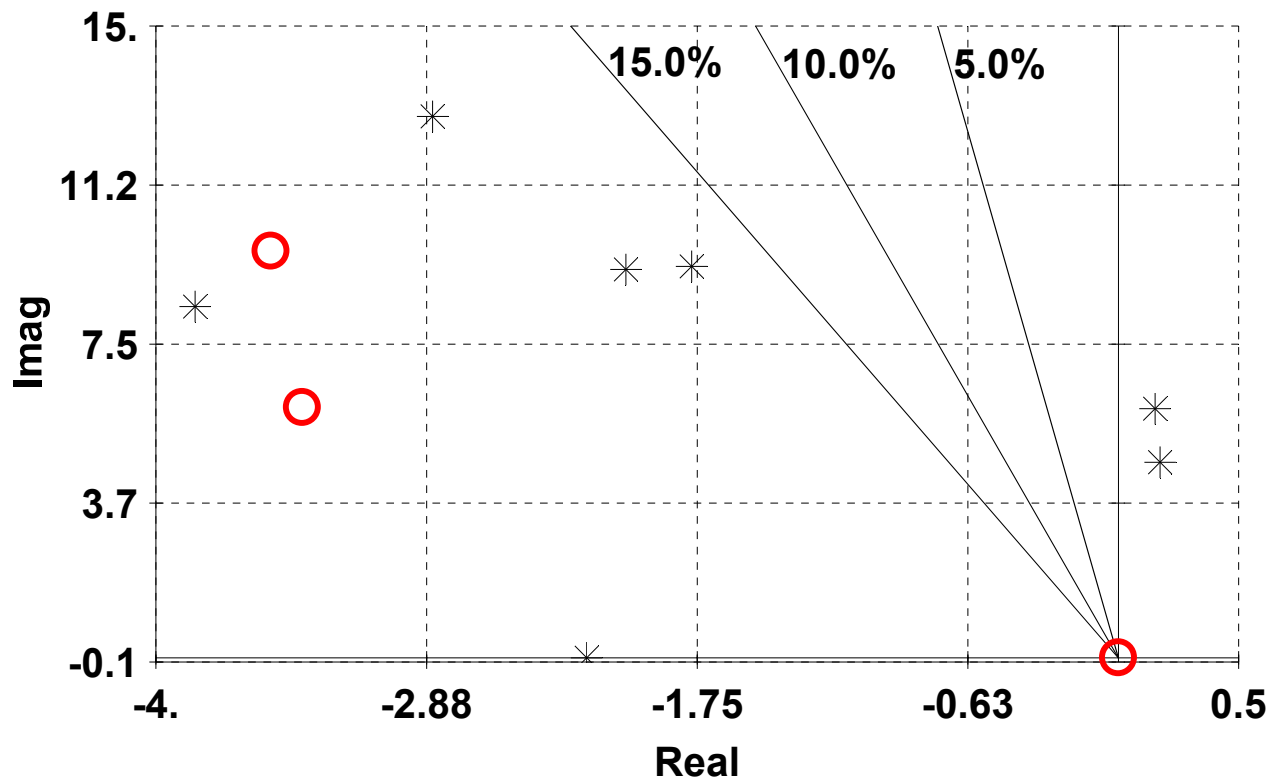
POLE PLACEMENT – 2 MODES AND 3 PSSs

- Three PSSs installed in:
 - Itaipu, Salto Segredo and Foz do Areia
- Pseudo-inverse algorithm will provide the solution with minimum norm for the gain vector $\underline{\Delta K}$
- The gains of the PSSs are computed for a desired shift in the real part of the eigenvalues
- At every iteration, the pseudo-inverse algorithm updates and solves the following matrix equation:

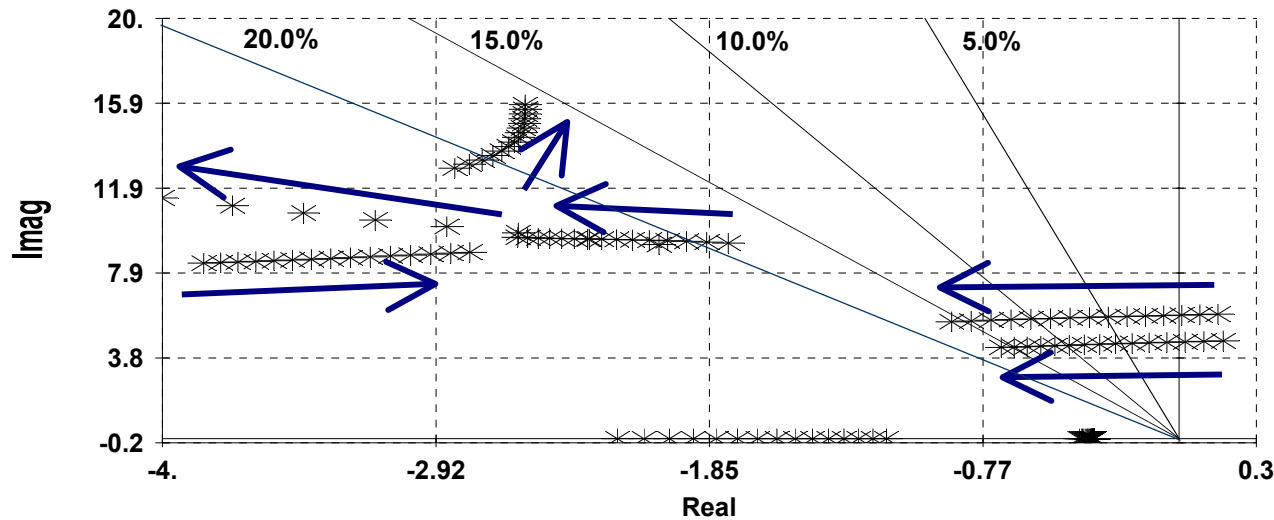
$$\begin{bmatrix} \Delta K_1 \\ \Delta K_2 \\ \Delta K_3 \end{bmatrix} = \left[\begin{array}{ccc} \operatorname{Re} \left[R \left(\frac{\Delta V_{PSS1}}{\Delta V_{REF1}}, \lambda_1 \right) \right] & R \left(\frac{\Delta V_{PSS2}}{\Delta V_{REF2}}, \lambda_1 \right) & R \left(\frac{\Delta V_{PSS3}}{\Delta V_{REF3}}, \lambda_1 \right) \\ \operatorname{Re} \left[R \left(\frac{\Delta V_{PSS1}}{\Delta V_{REF1}}, \lambda_2 \right) \right] & R \left(\frac{\Delta V_{PSS2}}{\Delta V_{REF2}}, \lambda_2 \right) & R \left(\frac{\Delta V_{PSS3}}{\Delta V_{REF3}}, \lambda_2 \right) \end{array} \right]^+ \begin{bmatrix} \operatorname{Re} \left[\Delta \lambda_1 \right] \\ \operatorname{Re} \left[\Delta \lambda_2 \right] \end{bmatrix}$$

POLE-ZERO MAP OF $[\Delta\omega/\Delta V_{REF}]_{3 \times 3}$

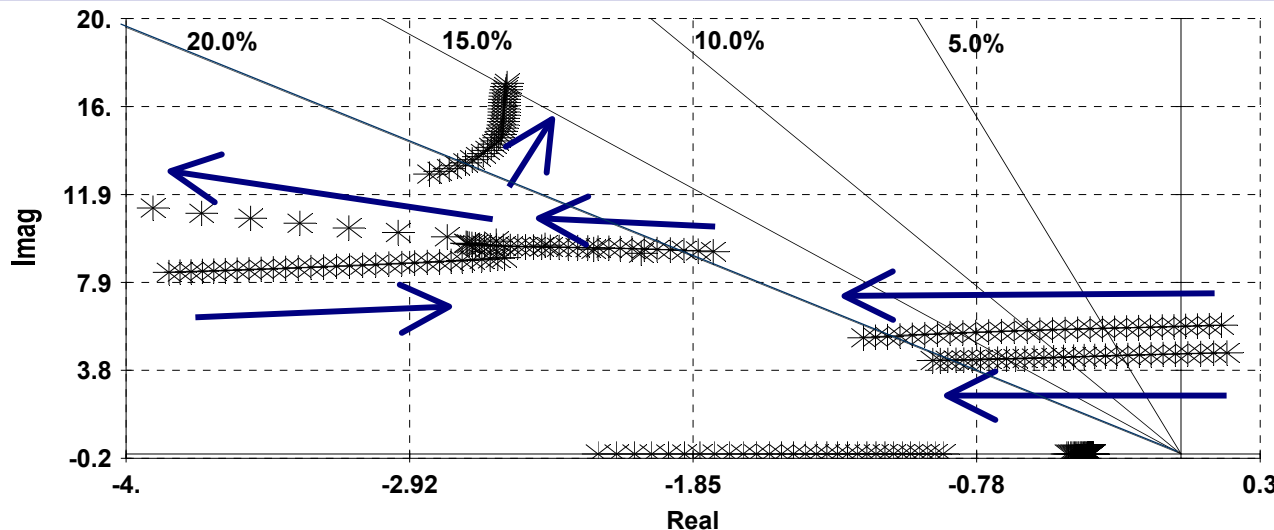
- Map of poles and zeros for the matrix transfer function $[\Delta\omega/\Delta V_{REF}]_{3 \times 3}$ with PSSs in Itaipu, S. Segredo and Foz do Areia



POLE PLACEMENT – 2 MODES AND 3 PSSS



$K_{Itaipu} = 8.1$
 $K_{S.Segredo} = 11.9$
 $K_{Foz\ do\ Areia} = 12.0$
 $\zeta_{\lambda 1} = 15.9\%$
 $\zeta_{\lambda 2} = 15.9\%$



$K_{Itaipu} = 10.4$
 $K_{S.Segredo} = 16.3$
 $K_{Foz\ do\ Areia} = 16.3$
 $\zeta_{\lambda 1} = 22.0\%$
 $\zeta_{\lambda 2} = 21.4\%$

CONCLUSIONS

- **Proposed pole placement algorithm:**
 - ➔ **Based on transfer function residues and Newton method**
 - ➔ **Uses generalized inverse matrices to address cases without unique solution**
- **Inspection of the pole-zero map is very useful**
- **Pole placement method**
 - ➔ **Selected pole location can impose constraints that may be unnecessarily severe**
 - ➔ **Results may be not feasible \Rightarrow pole placement may yield undesirably high values for the PSS gains**

FINAL REMARKS

- **Important developments and increased use of modal analysis**
- **Large-scale, control-oriented eigenanalysis**
- **Much room for further improvements**