IMPACT OF INTERACTIONS AMONG POWER SYSTEM CONTROLS

NELSON MARTINS[1] JULIO C.R. FERRAZ[1,2] SERGIO GOMES JR.[1,2]

[1]CEPEL [2]COPPE/UFRJ

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**

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

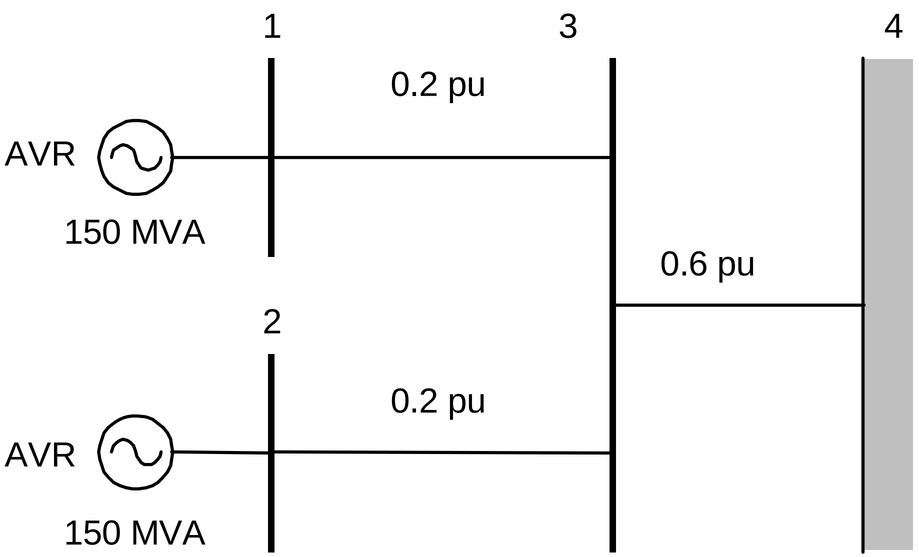
ADVERSE EFFECTS ON INTRA-PLANT MODES CAUSED BY PSS

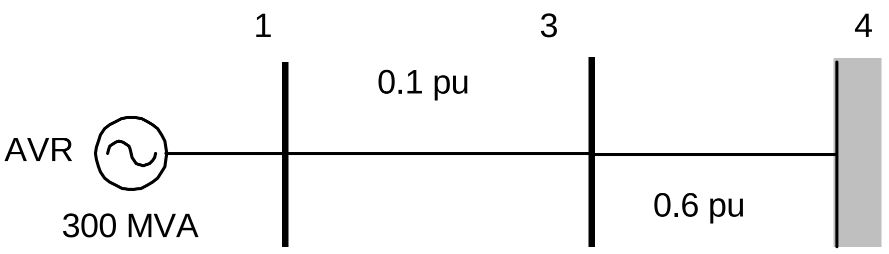
- Large systems $\Rightarrow$ most multi-unit power plants are usually modeled as single equivalent machines
  - ➔Reduces the number of system states, but…
  - ➔Does not capture the intra-plant dynamics

- When improperly designed, PSSs may cause adverse interactions and intra-plant mode instability

ADVERSE EFFECTS ON INTRA-PLANT MODES CAUSED BY PSS

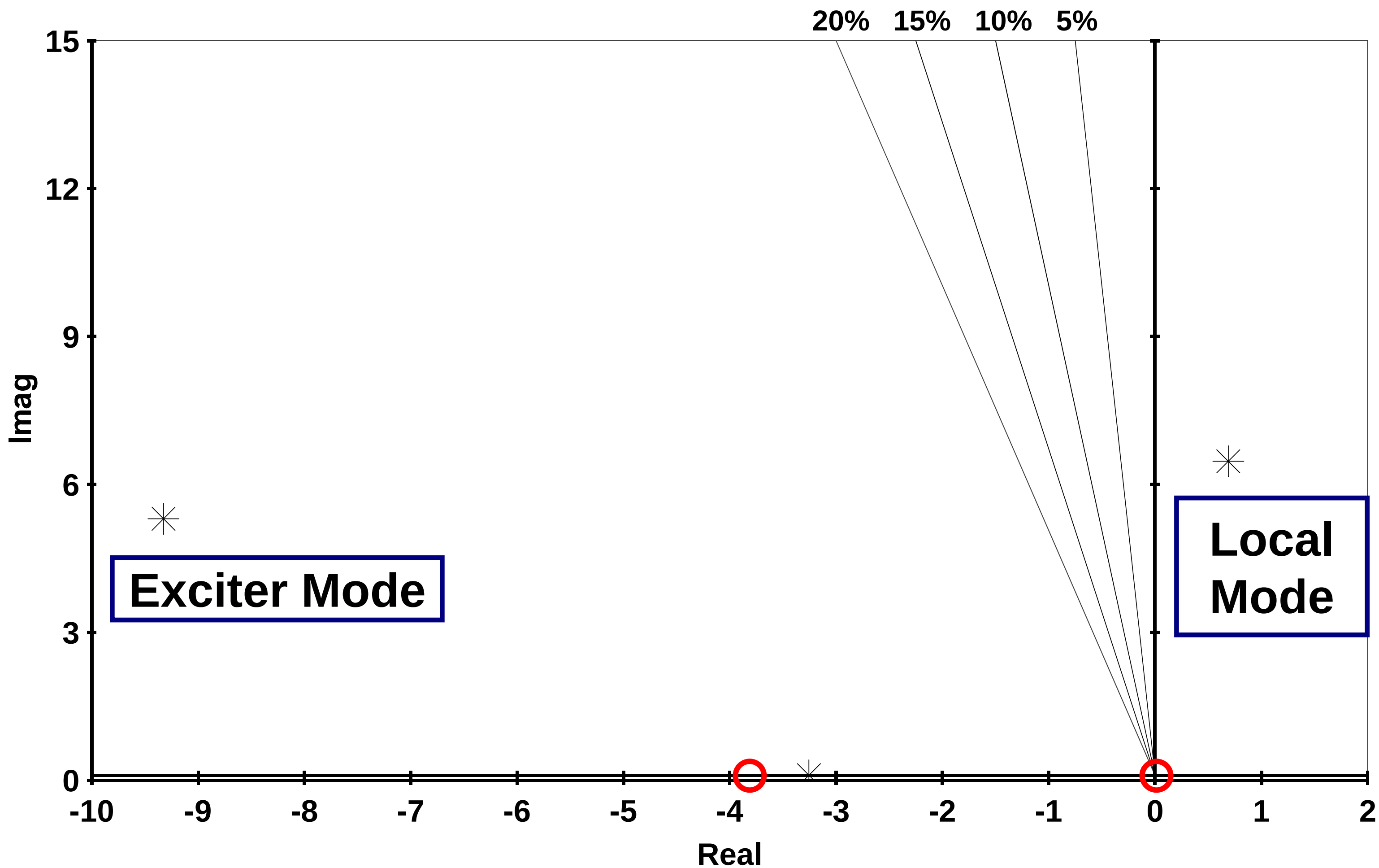
- **Two-unit power plant connected through a high impedance to the infinite bus**
  - **➔2-Machine system**
  - **➔Equivalent SMIB representation**





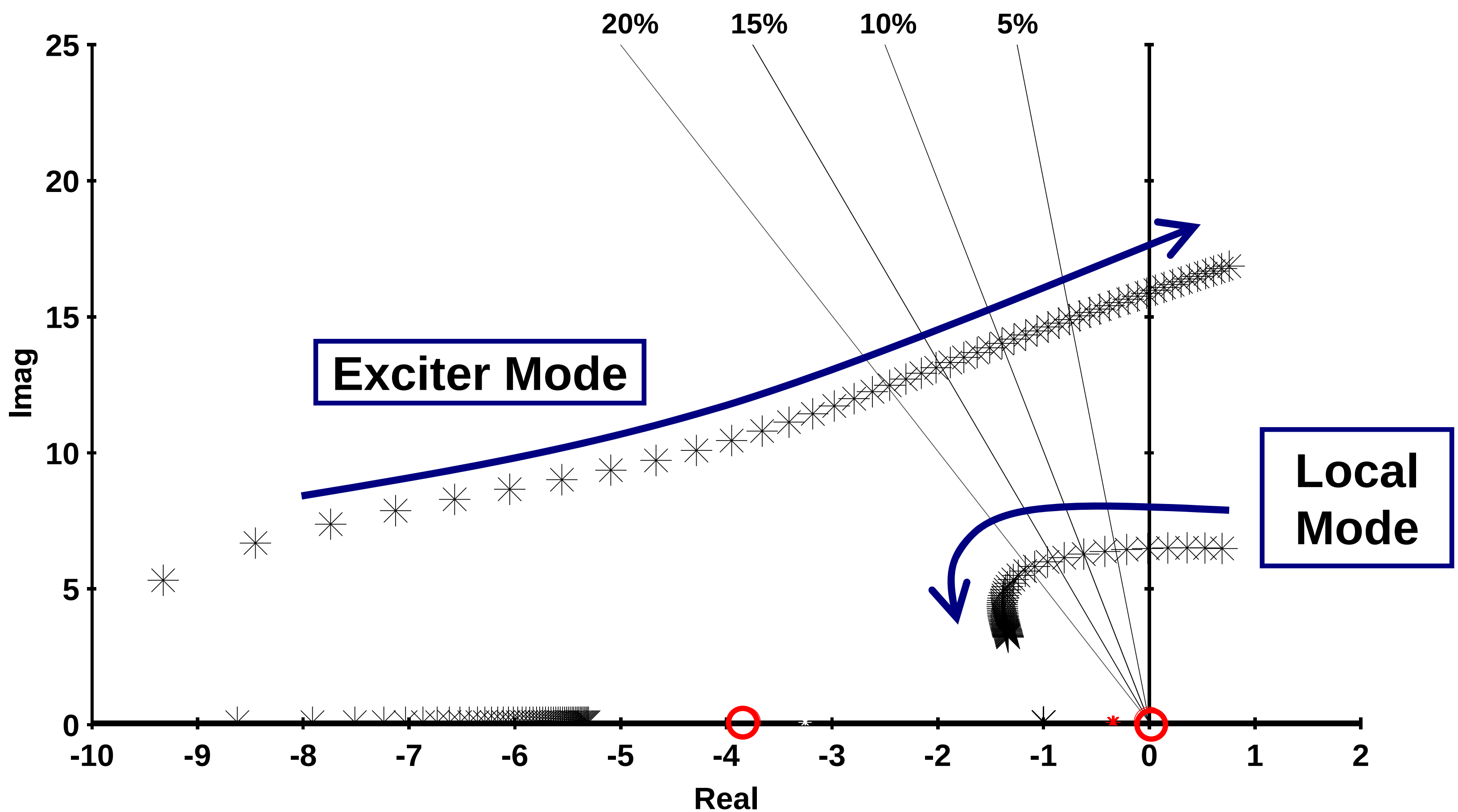
Adverse Effects ON Intra-Plant Modes Caused by PSS

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



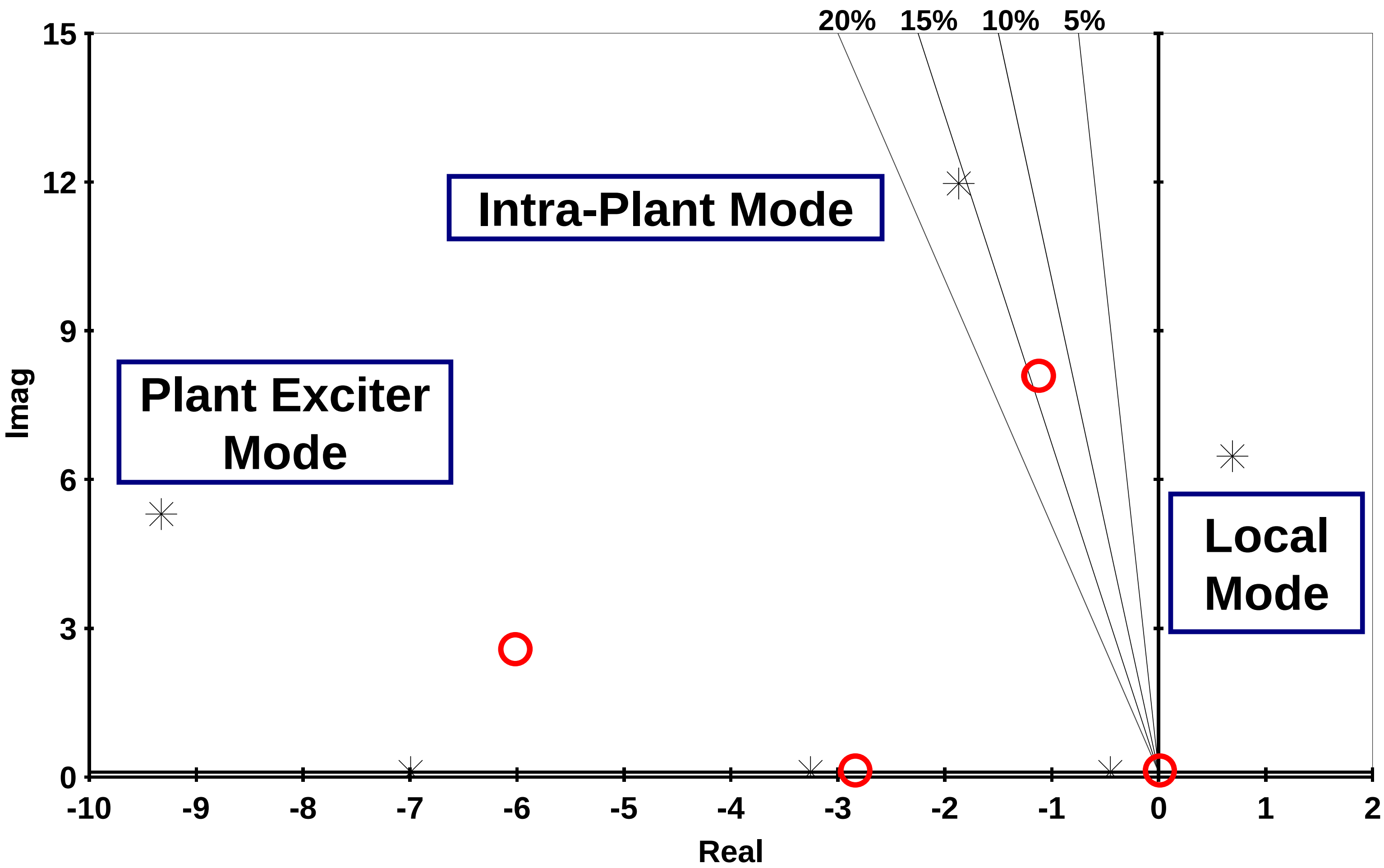
Adverse Effects on Intra-Plant Modes Caused by PSS

- **SMIB system – PSS (center frequency = 1.0 Hz)**



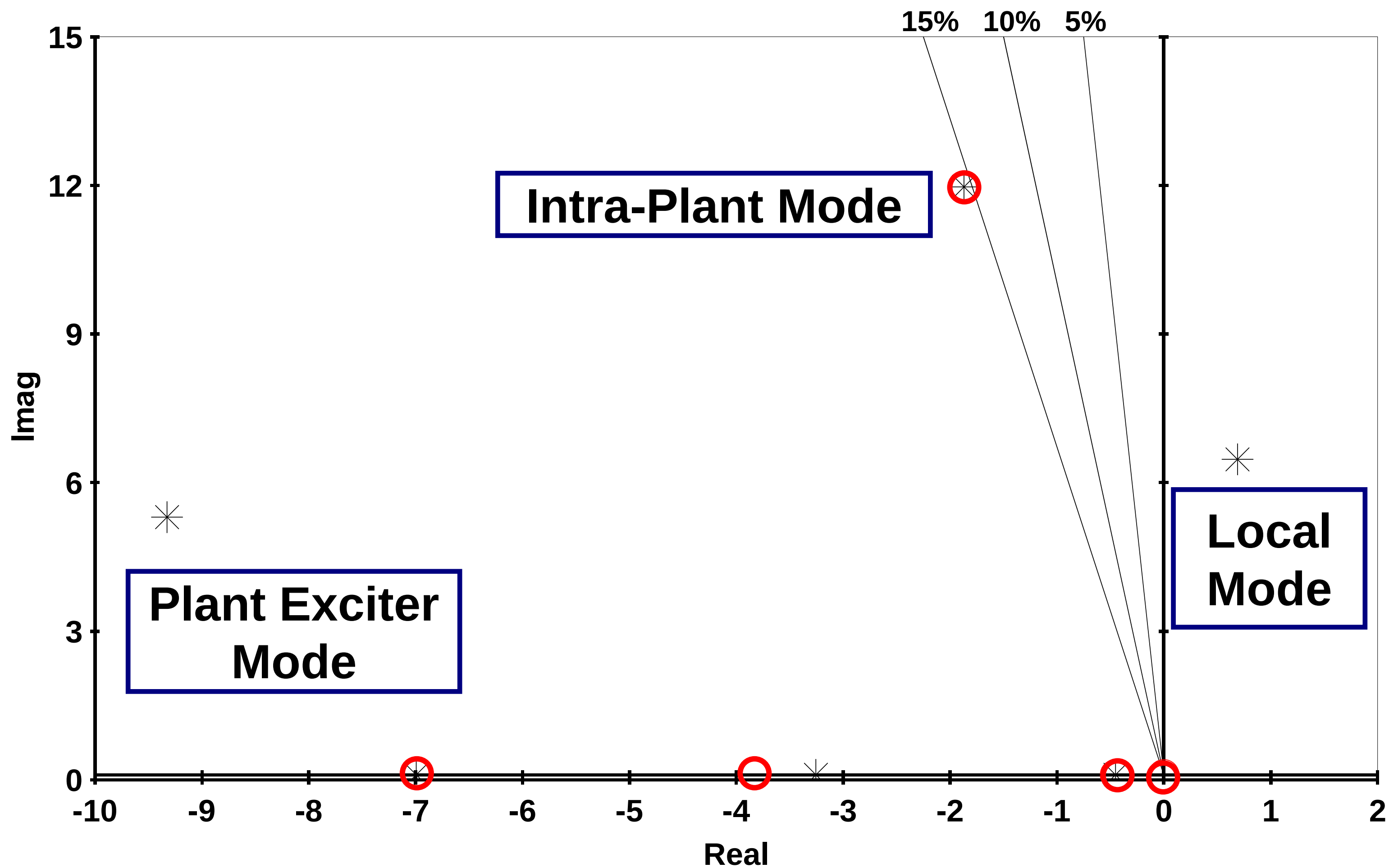
ADVERSE EFFECTS ON INTRA-PLANT MODES CAUSED BY PSS

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



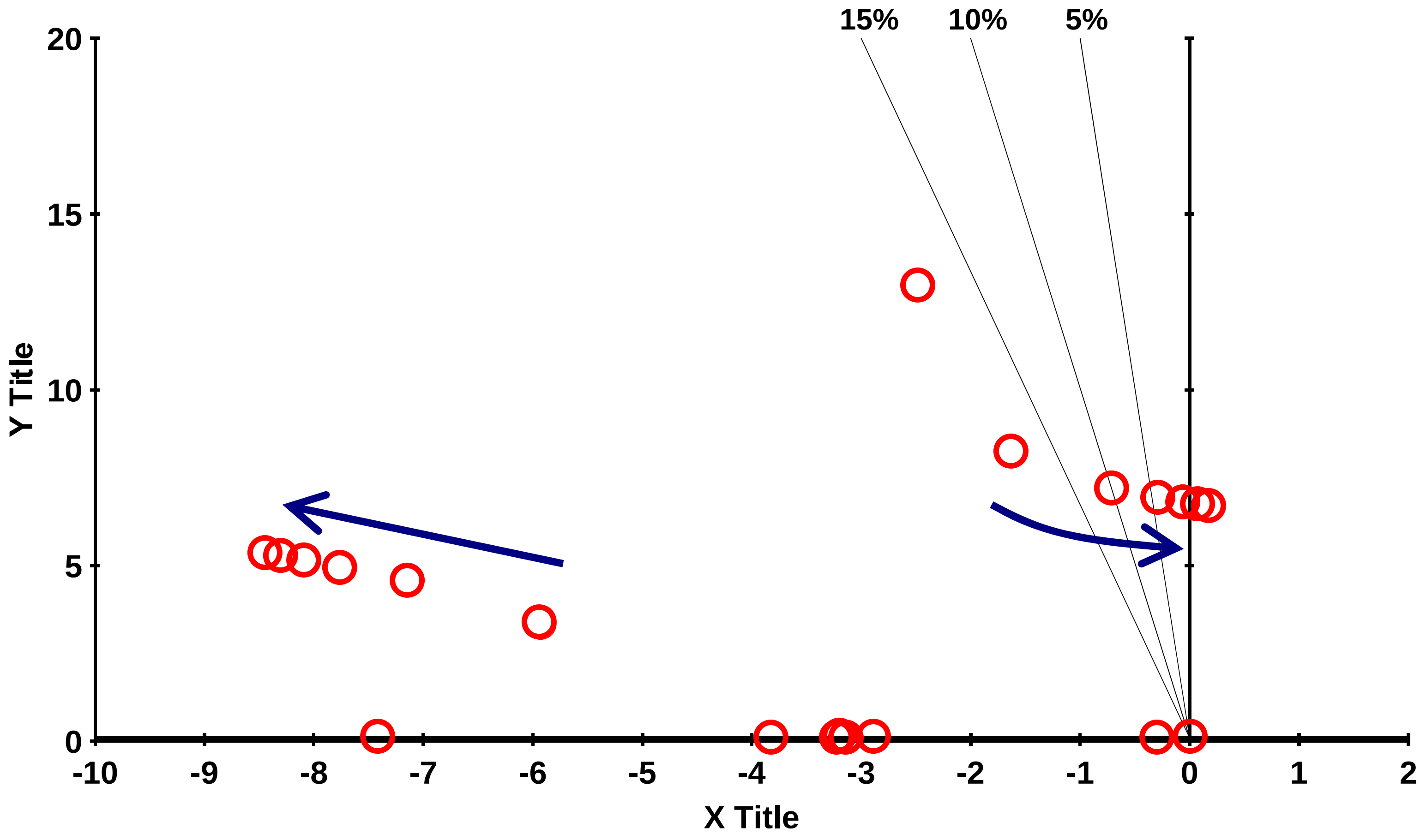
ADVERSE EFFECTS ON INTRA-PLANT MODES CAUSED BY PSS

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



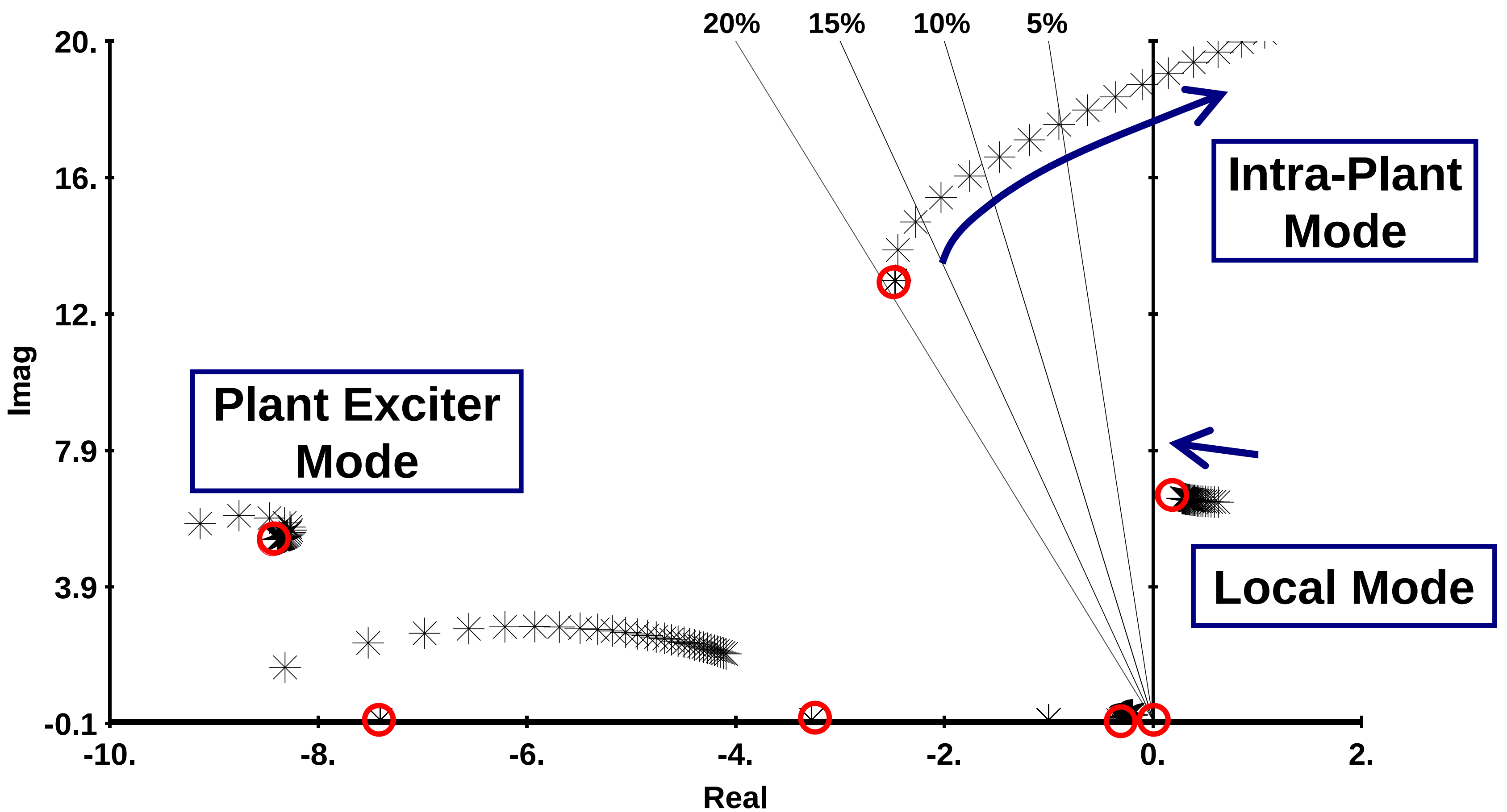
ADVERSE EFFECTS ON INTRA-PLANT MODES CAUSED BY PSS

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



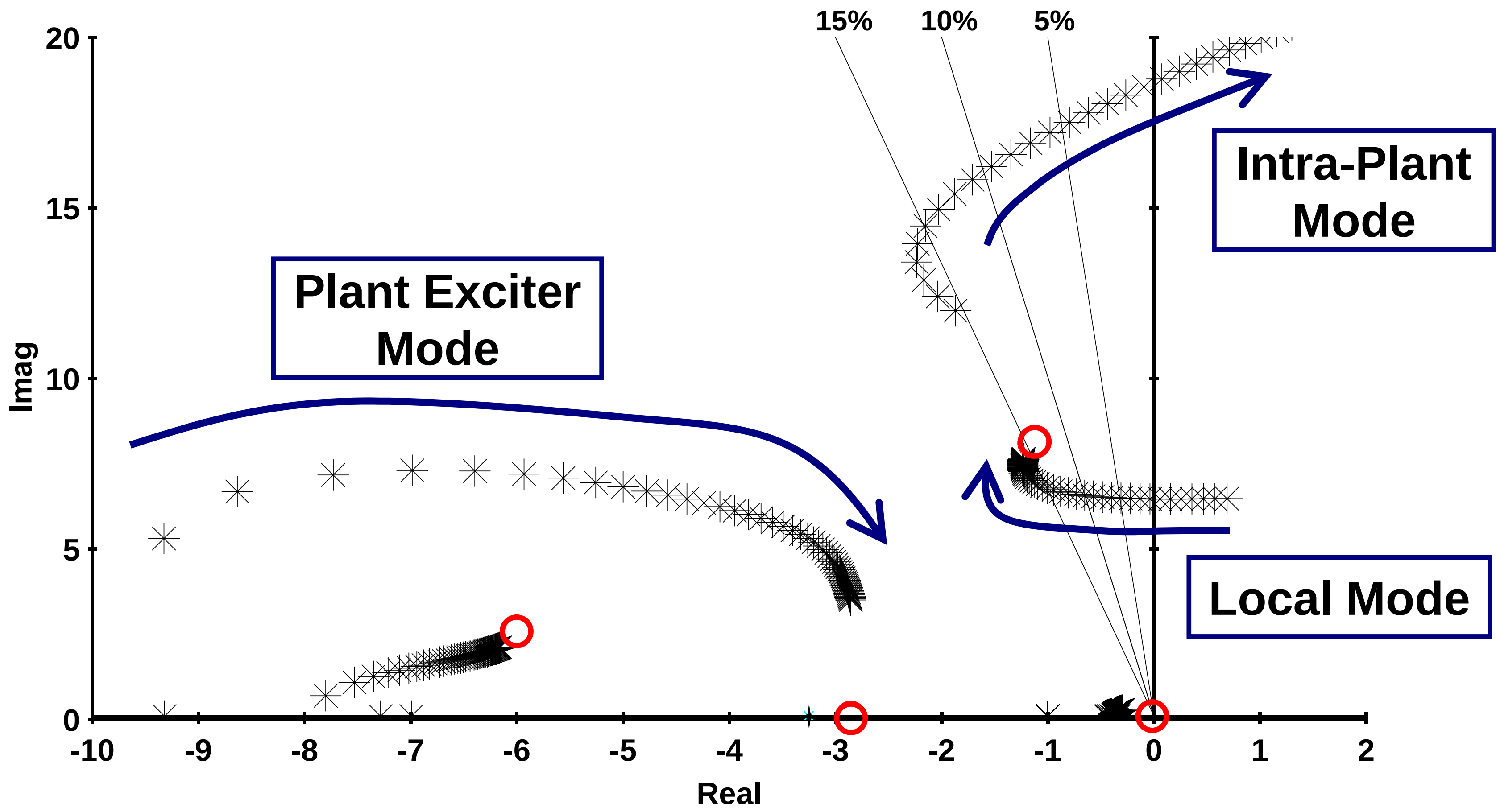
ADVERSE EFFECTS ON INTRA-PLANT MODES CAUSED BY PSS

- 7 Machines, 1 PSS



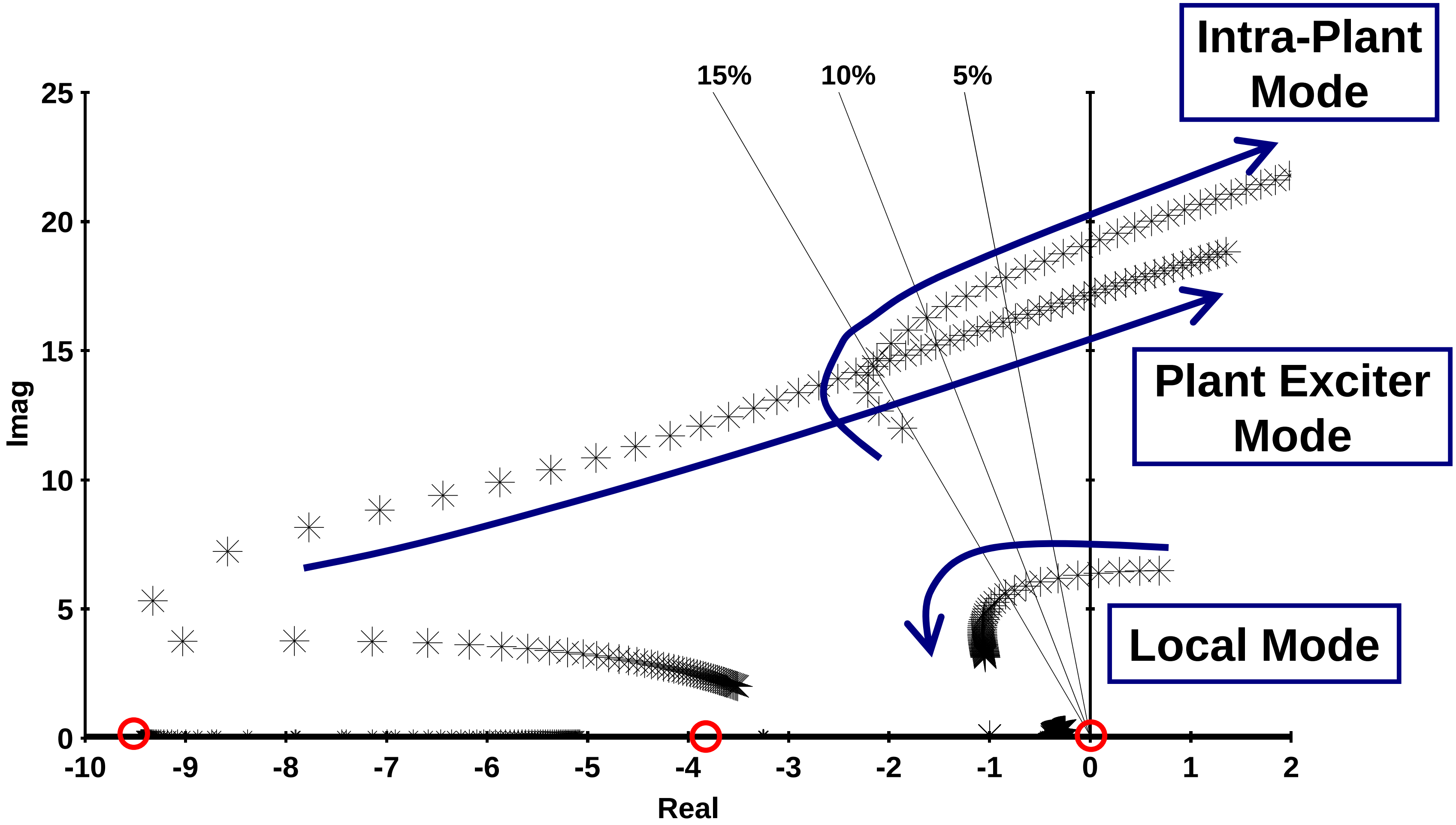
ADVERSE EFFECTS ON INTRA-PLANT MODES CAUSED BY PSS

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



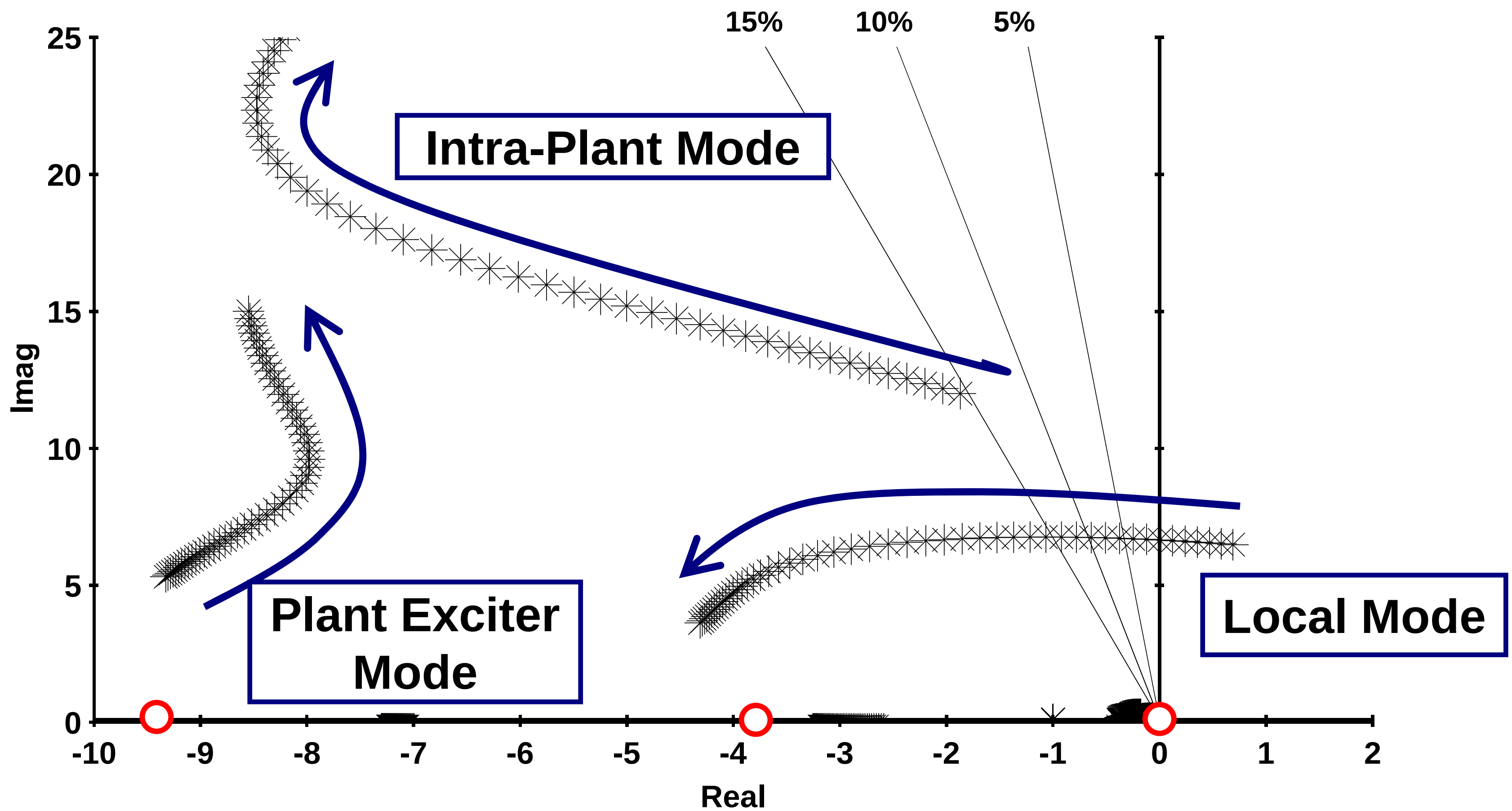
Adverse Effects ON Intra-Plant Modes Caused by PSS

- **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)



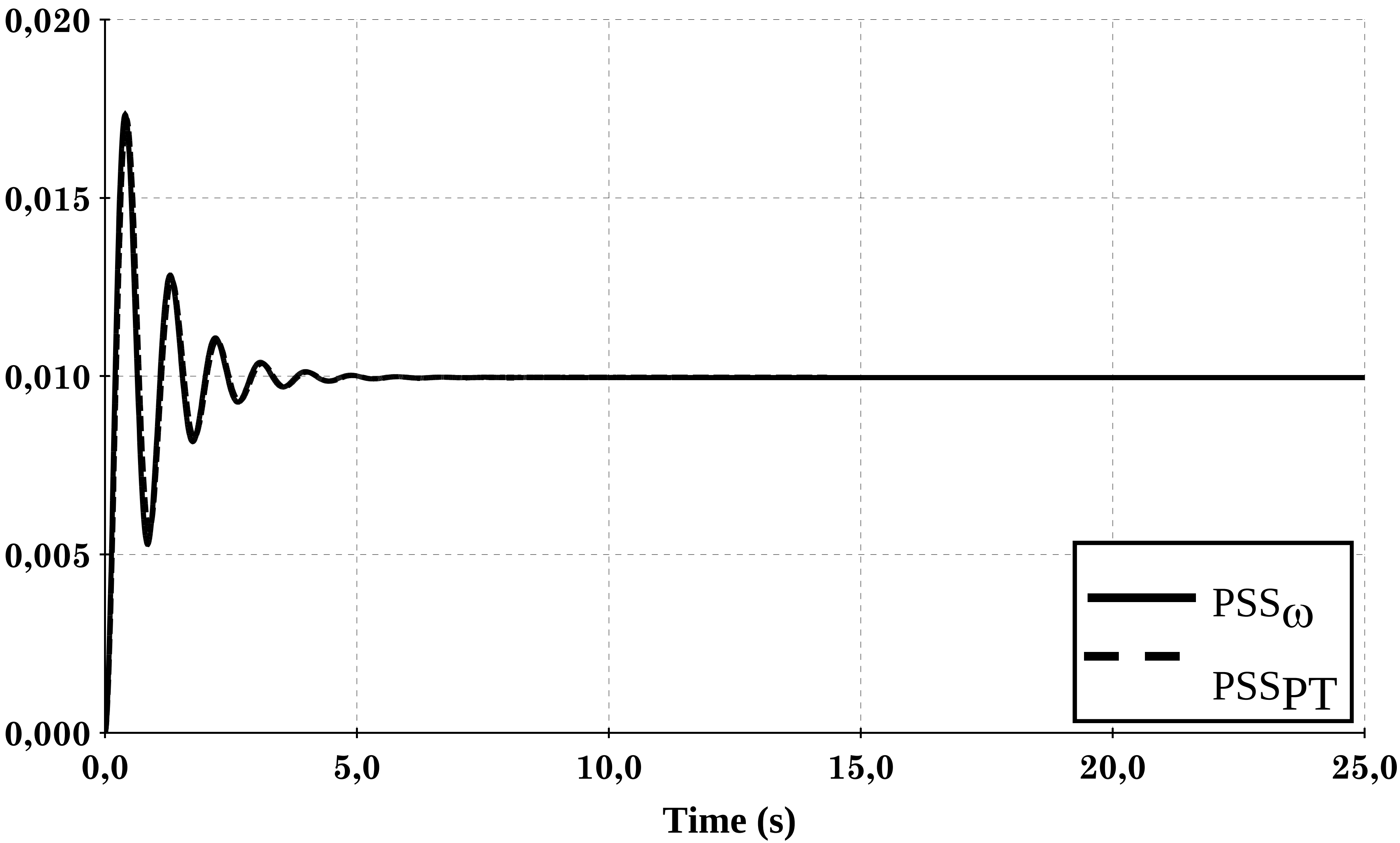
USING ZEROS TO UNDERSTAND THE ADVERSE TERMINAL VOLTAGE TRANSIENTS INDUCED BY THE PRESENCE OF PSSs

ADVERSE IMPACTS ON TERMINAL VOLTAGE DUE TO PSSs

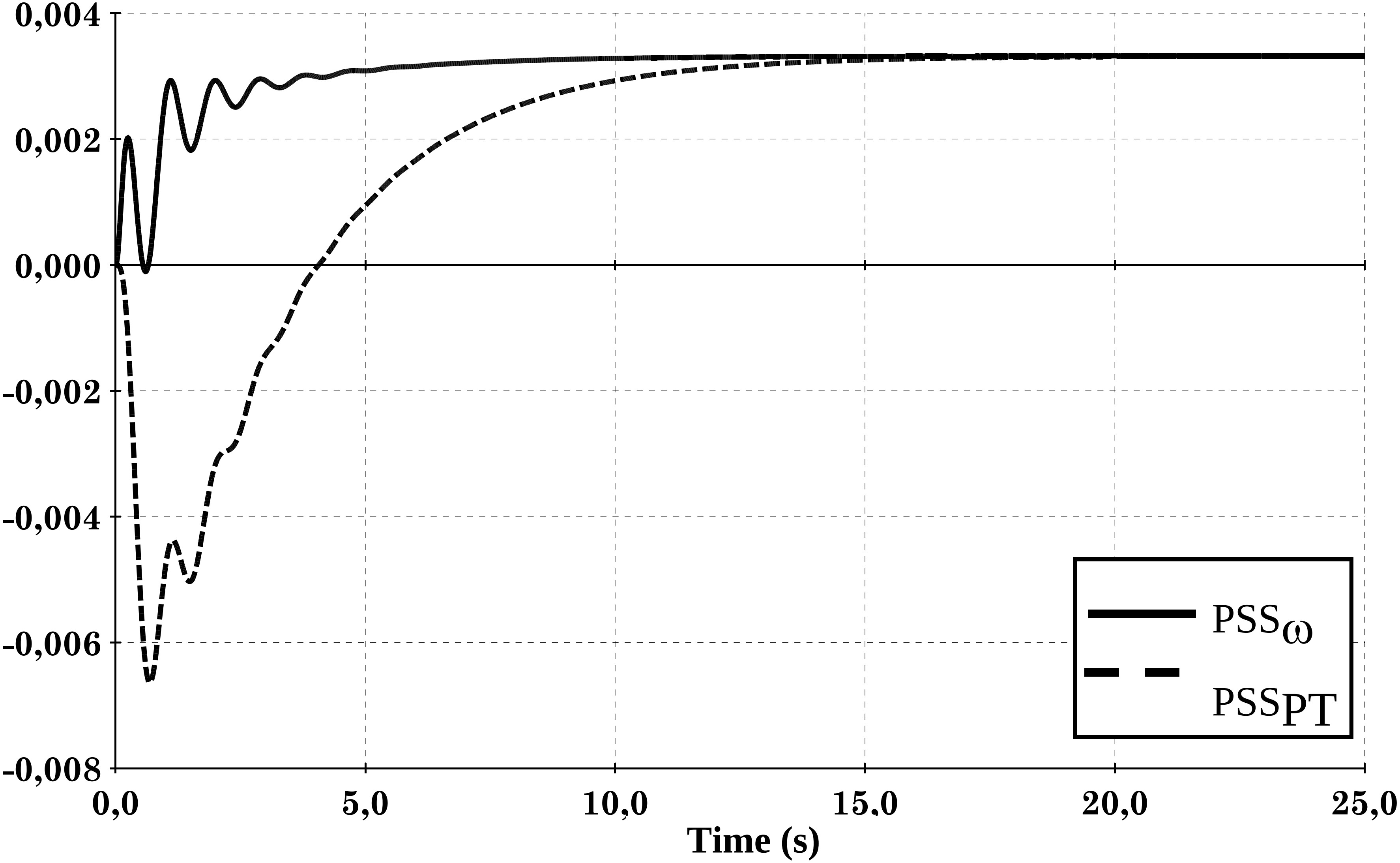
- **Studying zeros to understand the adverse voltage transients induced by the presence of PSSs**

- **Comparing the performances of PSSs derived from either rotor speed or terminal power signals**

ACTIVE POWER CHANGES FOLLOWING ΔPMEC IN SMIB

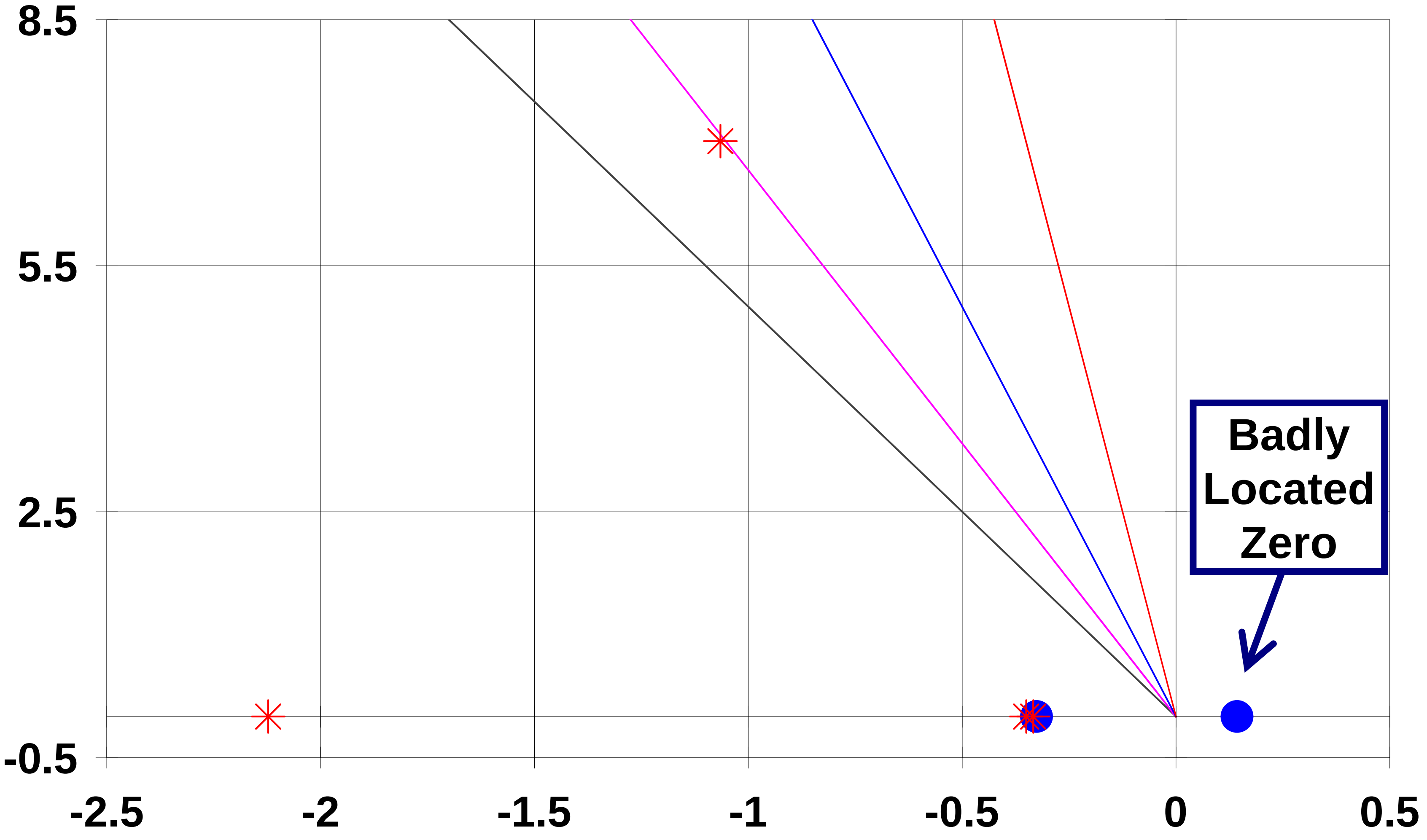


REACTIVE POWER CHANGES FOLLOWING ΔPMEC IN SMIB

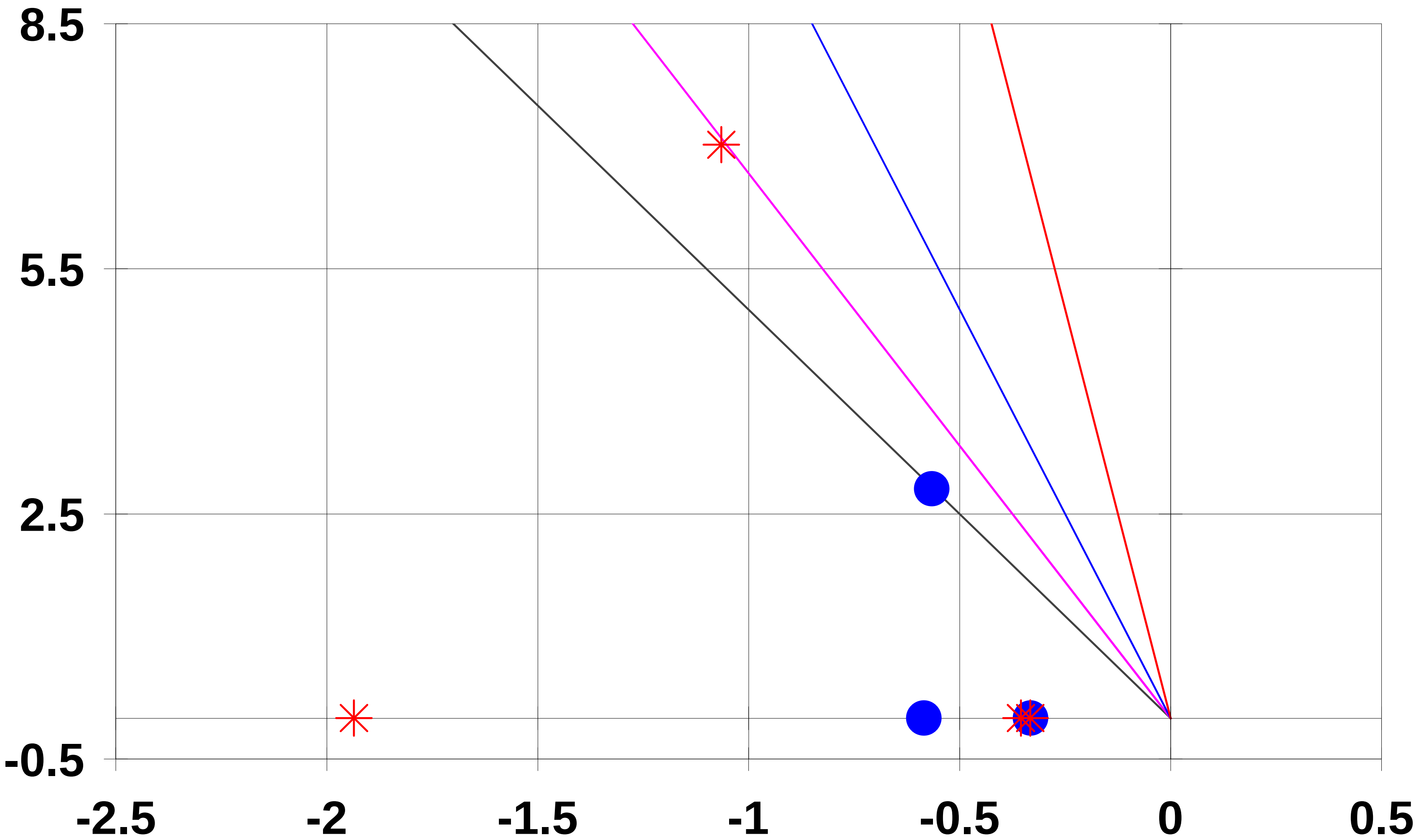


POLE-ZERO MAP FOR $\Delta Q_T / \Delta P_{MEC}$ (PSS$_{PT}$)

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



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



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**

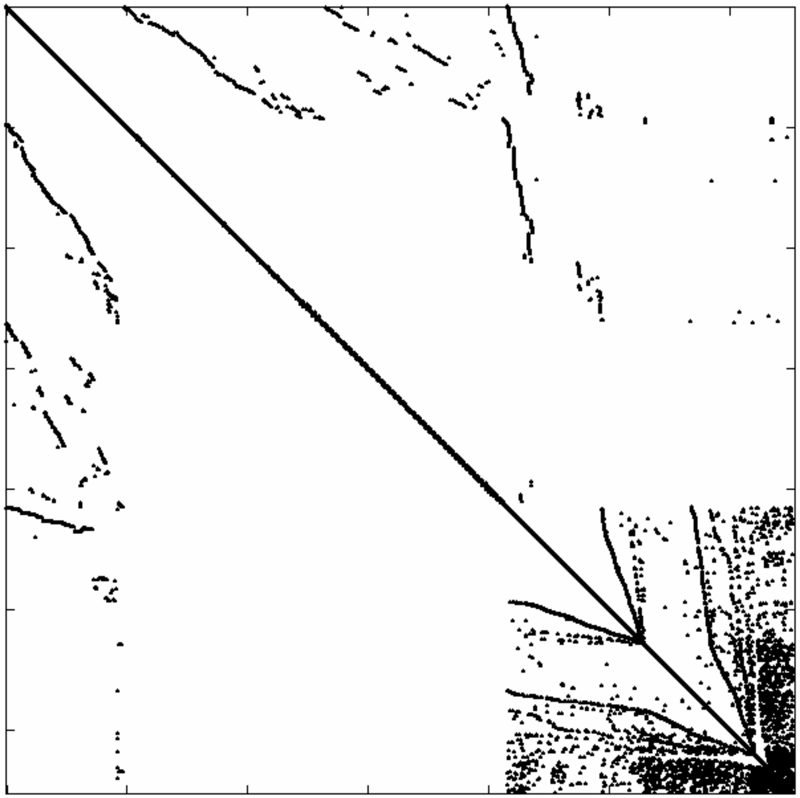
- **Hopf bifurcations are computed for:**

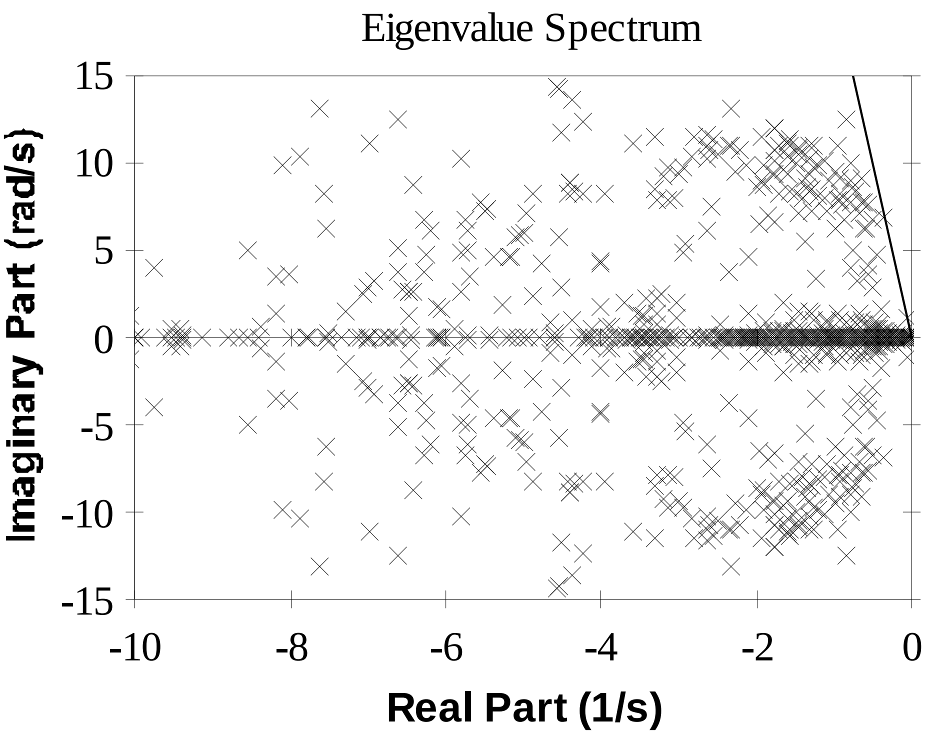
  - ➔ **Single-parameter changes**

  - ➔ **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



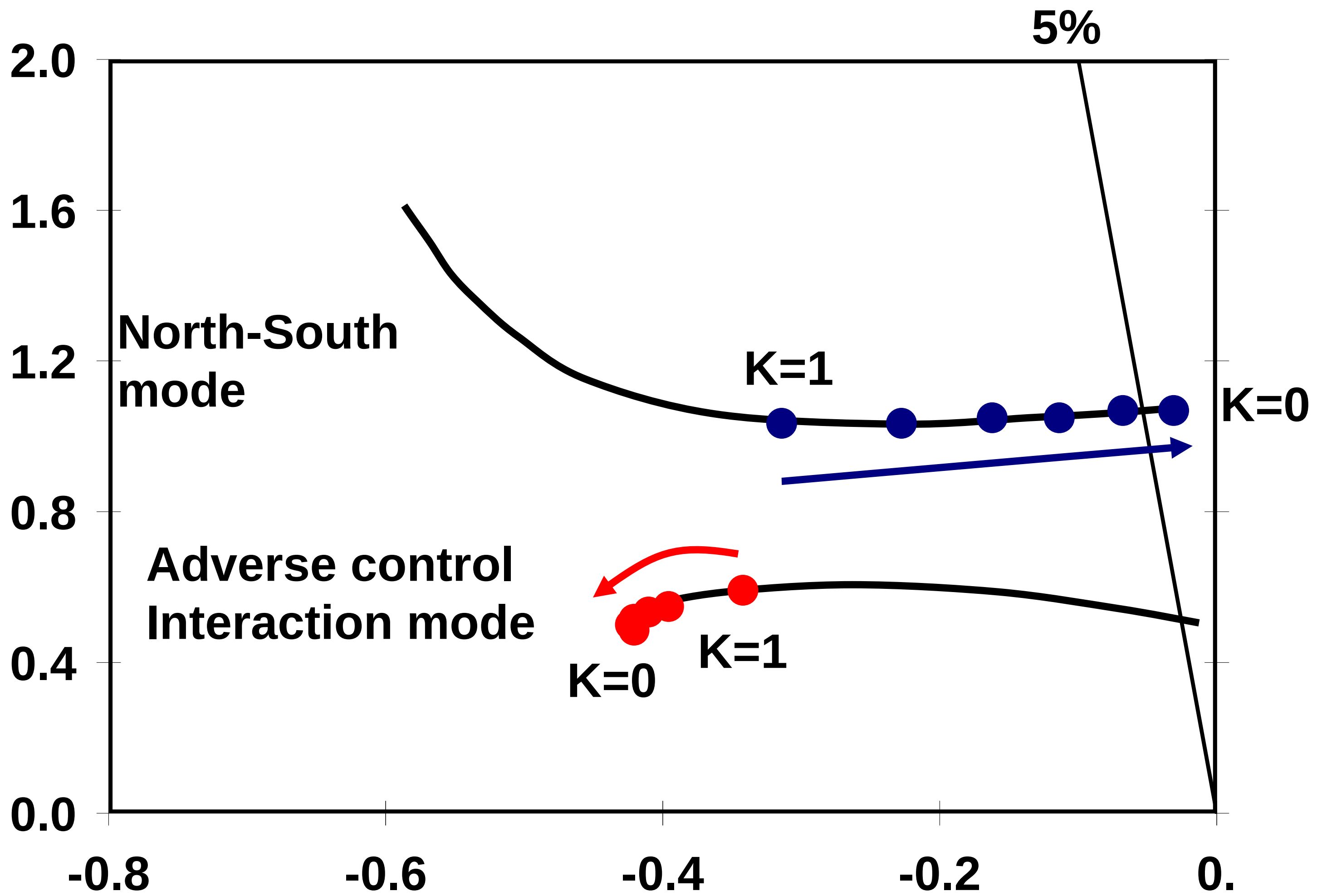


HOPF BIFURCATIONS – TEST SYSTEM PROBLEM

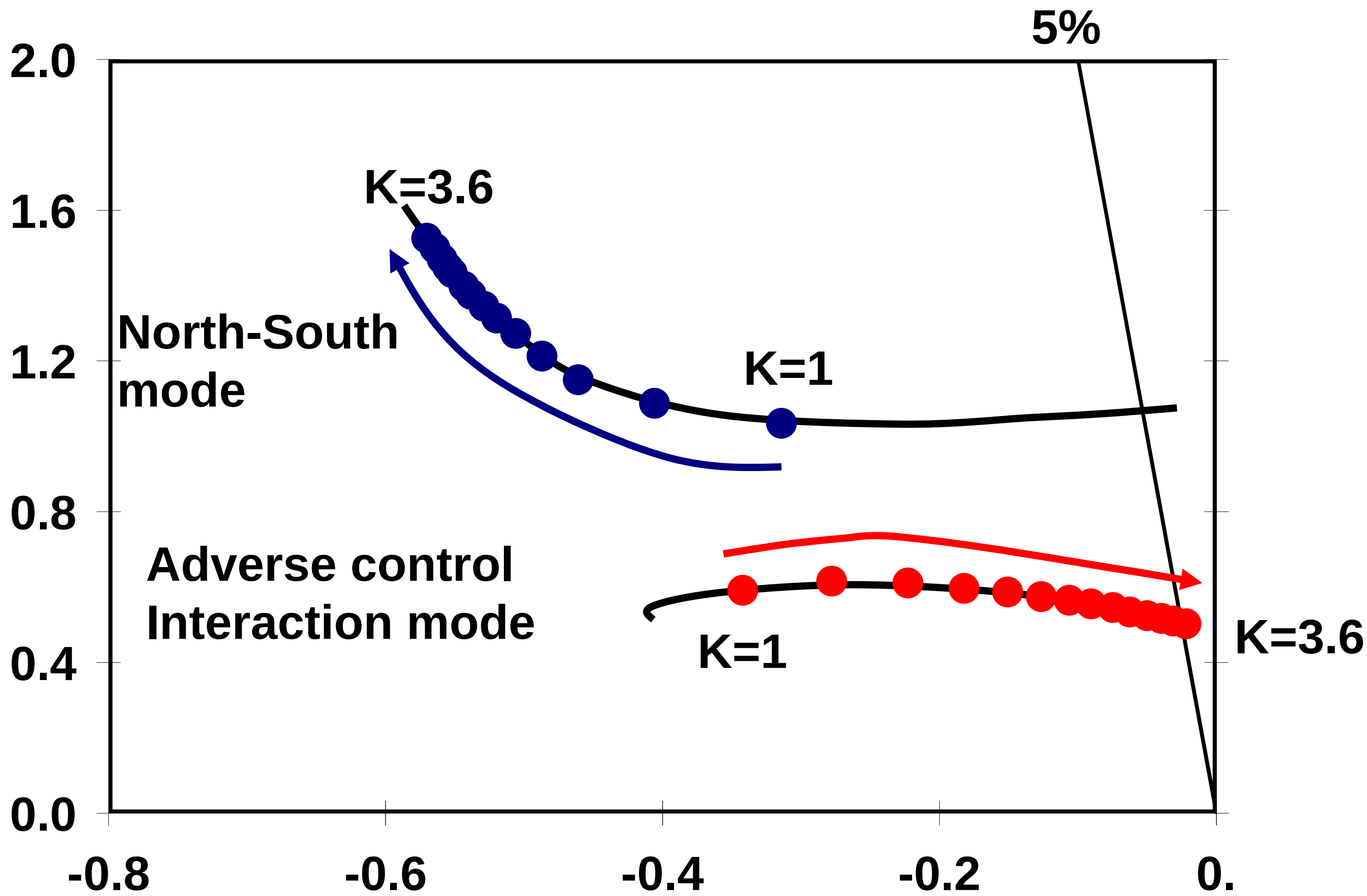
- **Two TCSCs located at each end of the North-South intertie, equiped with PODs to damp the 0.17 Hz mode**

- **The Hopf bifurcation algorithms were applied to compute eigenvalue crossings of the security boundary (5% damping ratio) for gain changes in the two PODs**

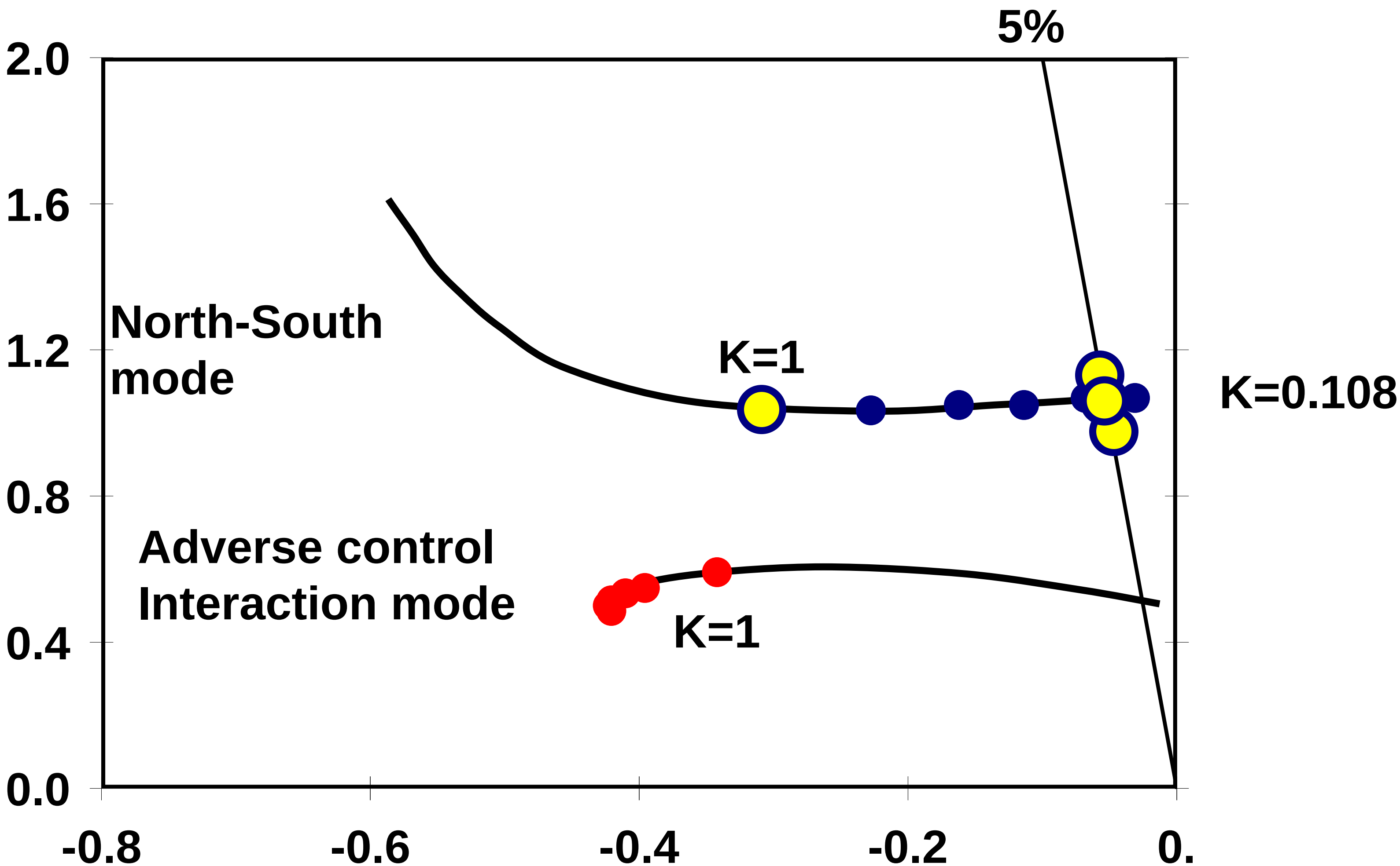
ROOT CONTOUR WHEN REDUCING THE GAINS OF THE 2 TCSCs



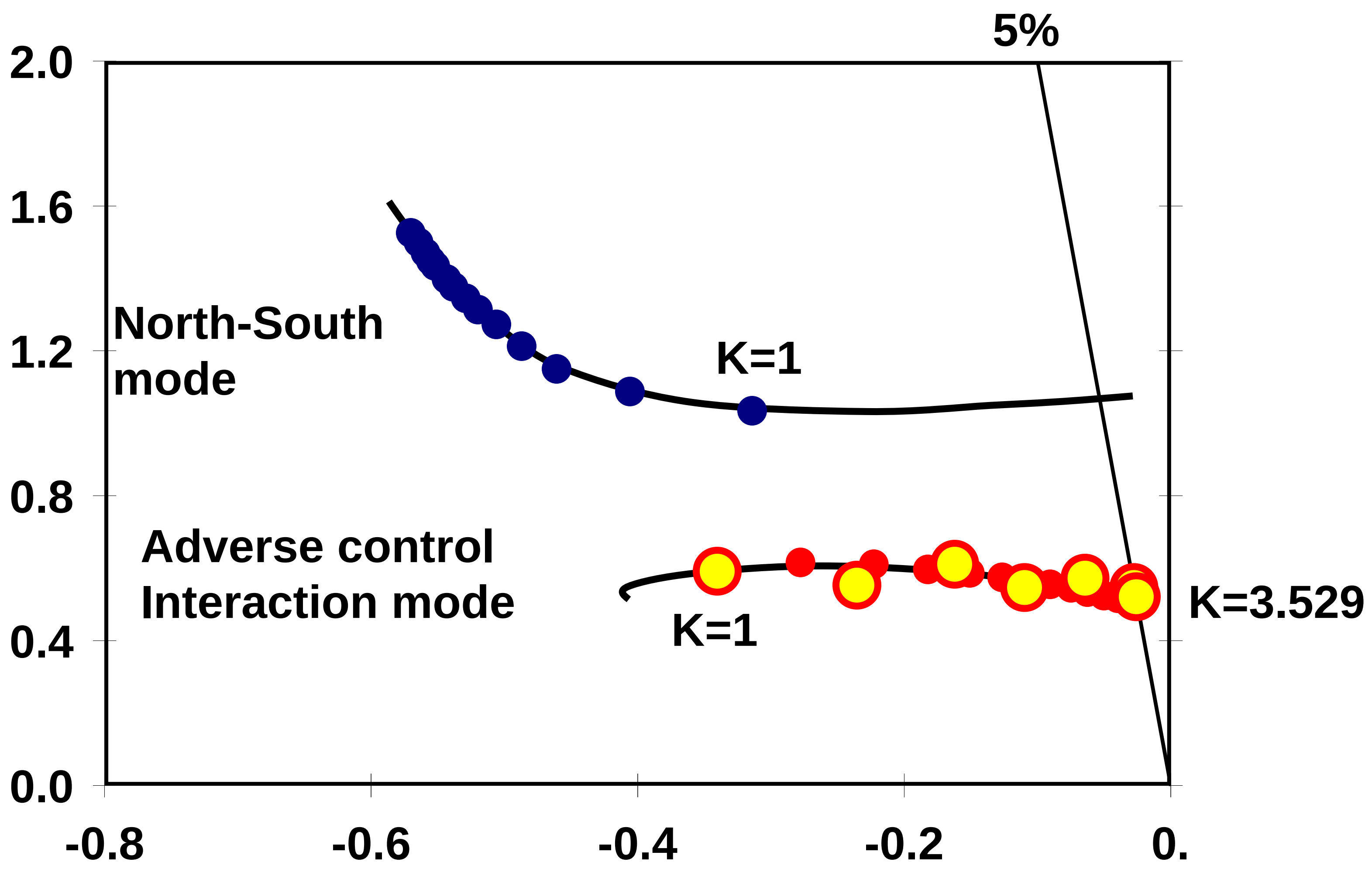
ROOT CONTOUR WHEN INCREASING THE GAINS OF THE 2 TCSCs



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)

SIMULTANEOUS PARTIAL POLE PLACEMENT

FOR

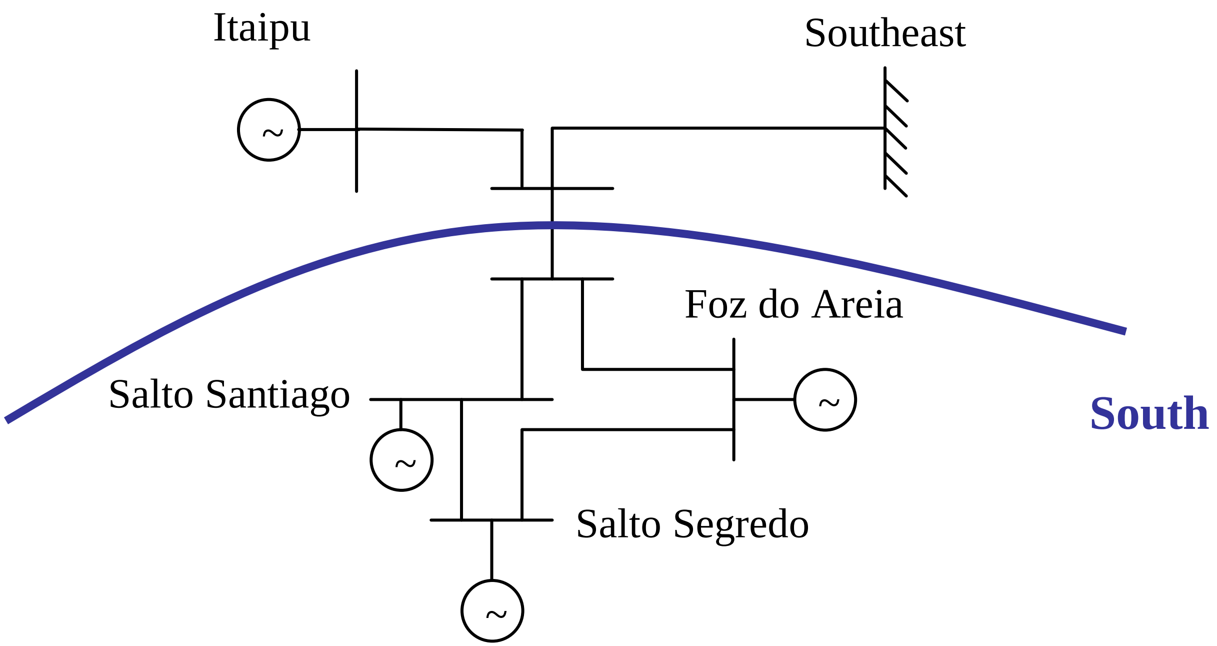
POWER SYSTEM OSCILLATION DAMPING CONTROL

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 (Ka = 100, Ta = 0.05 s)



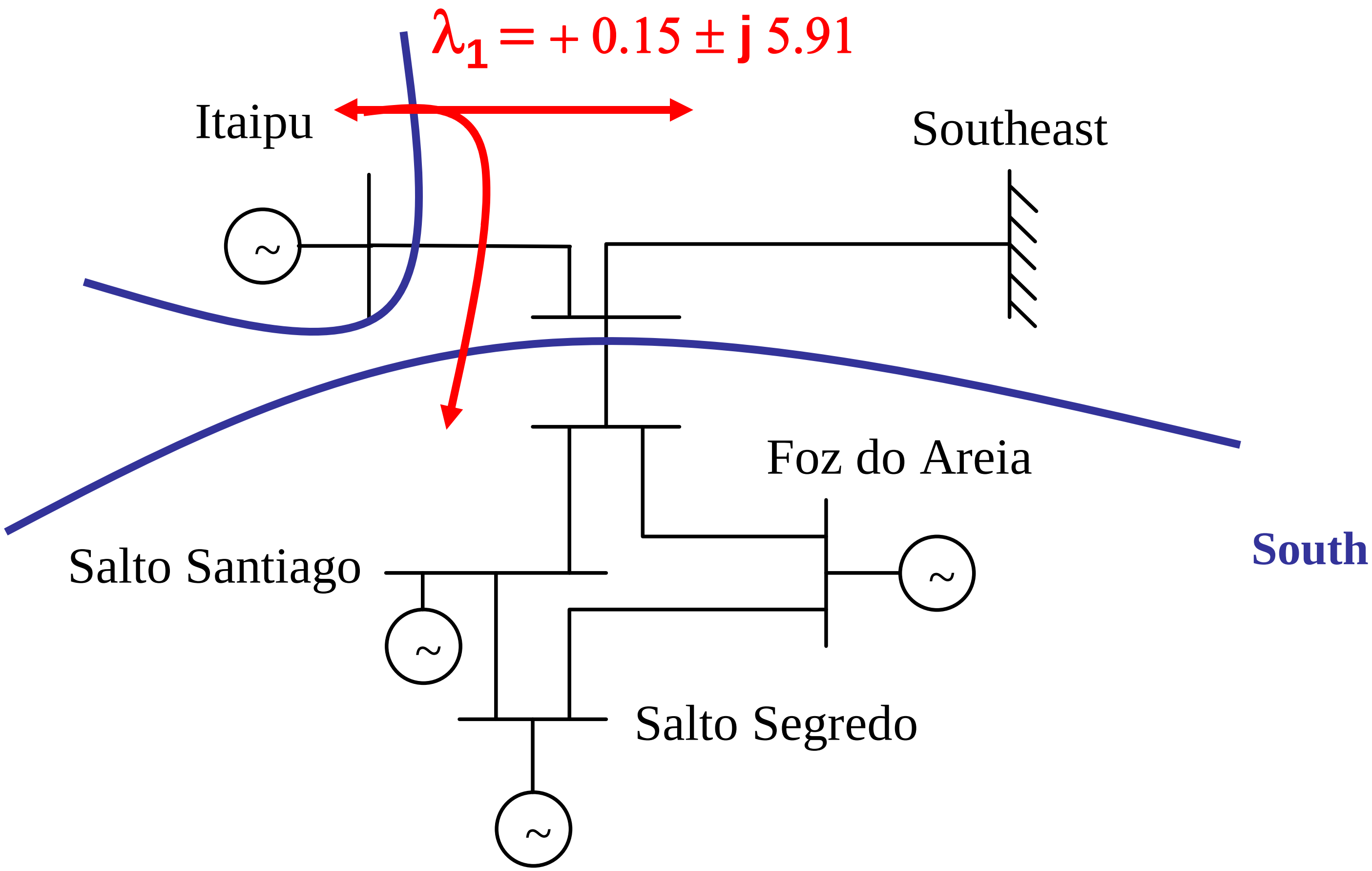
Critical electromechanical modes of oscillation

	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%

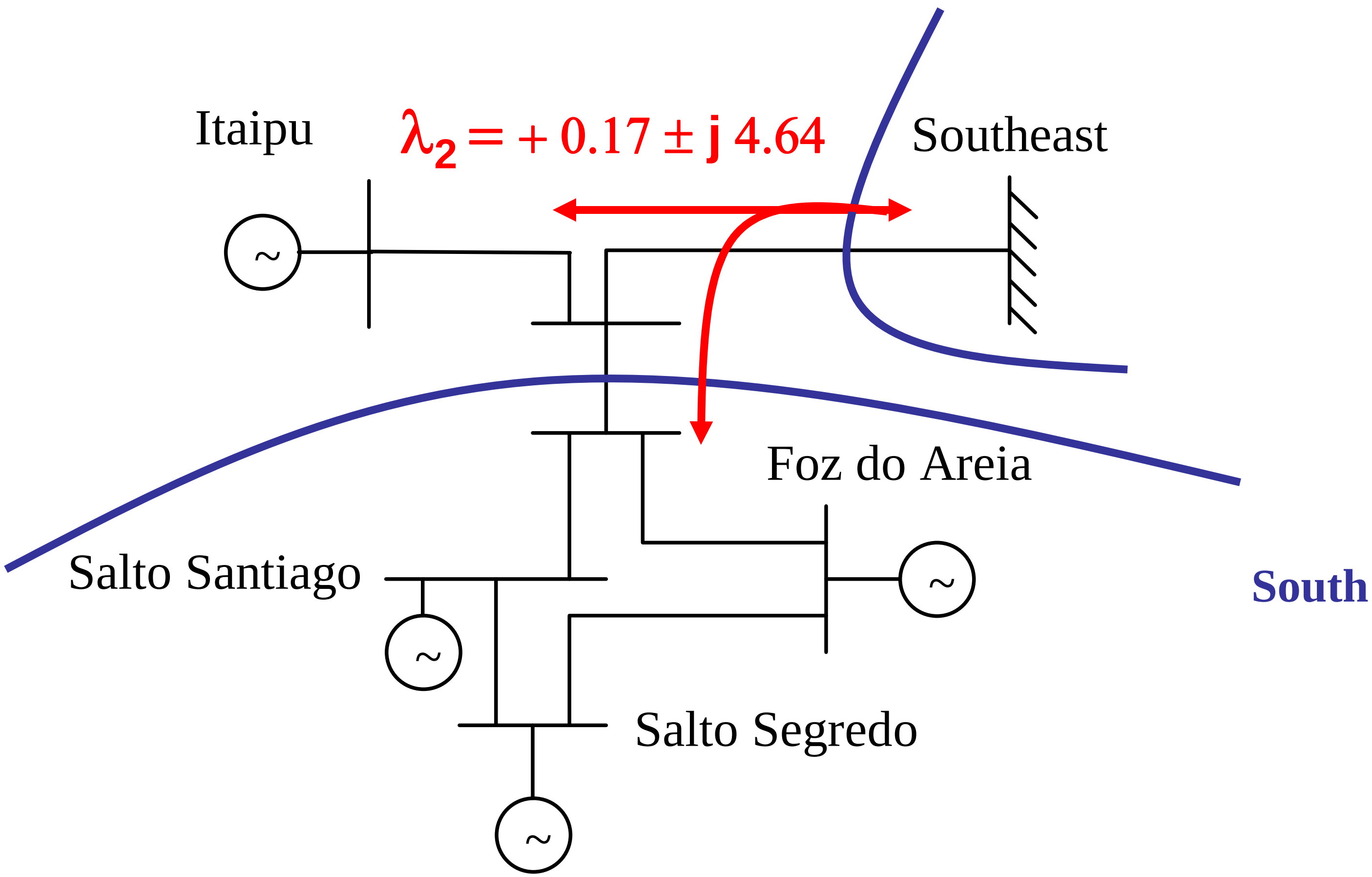
Parameters related to the phase tuning of the PSSs

Number of lead blocks	Tw (s)	Tn (s)	Td (s)
2	3	0.100	0.010

λ_1 : Itaipu x (South + Southeast)



λ_2 : Southeast x (Itaipu + South)



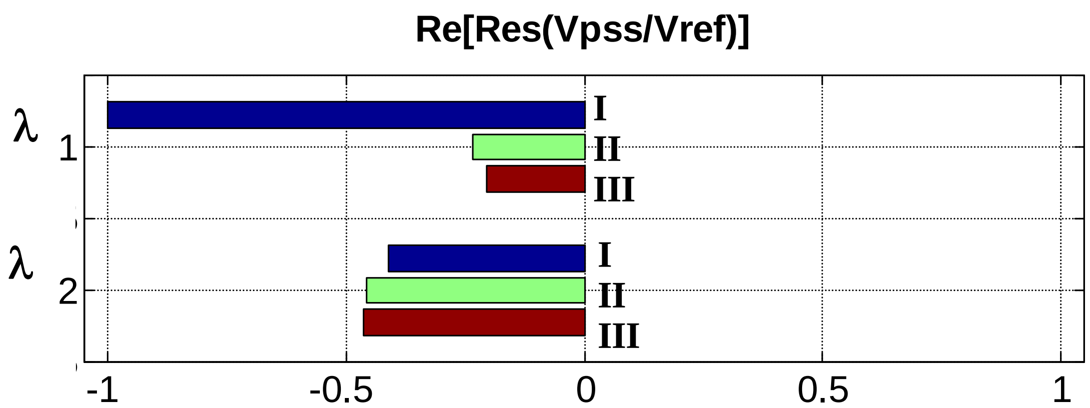
CONTRIBUTION OF EACH PSS TO THE λ SHIFT

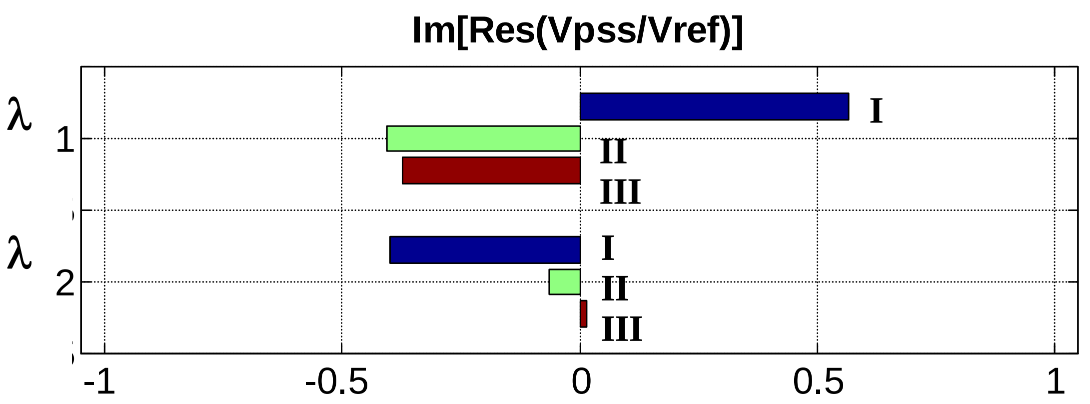
- **A change in the gain vector $\underline{\Delta K}$ will produce shifts in both the real and imaginary parts of the eigenvalues**
- **The contribution of each PSS to these shifts can be estimated using the matrix of transfer function residues**
- **For λ_1 and three PSSs:**

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

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

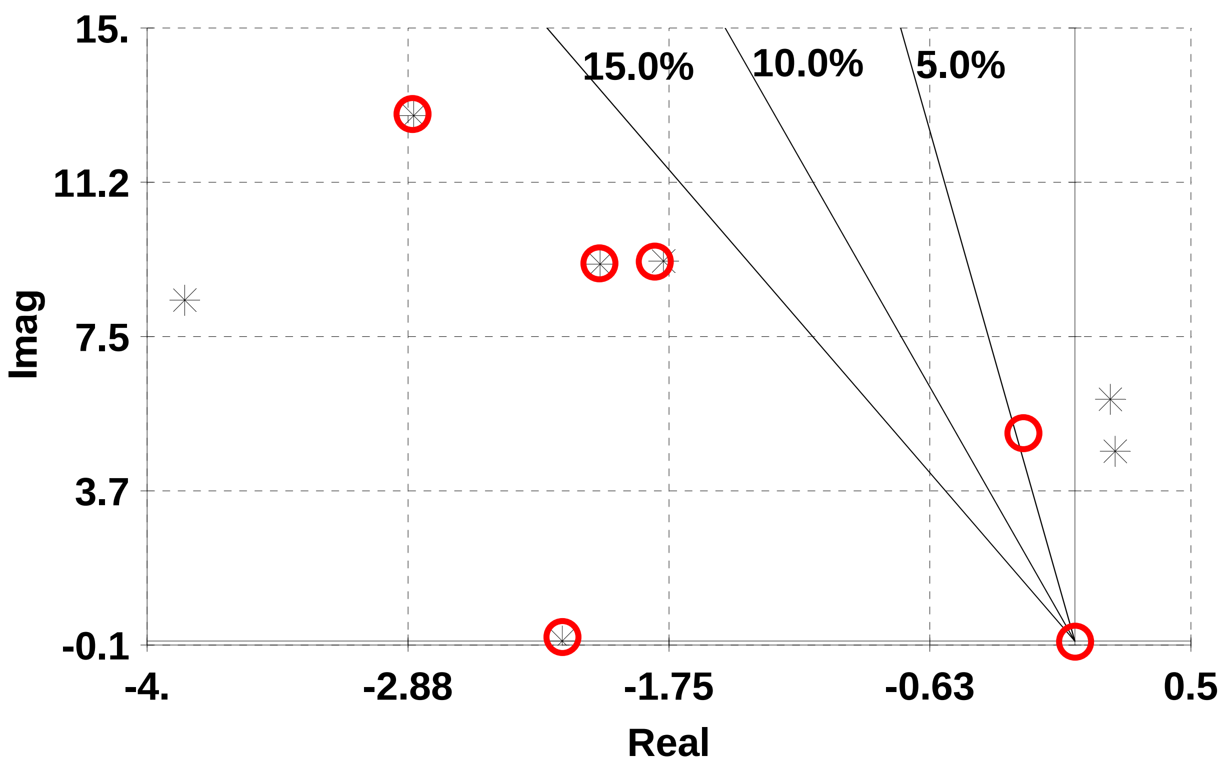
I – Itaipu

II – S. Segredo

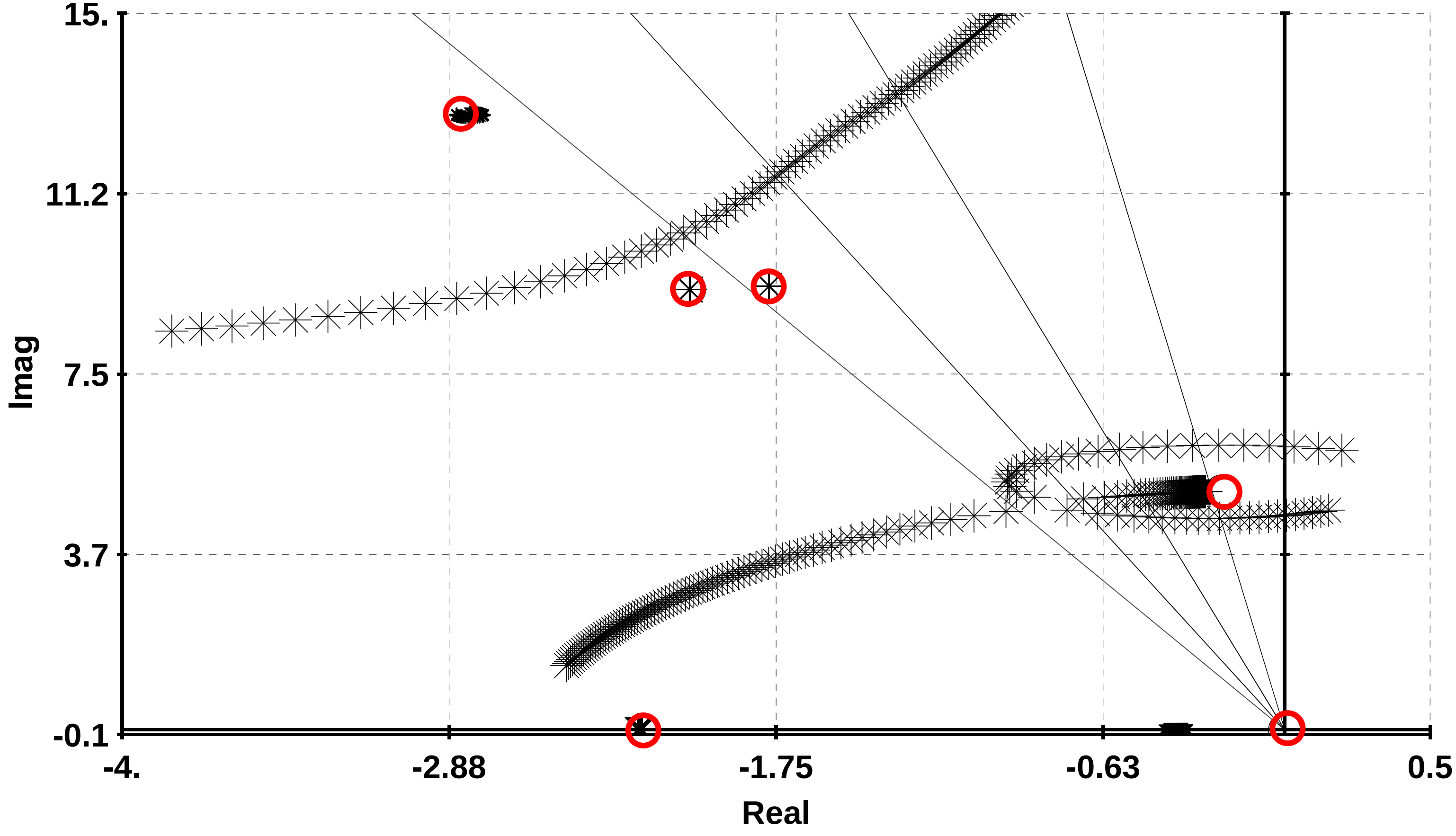
III – Foz do Areia

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**



Root-Locus for Gain Changes at Itaipu PSS



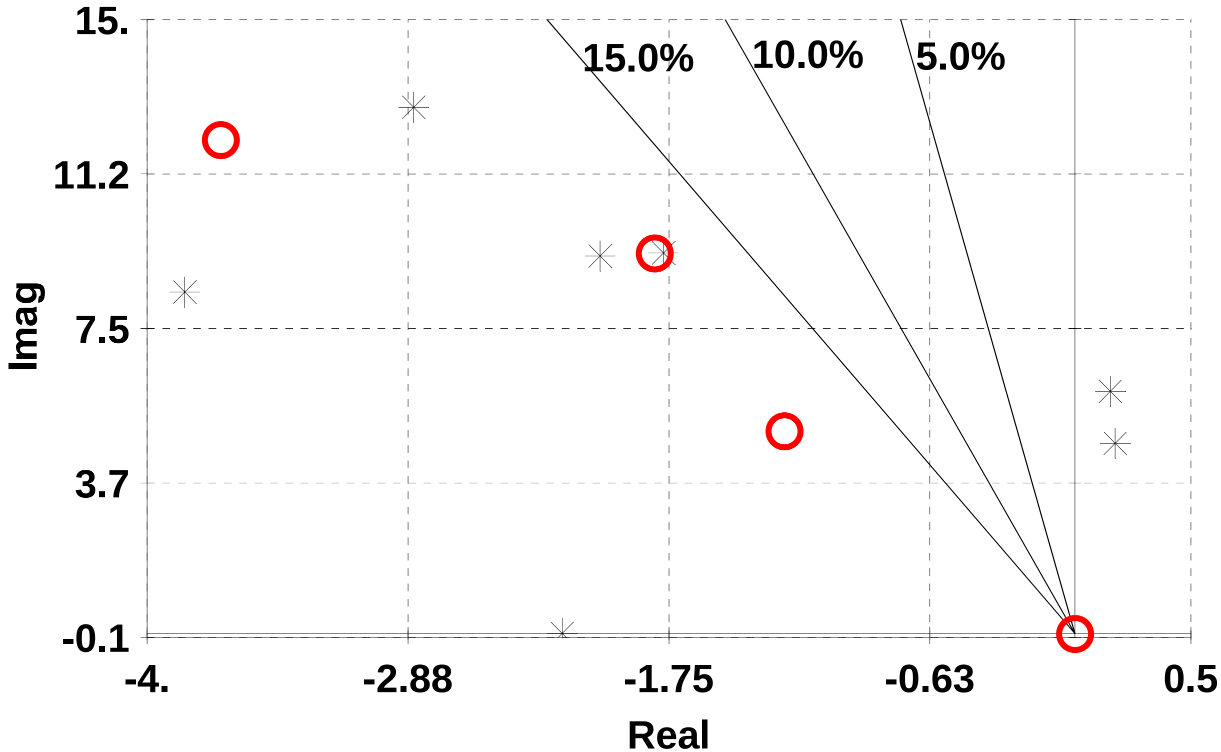
Pole Placement – 2 Modes and 2 PSSs

- **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:**

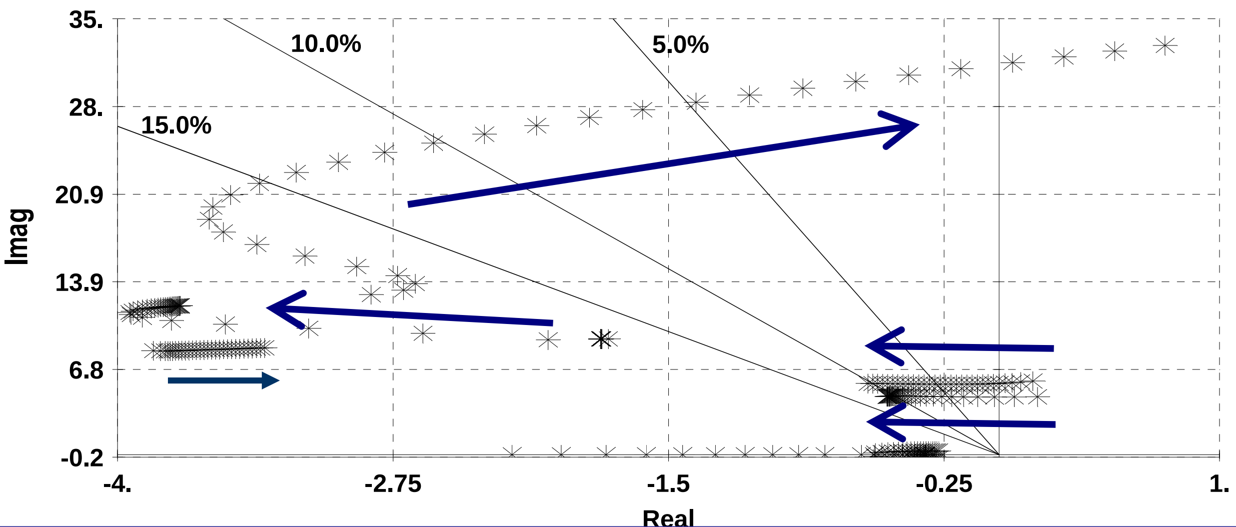
$$\begin{bmatrix} \Delta K_1 \\ \Delta K_2 \end{bmatrix} = \begin{bmatrix} \operatorname{Re}\left[R\left(\dfrac{\Delta V_{PSS1}}{\Delta V_{REF1}}, \lambda_1 \right) \quad R\left(\dfrac{\Delta V_{PSS2}}{\Delta V_{REF2}}, \lambda_1 \right) \right] \\ \operatorname{Re}\left[R\left(\dfrac{\Delta V_{PSS1}}{\Delta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

POLE-ZERO MAP OF $[\Delta\omega/\Delta V_{REF}]_{2x2}$

- **Map of poles and zeros for the matrix transfer function $[\Delta\omega/\Delta V_{REF}]_{2x2}$ with PSSs in Itaipu and S. Segredo**



POLE PLACEMENT – 2 MODES AND 2 PSSS

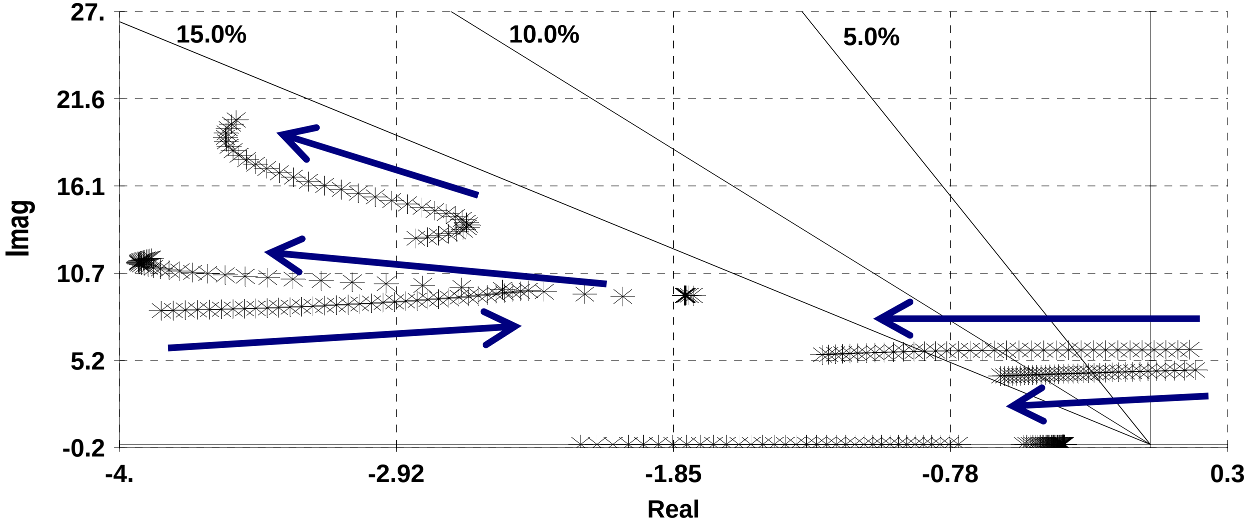


K_{Itaipu} = 5

$K_{S.Segredo}$ = 91

$\zeta_{\lambda 1}$ = 10.4 %

$\zeta_{\lambda 2}$ = 10.9 %



K_{Itaipu} = 14

$K_{S.Segredo}$ = 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 ⇒ more convenient pole-zero map
  - ➔ Number of PSSs differs from the number of poles to be placed ⇒ pseudo-inverse of a non-square matrix must be computed
  - ➔ Algorithm must be modified

PSEUDO-INVERSE ALGORITHM

- **Problems without unique solution ⇒ pseudo-inverse algorithm**

$$\mathrm{Re}[R]_{mxn}\,\underline{\Delta K}_{\,nx1} = \mathrm{Re}[\Delta\lambda]_{mx1}$$

m = number of modes

n = number of PSSs

- **If *<u>m < n</u>* ⇒ the algorithm will produce gain values that ensure a minimum norm for the gain vector**

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

- **If *<u>m > n</u>* ⇒ the algorithm will produce gain values that ensure a minimum norm for the error vector (solution of the least square problem)**

$$\min\left\|\mathrm{Re}[R]\underline{\Delta K} - \mathrm{Re}[\underline{\Delta\lambda}]\right\|$$

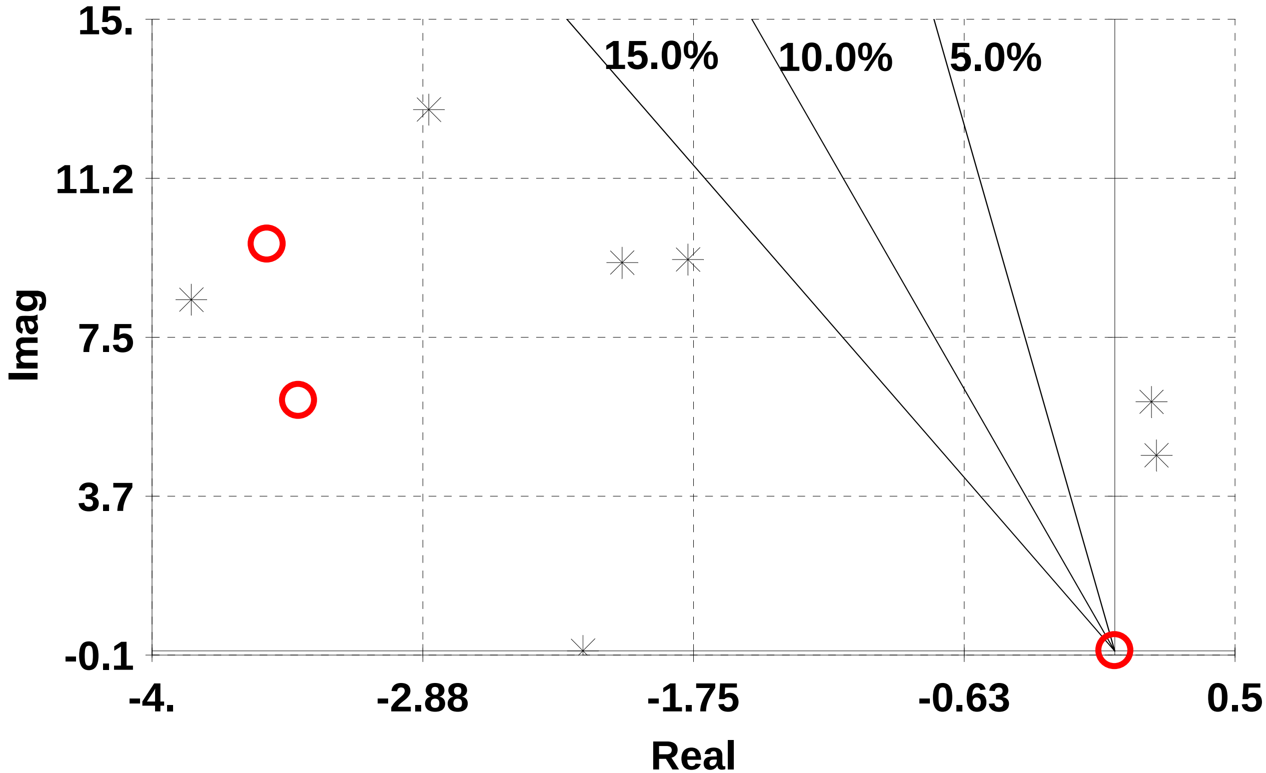
POLE PLACEMENT – 2 MODES AND 3 PSSS

- **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:**

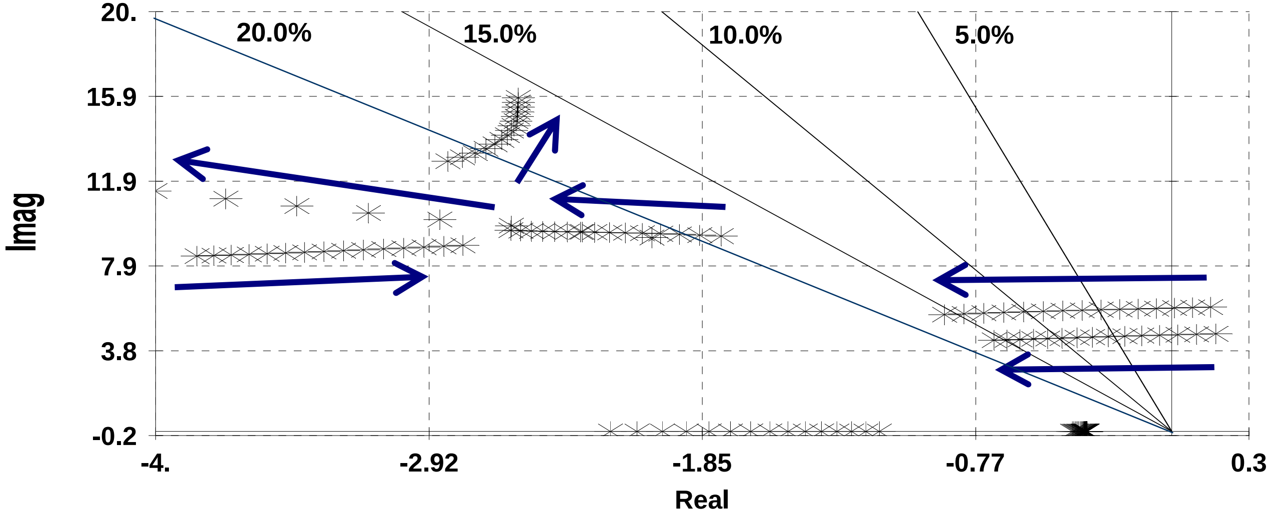
$$\begin{bmatrix} \Delta K_1 \\ \Delta K_2 \\ \Delta K_3 \end{bmatrix} = \begin{bmatrix} \mathrm{Re}\left[R\left(\dfrac{\Delta V_{PSS1}}{\Delta V_{REF1}}, \lambda_1\right) \quad R\left(\dfrac{\Delta V_{PSS2}}{\Delta V_{REF2}}, \lambda_1\right) \quad R\left(\dfrac{\Delta V_{PSS3}}{\Delta V_{REF3}}, \lambda_1\right)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

POLE-ZERO MAP OF $[\Delta\omega/\Delta V_{REF}]_{3x3}$

- **Map of poles and zeros for the matrix transfer function $[\Delta\omega/\Delta V_{REF}]_{3x3}$ with PSSs in Itaipu, S. Segredo and Foz do Areia**



POLE PLACEMENT – 2 MODES AND 3 PSSs



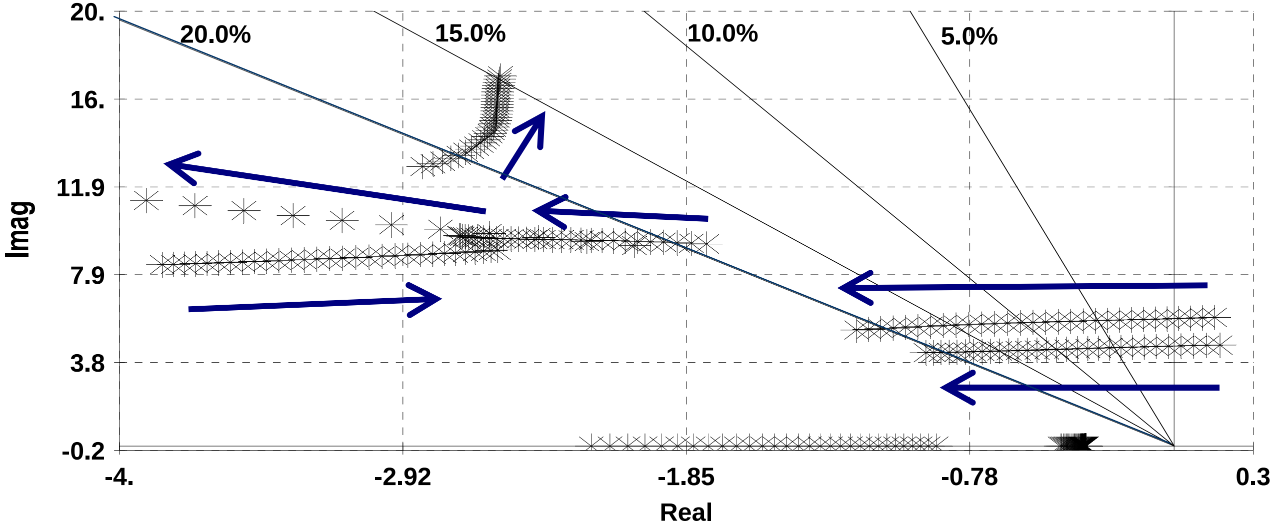
K_{Itaipu} = 8.1

$K_{S.Segredo}$ = 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