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Simultaneous Partial Pole Placement for Power System Oscillation Damping Control

JULIO C. R. FERRAZ (*COPPE/UFRJ – CEPEL*)
NELSON MARTINS (*CEPEL*)
GLAUCO N. TARANTO (*COPPE/UFRJ*)

COPPE/UFRJ

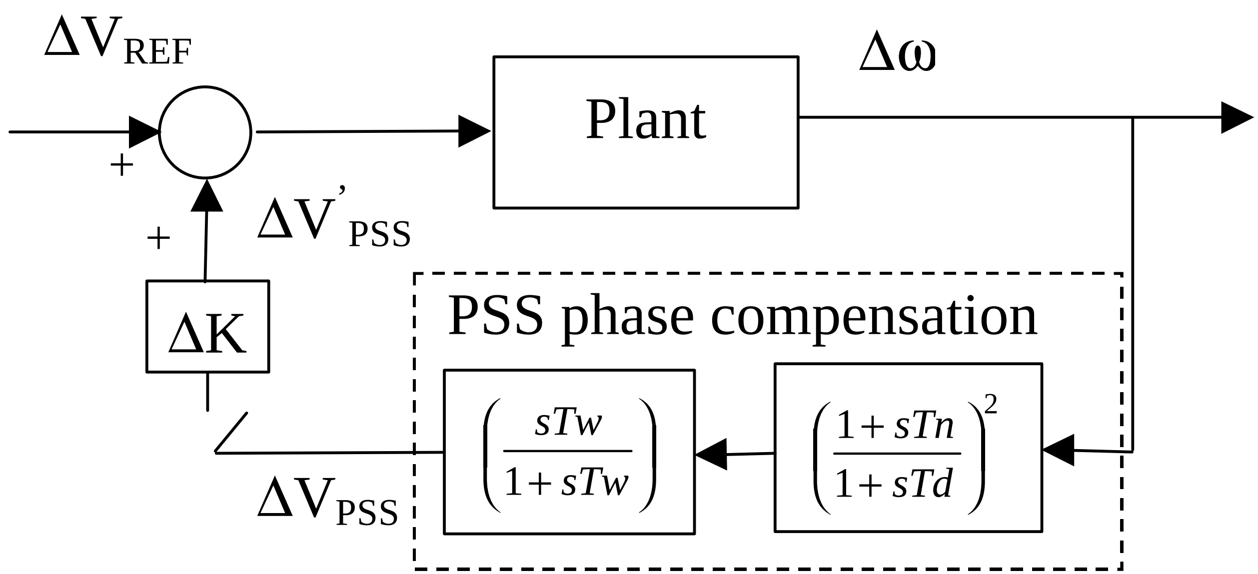
CEPEL
EMPRESA DO SISTEMA ELETROBRÁS

INTRODUCTION

- **Purpose Þ choose adequate gains for the Power System Stabilizers (PSSs) installed in generators of a test system**
- **PSSs Þ installed 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**

USING TRANSFER FUNCTION RESIDUES

- **The variation of a given feedback gain significantly affects the location of certain system eigenvalues:**



$$\frac{dl_i}{dK} = R\left(\frac{\Delta V_{PSS}}{\Delta V_{REF}}, l_i\right) \quad \Rightarrow \quad \mathrm{Re}\left[\frac{\Delta l_i}{\Delta K}\right] = \mathrm{Re}\left[R\left(\frac{\Delta V_{PSS}}{\Delta V_{REF}}, l_i\right)\right]$$

GAIN TUNING NEWTON-RAPHSON ALGORITHM

begin

- Calculate eigenvalue and the associated ($\Delta V_{PSS}/\Delta V_{REF}$) transfer function residue;

- Calculate $K^{l+1} = K^{l} + \Delta K$, where $\Delta K = \left[\mathrm{Re}\left[R\left(\frac{\Delta V_{PSS}}{\Delta V_{REF}}, l \right) \right] \right]^{-1} \mathrm{Re}[\Delta l]$;

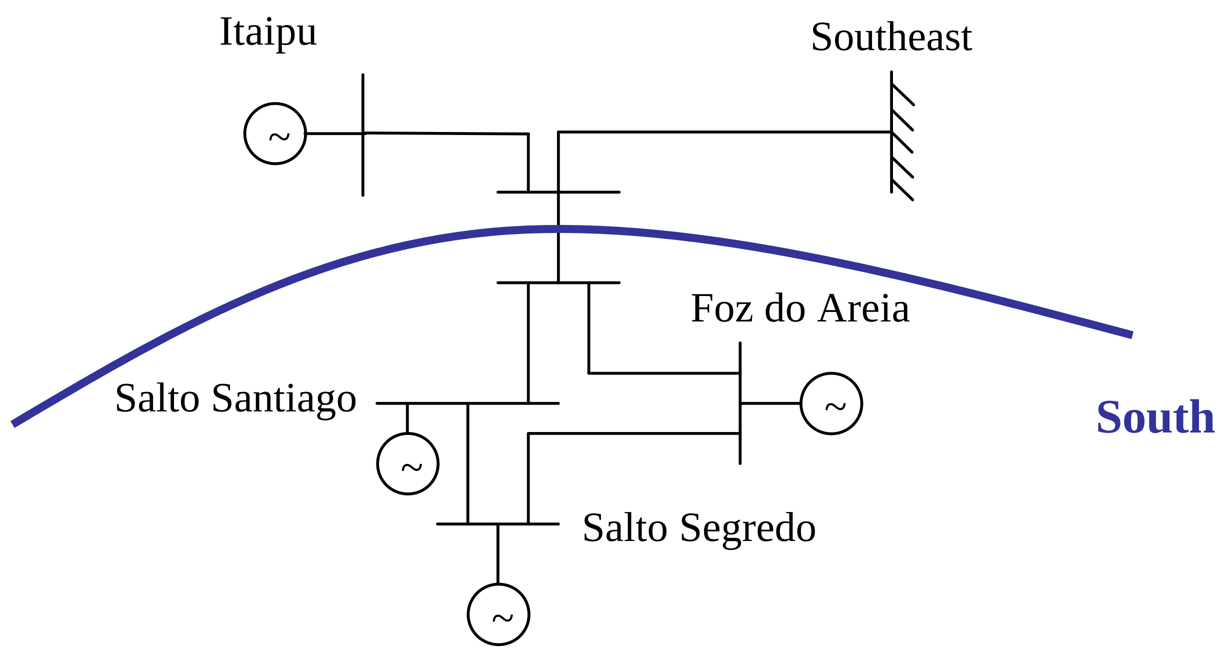
- Calculate new λ and new TF residue;

- While the mismatch ($\mathrm{Re}\left[l\left(K^{l+1} \right) \right] - s_d$) is bigger than the tolerance, increase counter ($l=l+1$) and return to begin.

end

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 OSCILLATORY MODES

Critical electromechanical modes of oscillation

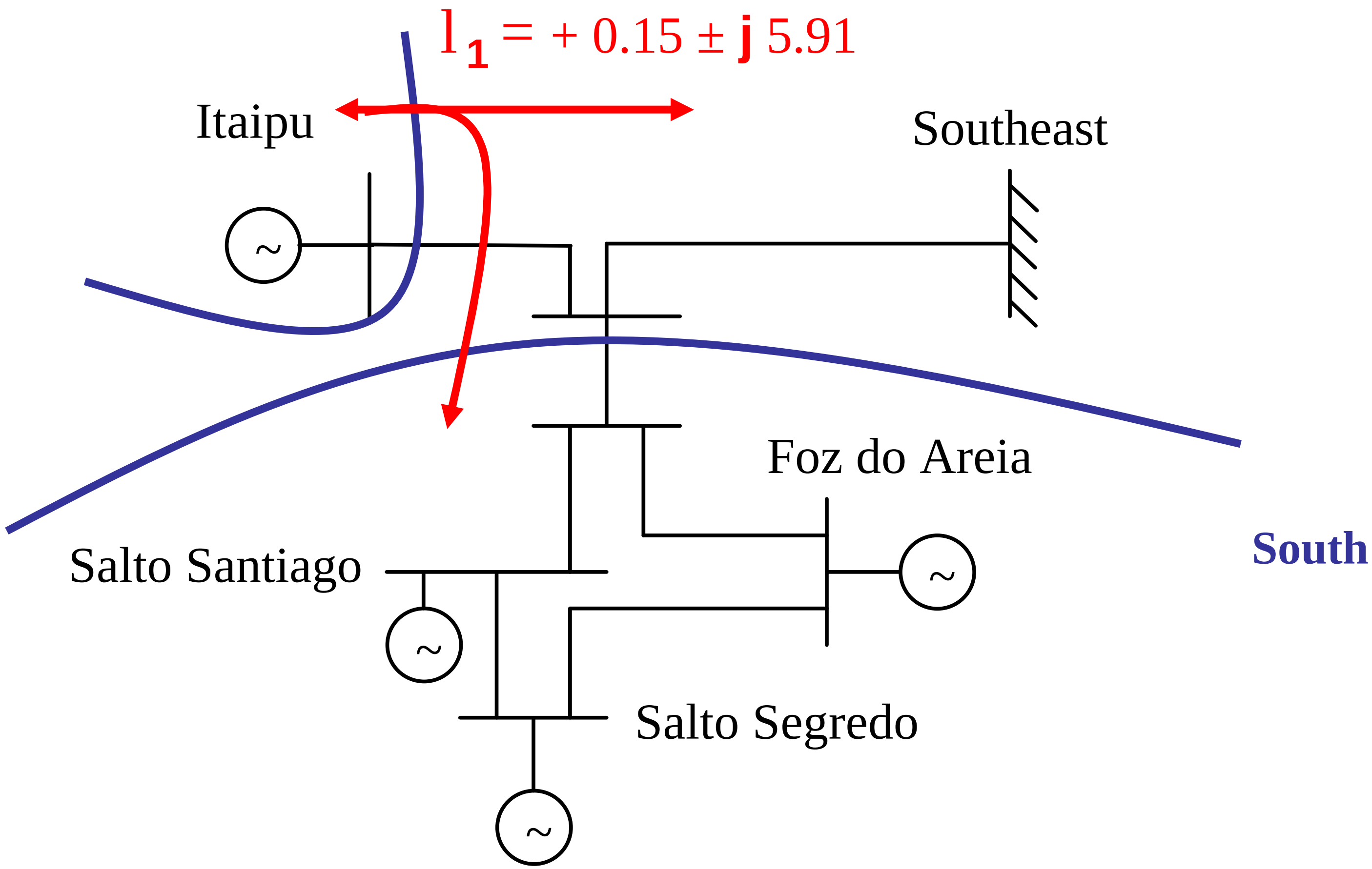
	Real	Imag.	Freq. (Hz)	Damping
λ_1	+0.15309	±5.9138	0.94121	-2.59%
λ_2	+0.17408	±4.6435	0.73904	-3.75%

Parameters related to the phase tuning of the PSSs

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

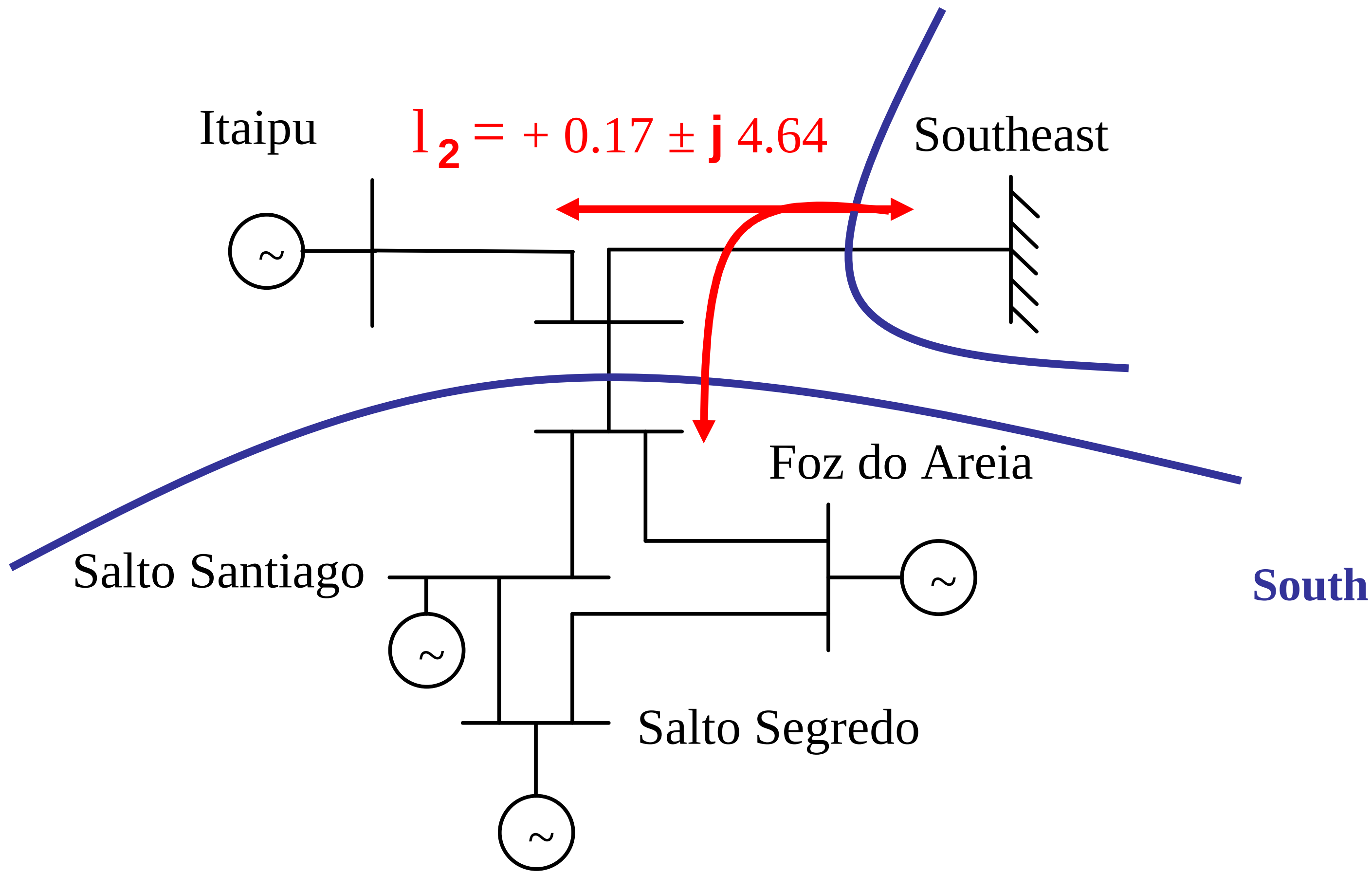
CRITICAL OSCILLATORY MODES

- l_1 : **Itaipu x (South + Southeast)**



Critical Oscillatory Modes

- λ_2 : **Southeast x (Itaipu + South)**



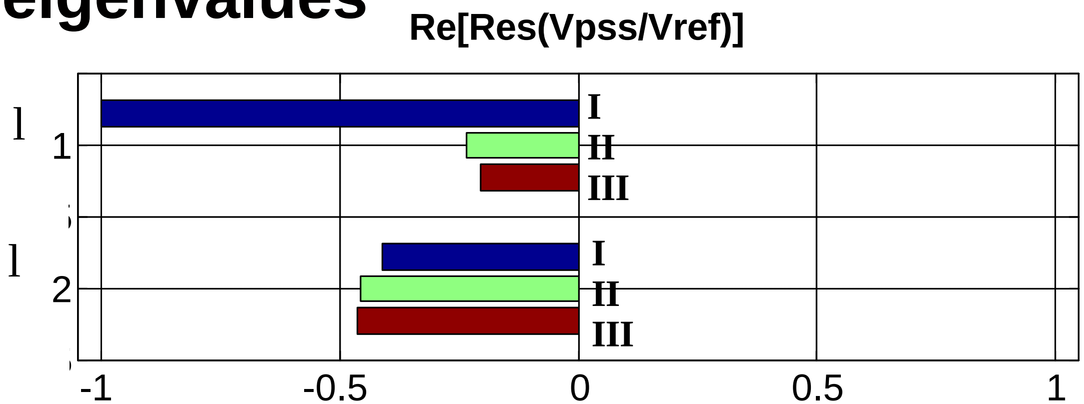
CONTRIBUTION OF EACH PSS TO THE l SHIFT

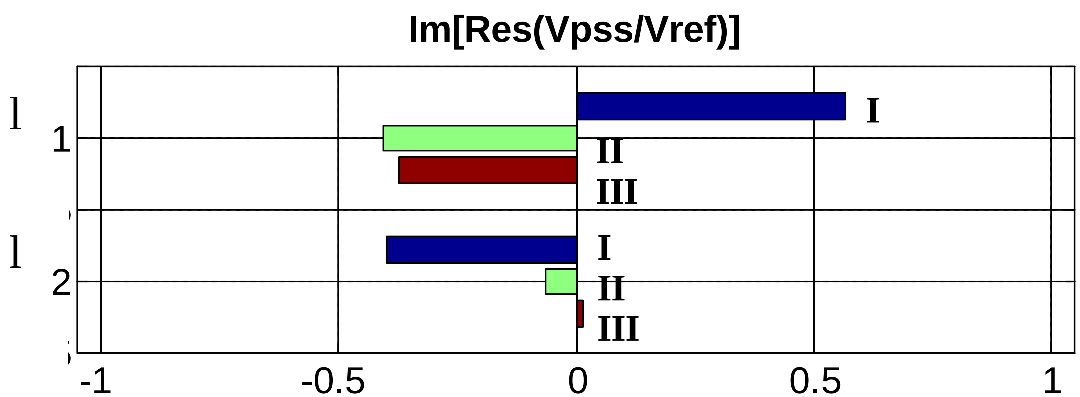
- **A change in the gain vector <u>*DK*</u> will produce shifts in both the real and imaginary parts of the eigenvalues**
- **The contribution of each PSS to these shifts can be estimated using the matrix of transfer function residues**
- **For l_1 and three PSSs:**

$$\begin{bmatrix} \mathrm{Re}[\Delta l_1] \\ \mathrm{Im}[\Delta l_1] \end{bmatrix} = \begin{bmatrix} \mathrm{Re}\left[R\left(\frac{\Delta V_{PSS1}}{\Delta V_{REF1}}, l_1\right) \quad R\left(\frac{\Delta V_{PSS2}}{\Delta V_{REF2}}, l_1\right) \quad R\left(\frac{\Delta V_{PSS3}}{\Delta V_{REF3}}, l_1\right) \right] \\ \mathrm{Im}\left[R\left(\frac{\Delta V_{PSS1}}{\Delta V_{REF1}}, l_1\right) \quad R\left(\frac{\Delta V_{PSS2}}{\Delta V_{REF2}}, l_1\right) \quad R\left(\frac{\Delta V_{PSS3}}{\Delta V_{REF3}}, l_1\right) \right] \end{bmatrix} \begin{bmatrix} \Delta K_1 \\ \Delta K_2 \\ \Delta K_3 \end{bmatrix}$$

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**





<u>Oscillatory Modes</u>

λ_1 – Itaipu mode

λ_2 – Southern mode

<u>PSS Location</u>

I – Itaipu

II – S. Segredo

III – Foz do Areia

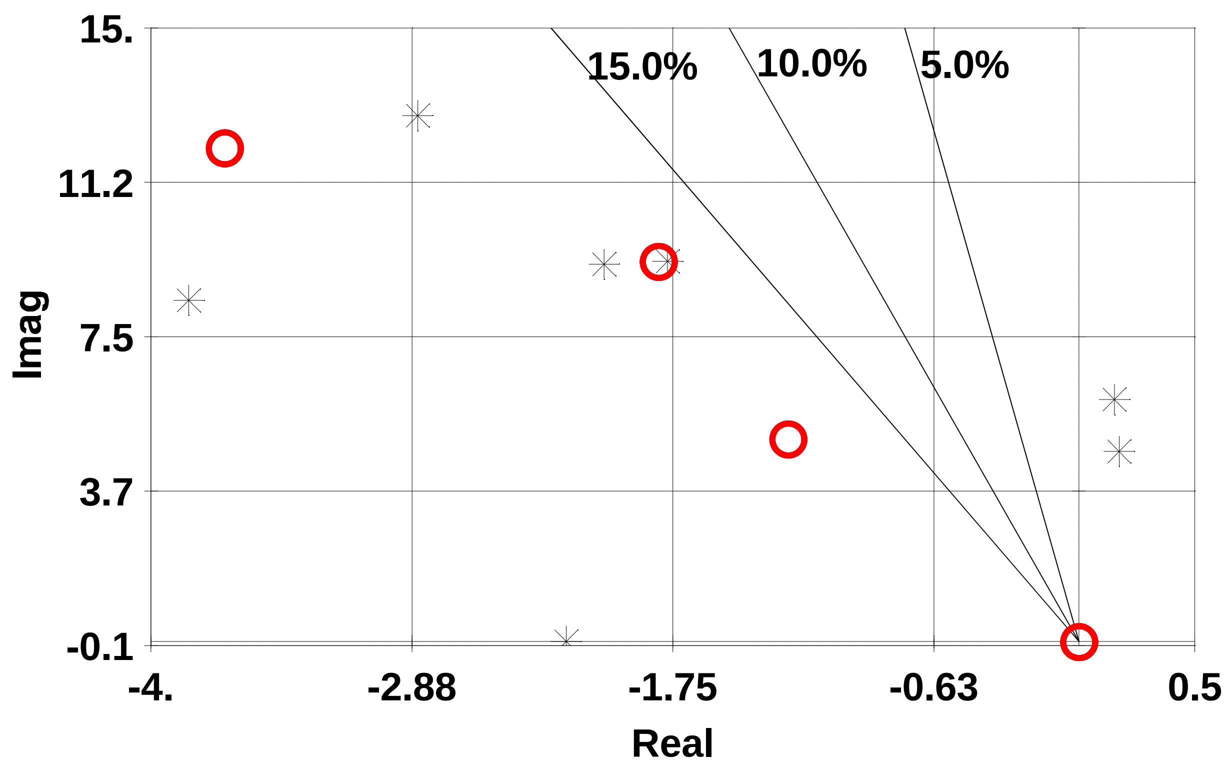
Pole Placement – 2 Modes and 2 PSSs

- **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 $\underline{DK}$ will be calculated at each Newton iteration using the following relation:**

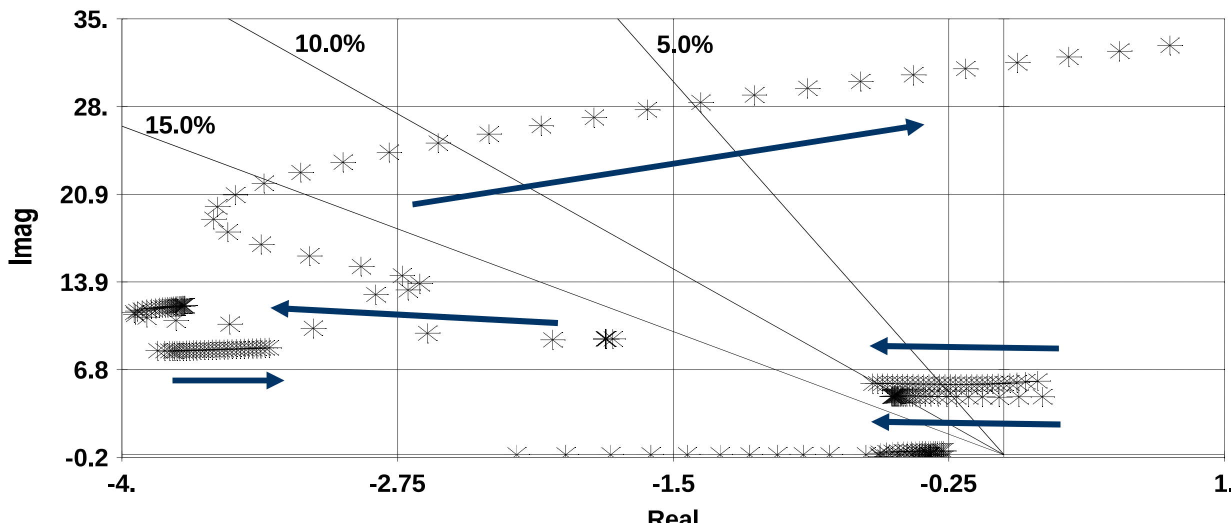
$$\begin{bmatrix} \Delta K_1 \\ \Delta K_2 \end{bmatrix} = \begin{bmatrix} \mathrm{Re}\left[R\left(\dfrac{\Delta V_{PSS1}}{\Delta V_{REF1}}, l_1\right) \quad R\left(\dfrac{\Delta V_{PSS2}}{\Delta V_{REF2}}, l_1\right)\right] \\ \mathrm{Re}\left[R\left(\dfrac{\Delta V_{PSS1}}{\Delta V_{REF1}}, l_2\right) \quad R\left(\dfrac{\Delta V_{PSS2}}{\Delta V_{REF2}}, l_2\right)\right] \end{bmatrix}^{-1} \left[\mathrm{Re}\begin{bmatrix} \Delta l_1 \\ \Delta l_2 \end{bmatrix} \right]$$

POLE-ZERO MAP OF $[Dw/DV_{REF}]_{2x2}$

- **Map of poles (❄) and zeros (O) for the matrix transfer function $[Dw/DV_{REF}]_{2x2}$ with PSSs in Itaipu and S. Segredo**



Pole Placement – 2 Modes and 2 PSSs



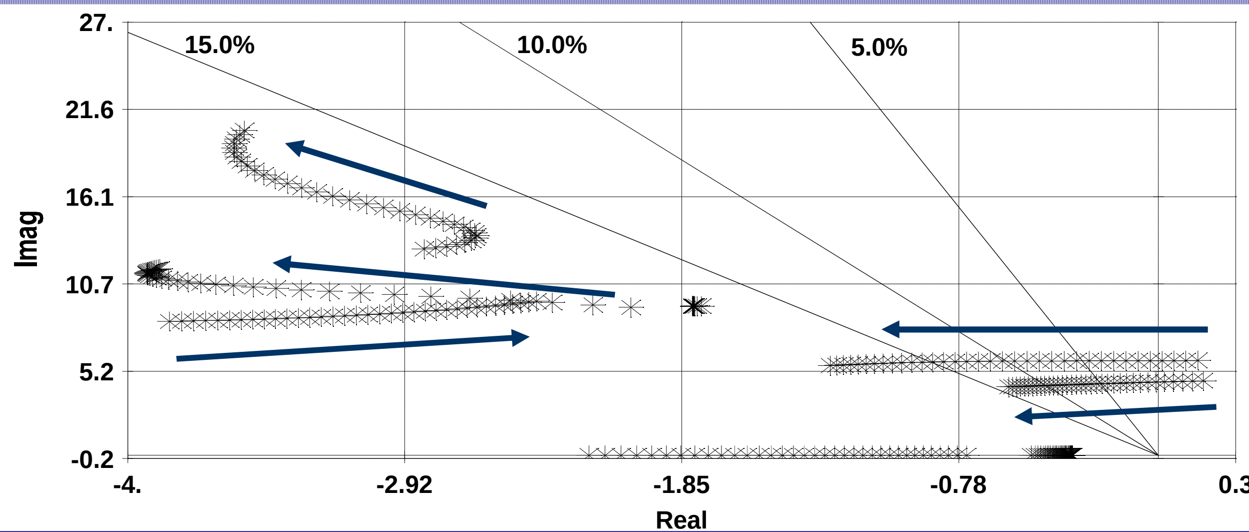
Case 2

$K_{Itaipu} = 5$

$K_{S.Segredo} = 91$

$z_{11} = 10.4\ \%$

$z_{12} = 10.9\ \%$



Case 3

$K_{Itaipu} = 14$

$K_{S.Segredo} = 29$

$z_{11} = 22.0\ \%$

$z_{12} = 13.5\ \%$

Pole Placement – 2 Modes and 2 PSSs

- The pole location must be carefully chosen
  - ➔ Certain pole locations could require high gain values and cause exciter mode instability
- Installation of a third PSS
  - ➔ Facilitates the pole placement Þ more convenient pole-zero map
  - ➔ Number of PSSs differs from the number of poles to be placed Þ pseudo-inverse of a non-square matrix must be computed
  - ➔ Algorithm must be modified

PSEUDO-INVERSE ALGORITHM

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

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

m = number of modes

n = number of PSSs

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

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

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

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

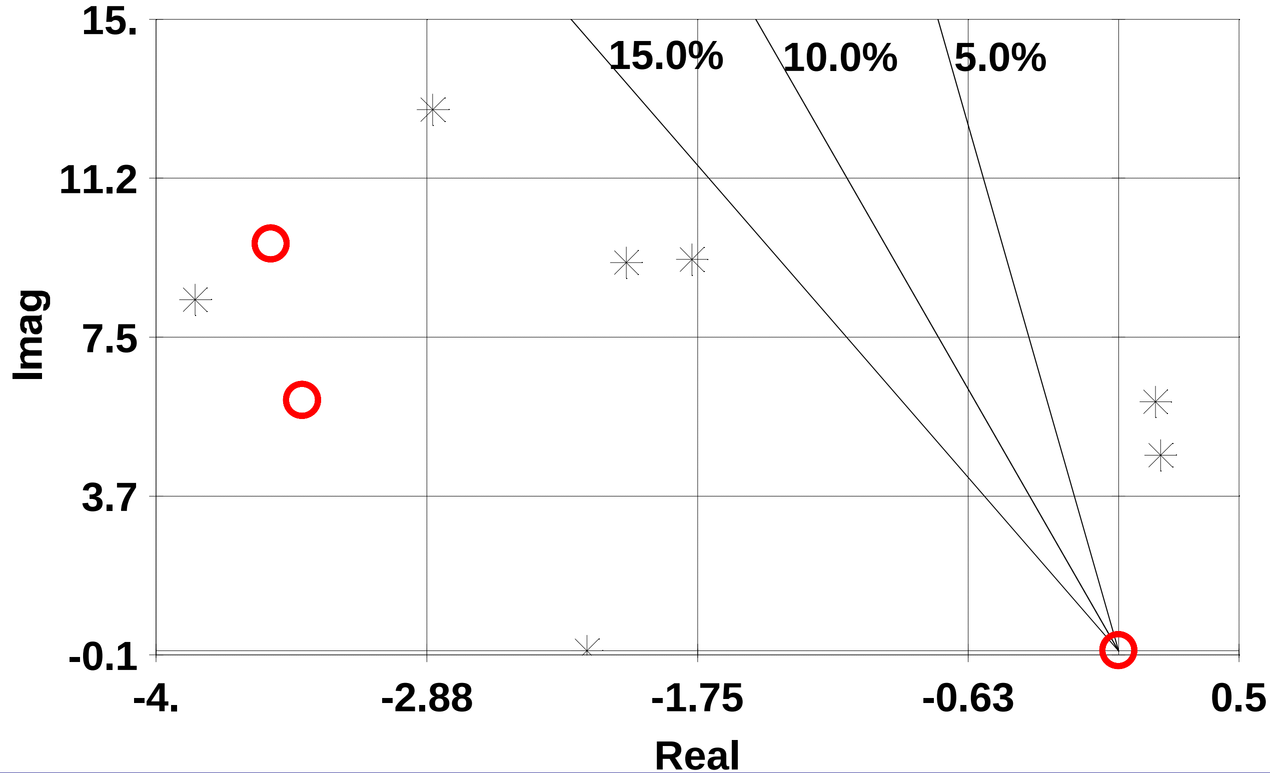
POLE PLACEMENT – 2 MODES AND 3 PSSs

- 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 $\underline{DK}$
- The gains of the PSSs are computed for a desired shift in the real part of the eigenvalues
- Every iteration, the pseudo-inverse algorithm updates and solves the following matrix equation:

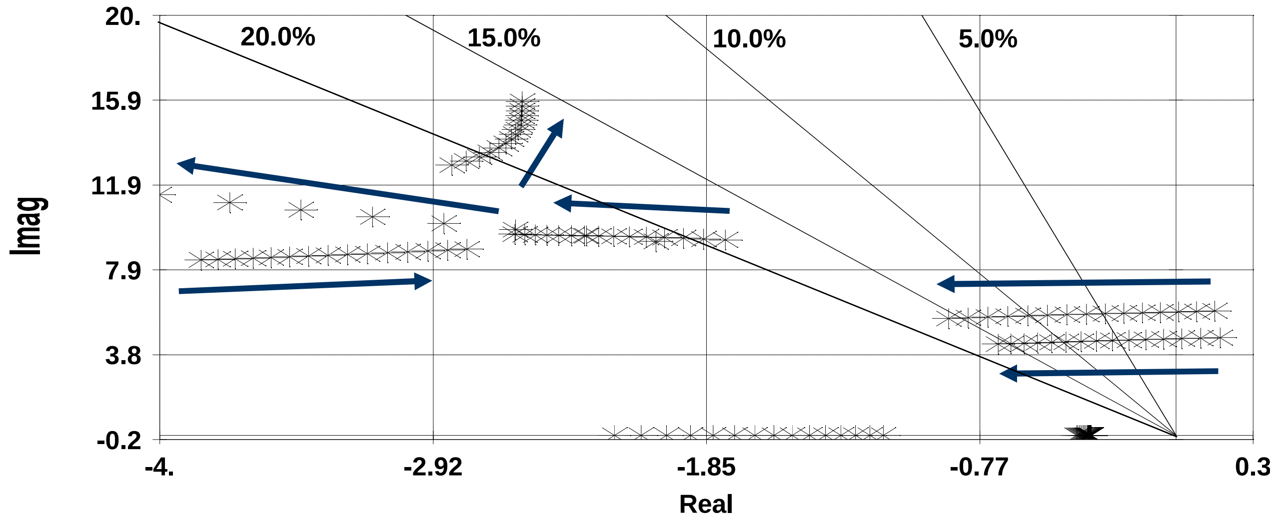
$$\begin{bmatrix} \Delta K_1 \\ \Delta K_2 \\ \Delta K_3 \end{bmatrix} = \begin{bmatrix} \operatorname{Re}\left[R\left(\dfrac{\Delta V_{PSS1}}{\Delta V_{REF1}}, l_1\right) \quad R\left(\dfrac{\Delta V_{PSS2}}{\Delta V_{REF2}}, l_1\right) \quad R\left(\dfrac{\Delta V_{PSS3}}{\Delta V_{REF3}}, l_1\right) \right] \\ \operatorname{Re}\left[R\left(\dfrac{\Delta V_{PSS1}}{\Delta V_{REF1}}, l_2\right) \quad R\left(\dfrac{\Delta V_{PSS2}}{\Delta V_{REF2}}, l_2\right) \quad R\left(\dfrac{\Delta V_{PSS3}}{\Delta V_{REF3}}, l_2\right) \right] \end{bmatrix}^{+} \left[\operatorname{Re}\begin{bmatrix} \Delta l_1 \\ \Delta l_2 \end{bmatrix} \right]$$

POLE-ZERO MAP OF $[Dw/DV_{REF}]_{3x3}$

- **Map of poles (❄) and zeros (O) for the matrix transfer function $[Dw/DV_{REF}]_{3x3}$ with PSSs in Itaipu, S. Segredo and Foz do Areia**



Pole Placement – 2 Modes and 3 PSSs



Case 4

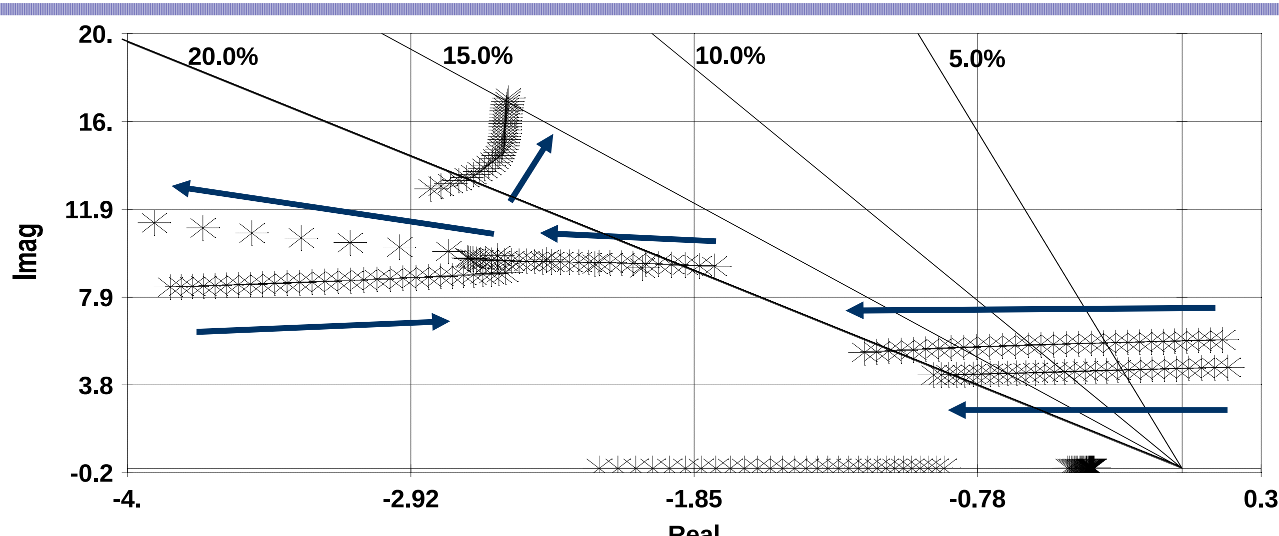
K_{Itaipu} = 8.1

$K_{S.Segredo}$ = 11.9

$K_{Foz\ do\ Areia}$ = 12.0

z_{11} = 15.9 %

z_{12} = 15.9 %



Case 5

K_{Itaipu} = 10.4

$K_{S.Segredo}$ = 16.3

$K_{Foz\ do\ Areia}$ = 16.3

z_{11} = 22.0 %

z_{12} = 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 Þ pole placement may yield undesirably high values for the PSS gains