**Panel Session on Recent Applications of Linear Analysis Techniques**

# SOME RECENT DEVELOPMENTS IN SMALL-SIGNAL STABILITY AND CONTROL

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# PAPER CONTENTS

- Several modal analysis applications to power system problems are described, including:

  - ➔Hopf bifurcations in the control parameters space

  - ➔Modal equivalents of multivariable transfer functions

  - ➔Pole - zero analysis in harmonic studies

  - ➔Using zeros to understand the adverse terminal voltage transients induced by the presence of PSSs

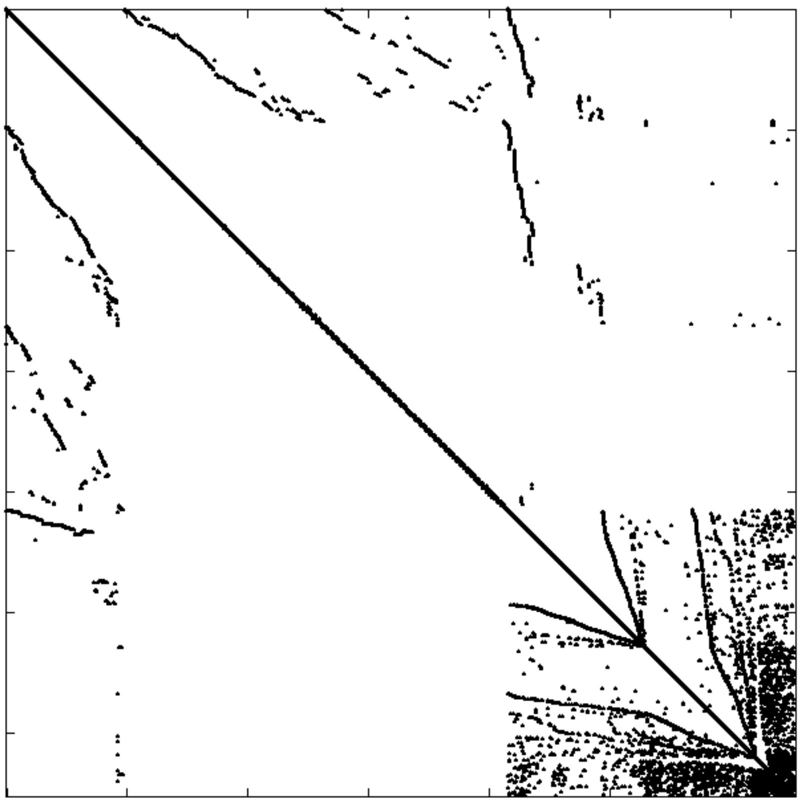
# Hopf Bifurcation Algorithms

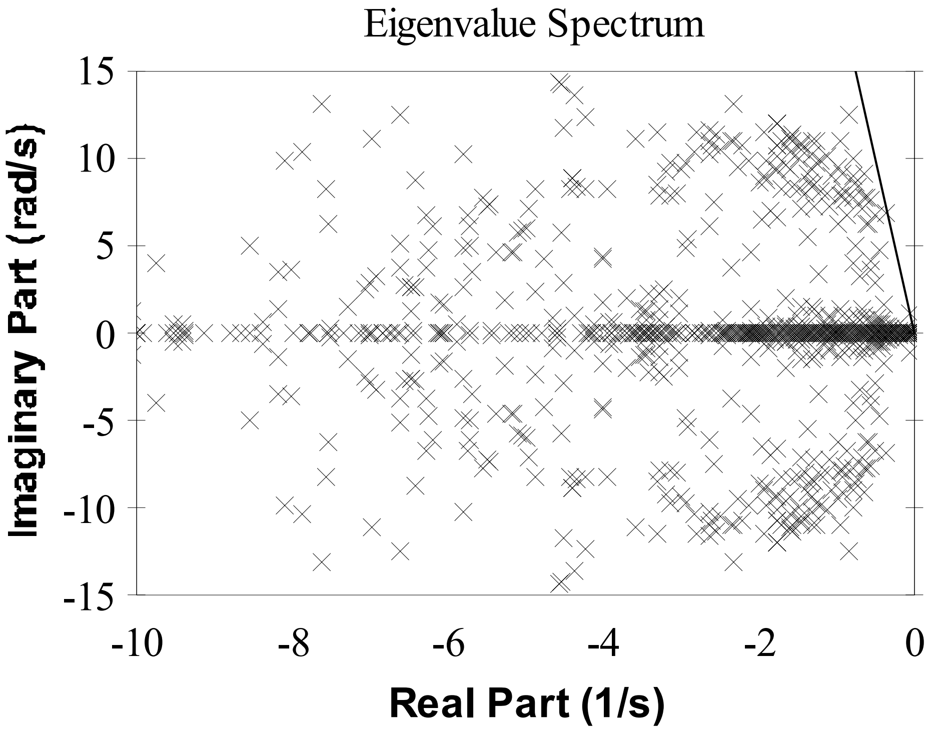
- Compute parameter values that cause crossings of the small-signal stability boundary by critical eigenvalues

- 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



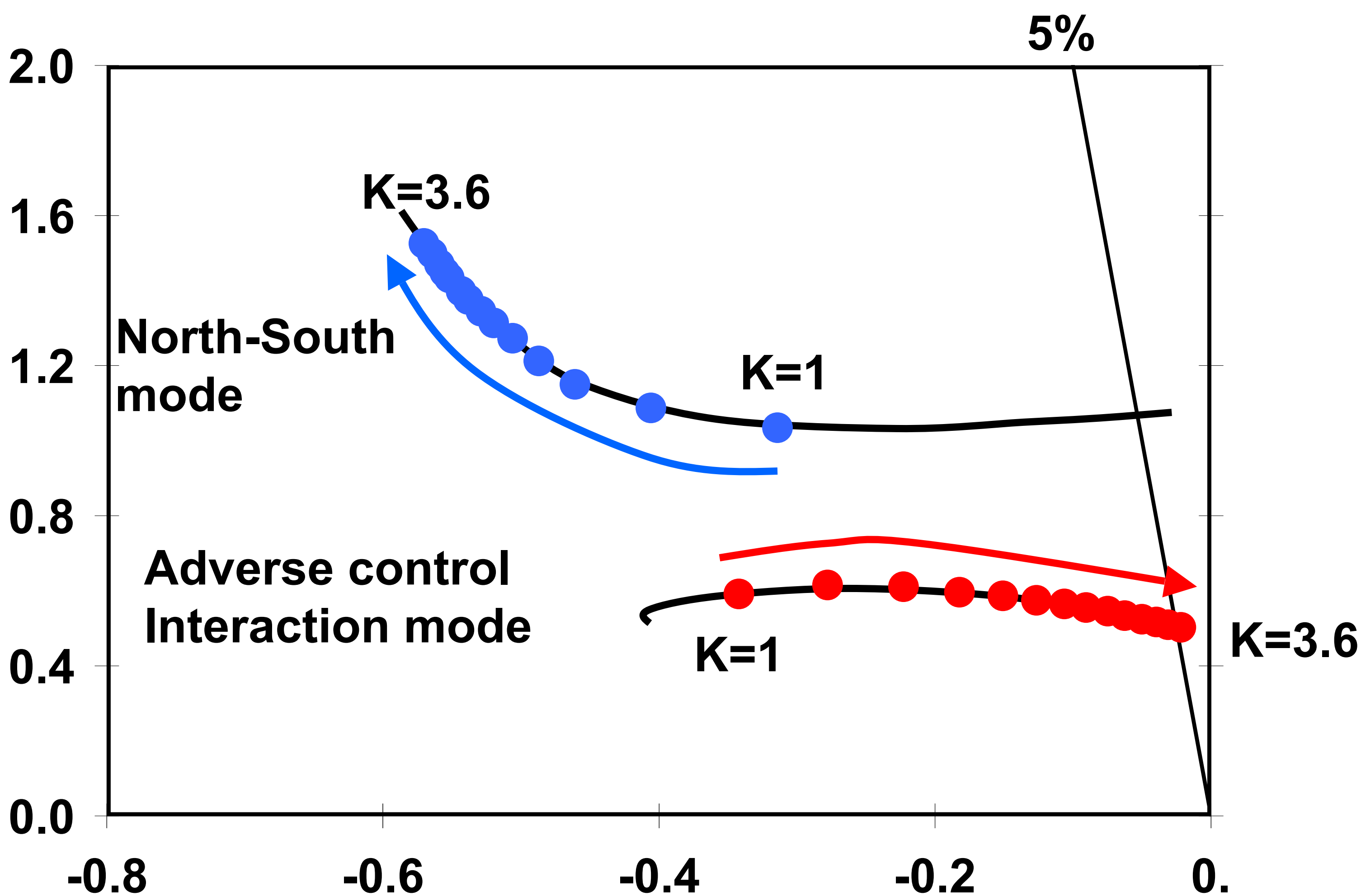


# HOPF BIFURCATIONS – TEST SYSTEM PROBLEM

- 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 INCREASING THE GAINS OF THE 2 TCSCs



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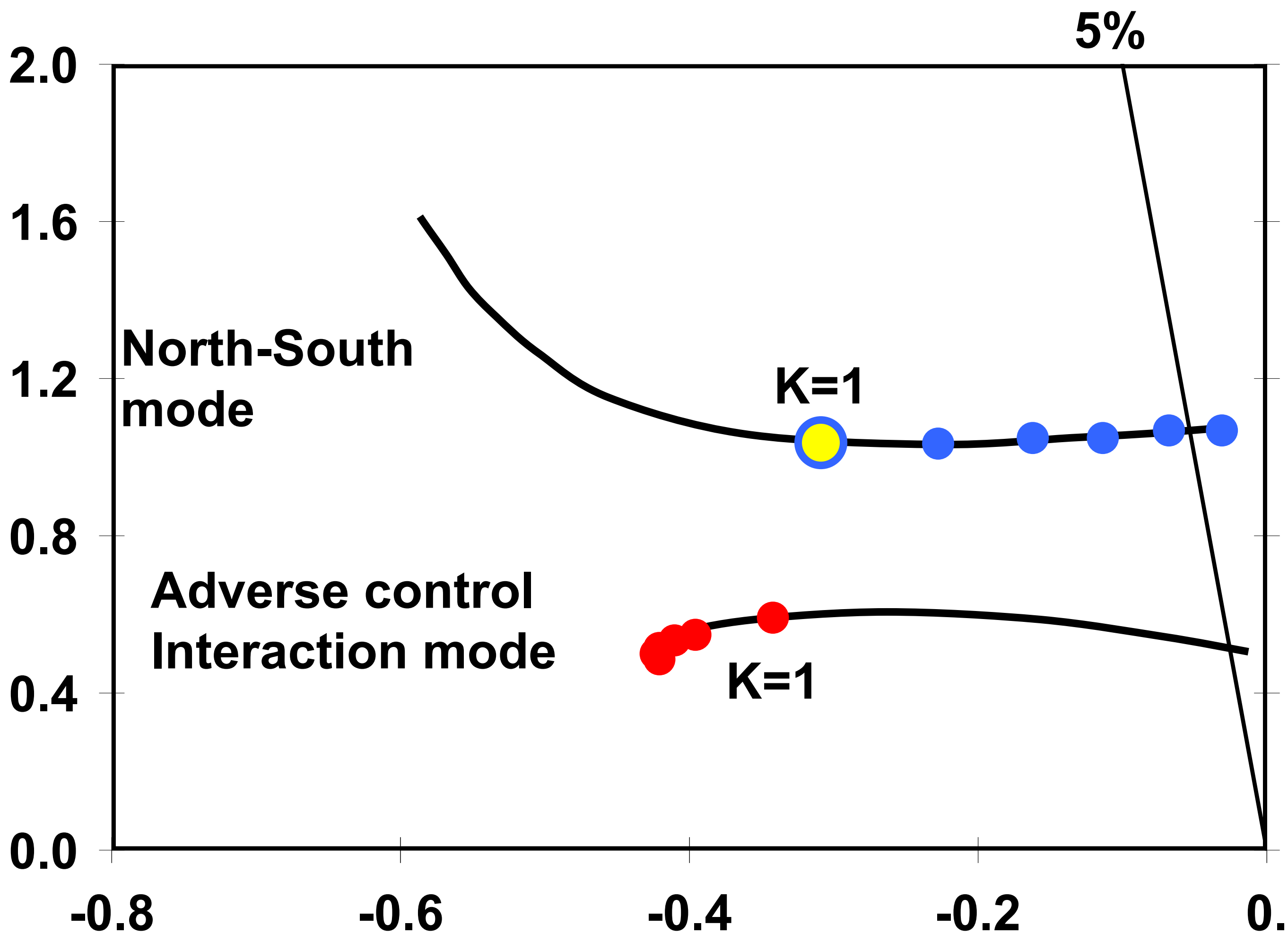

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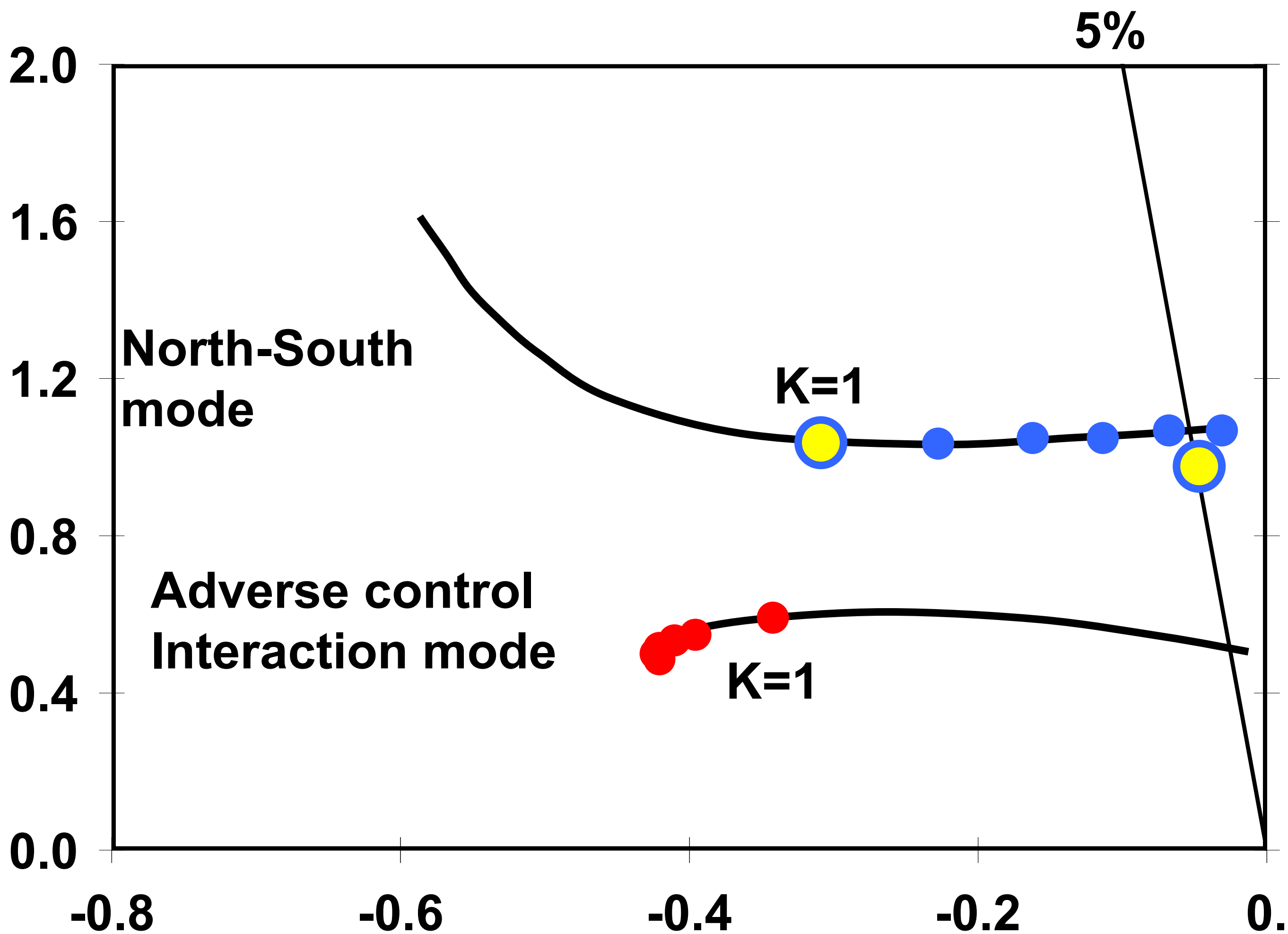

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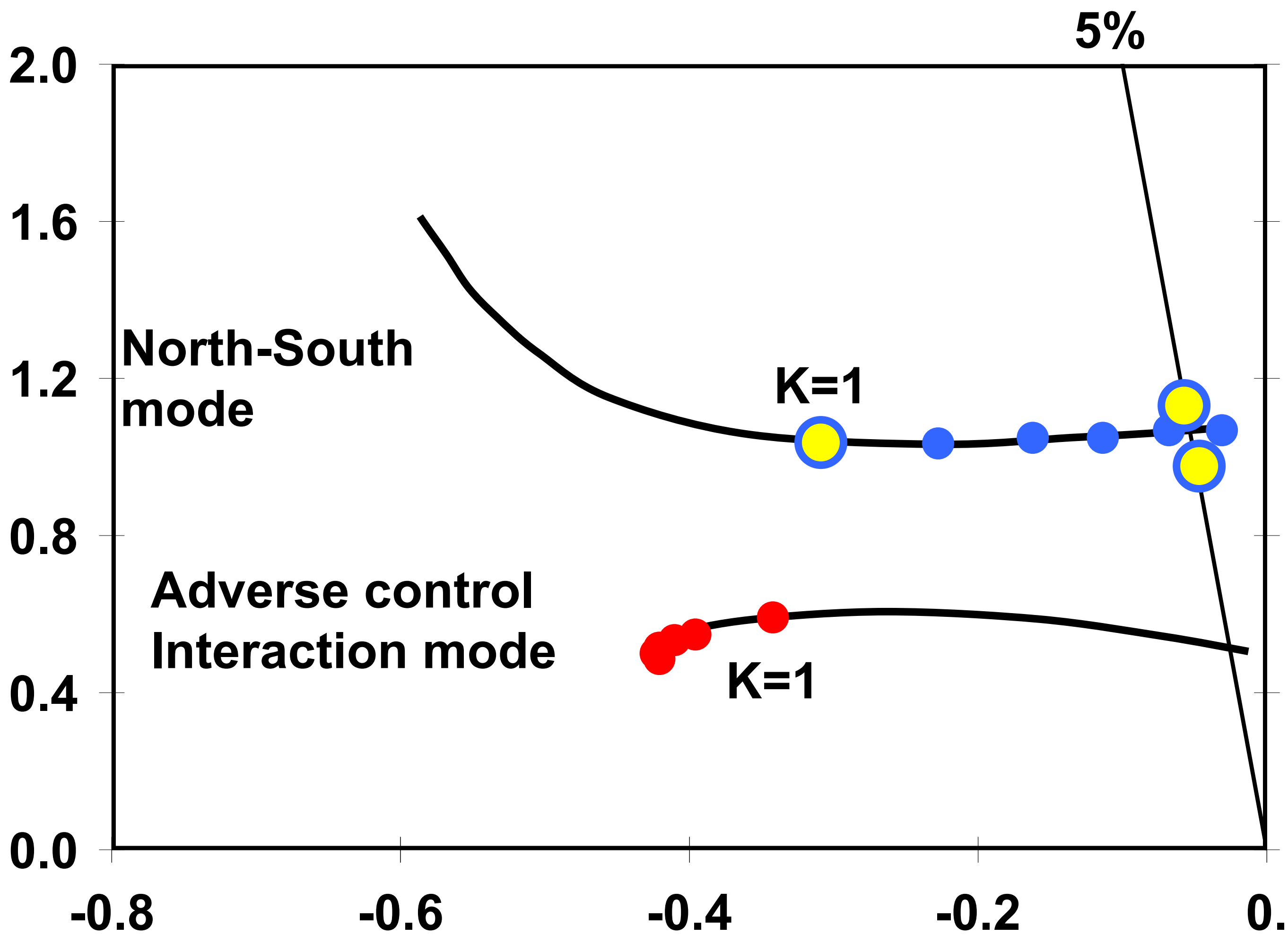

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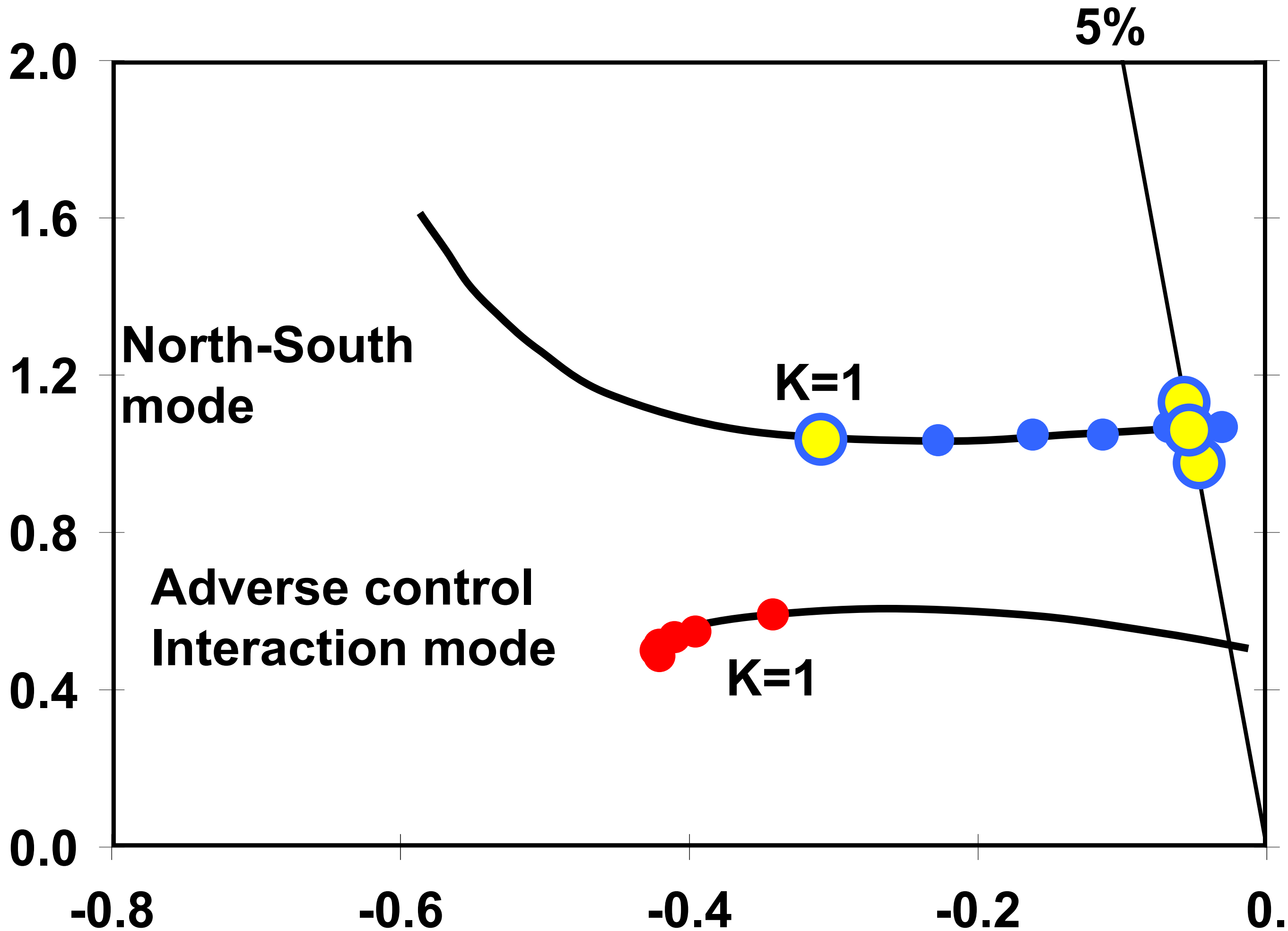

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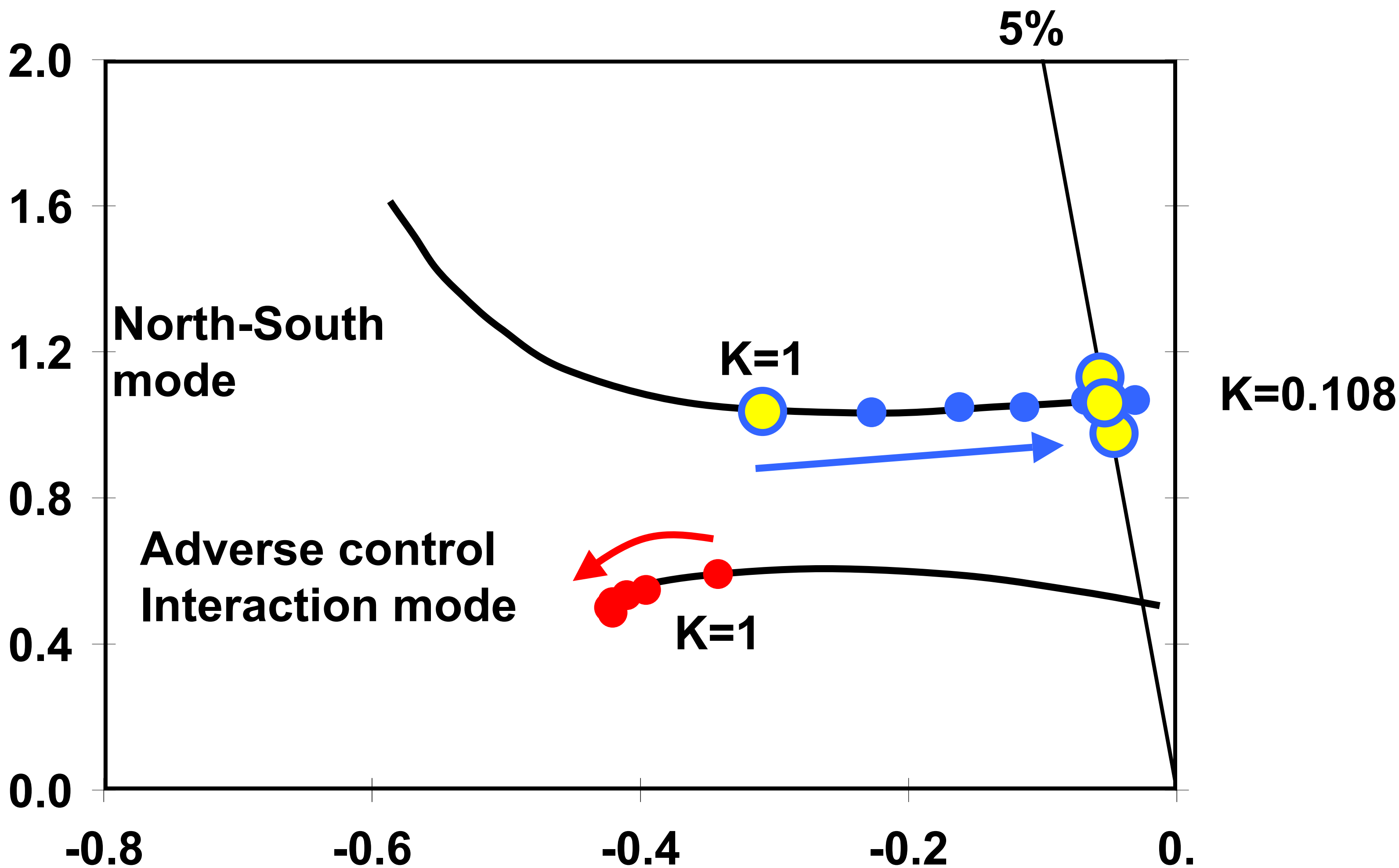

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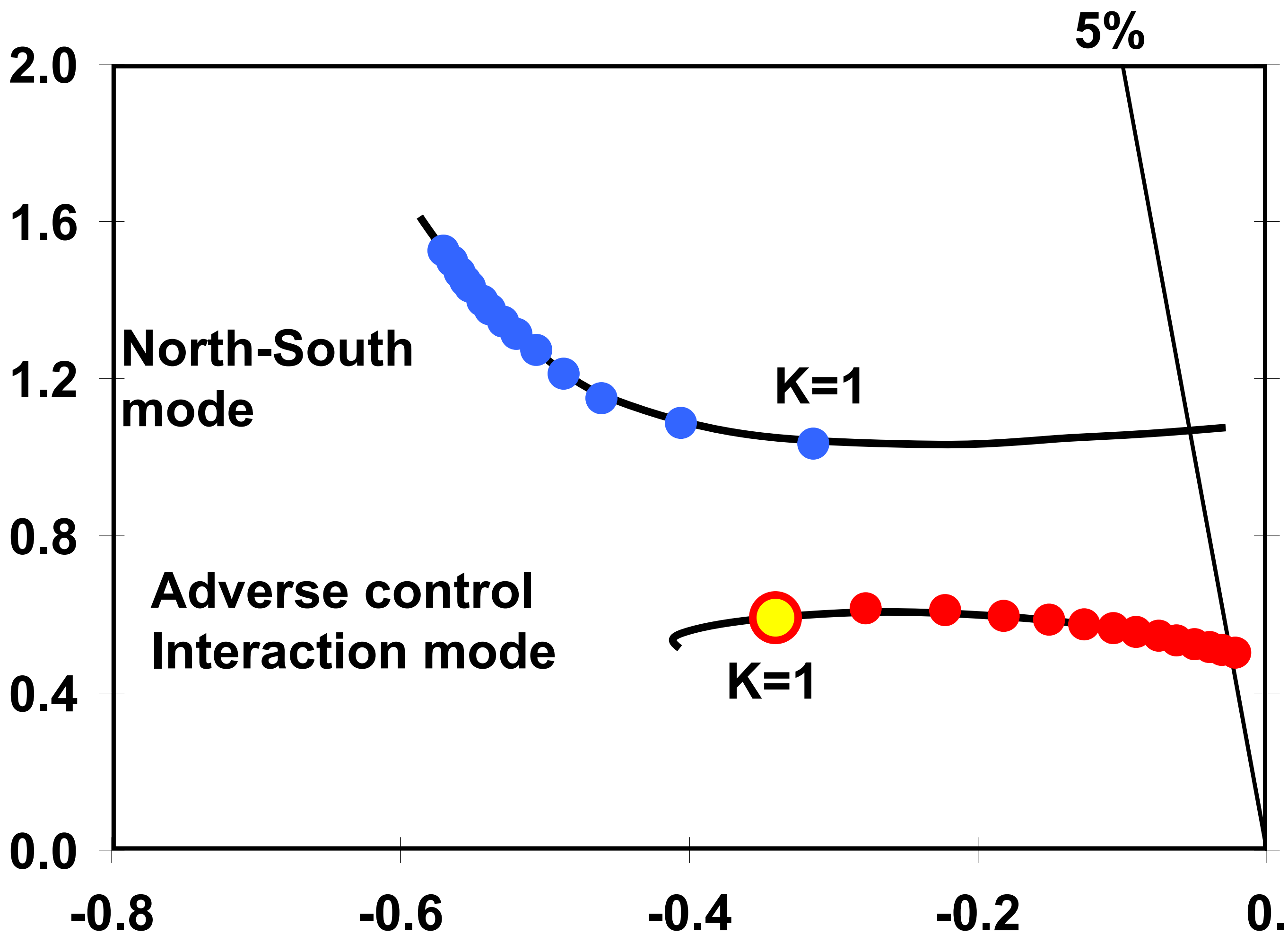

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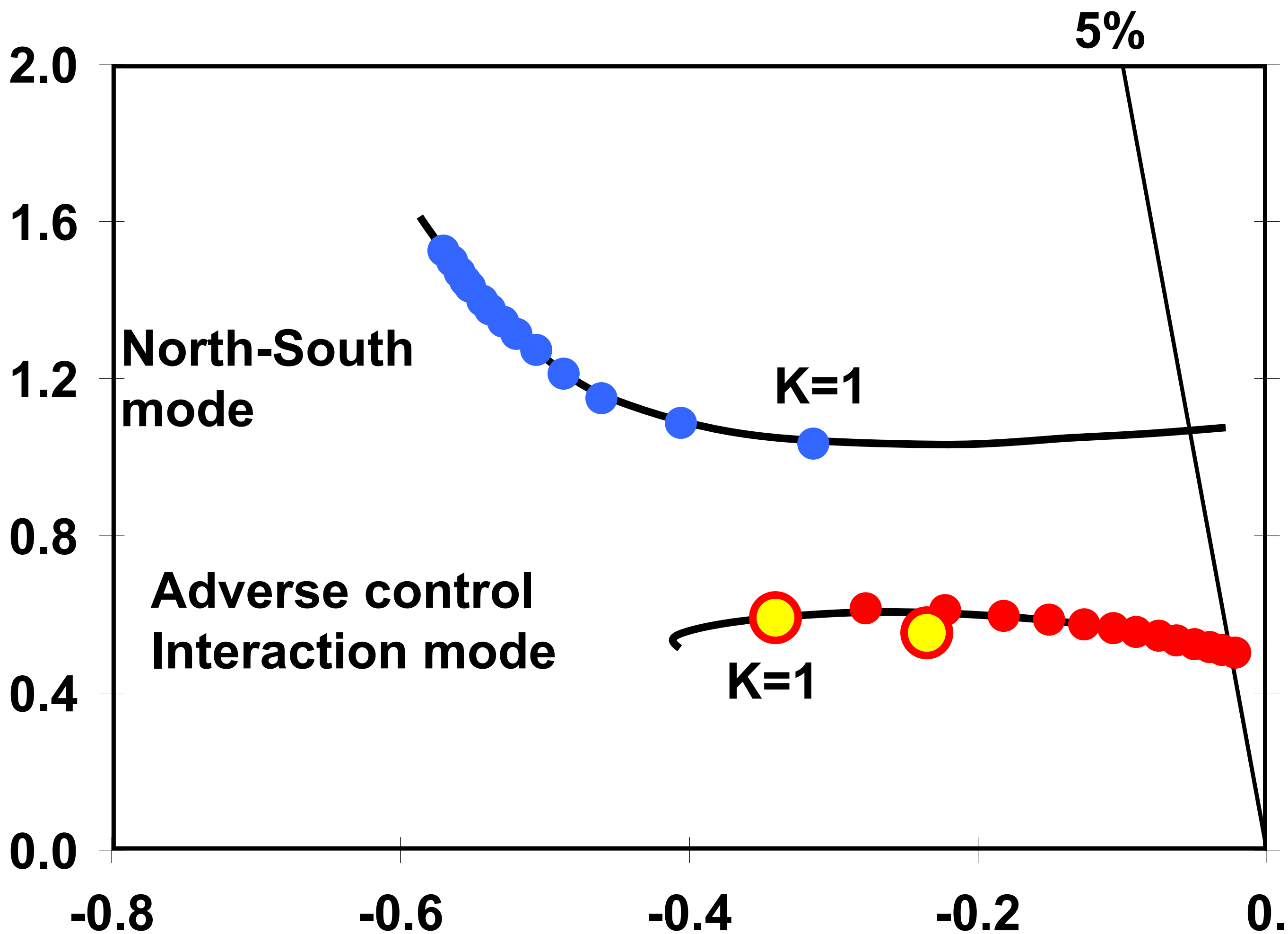

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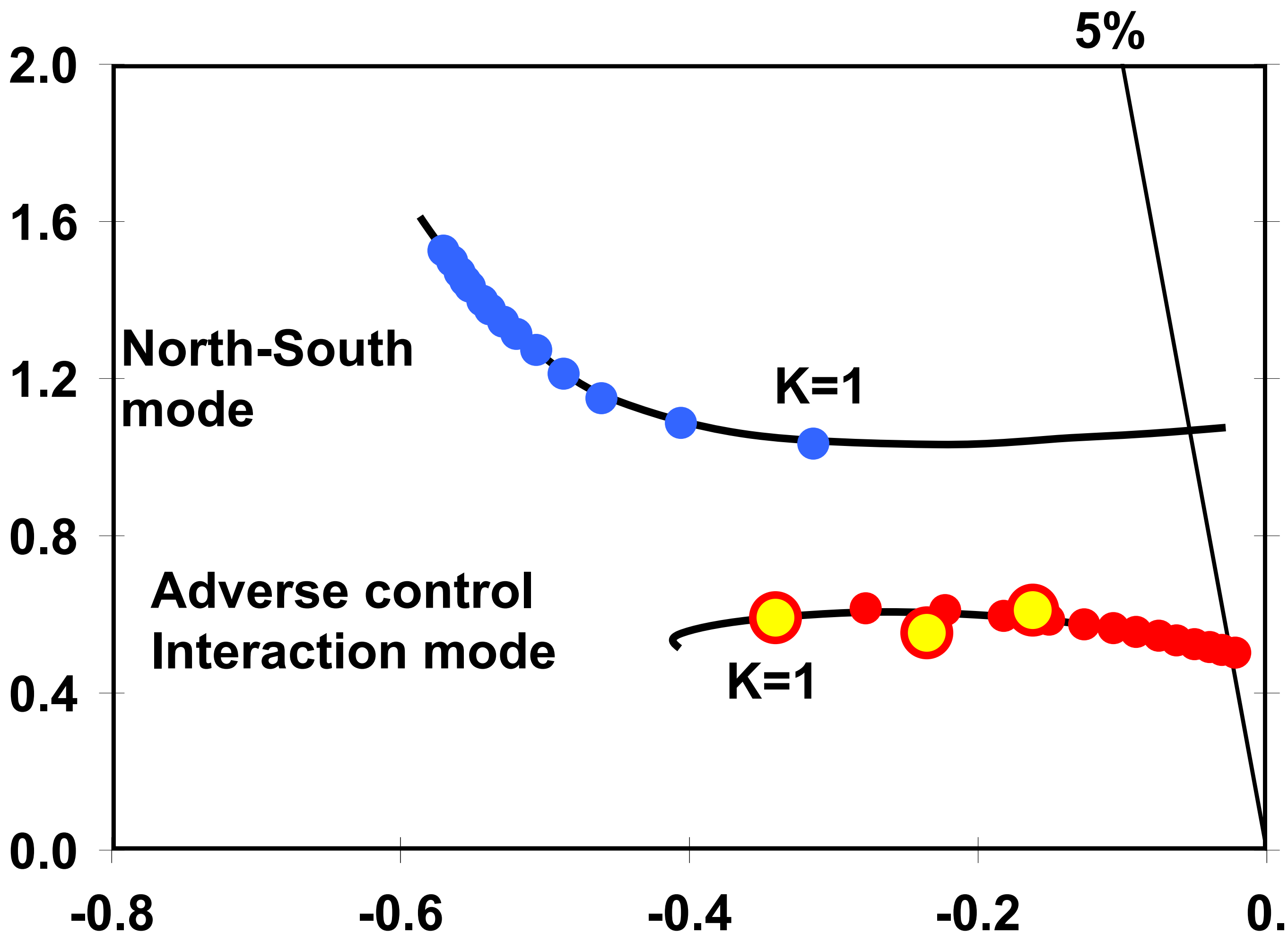

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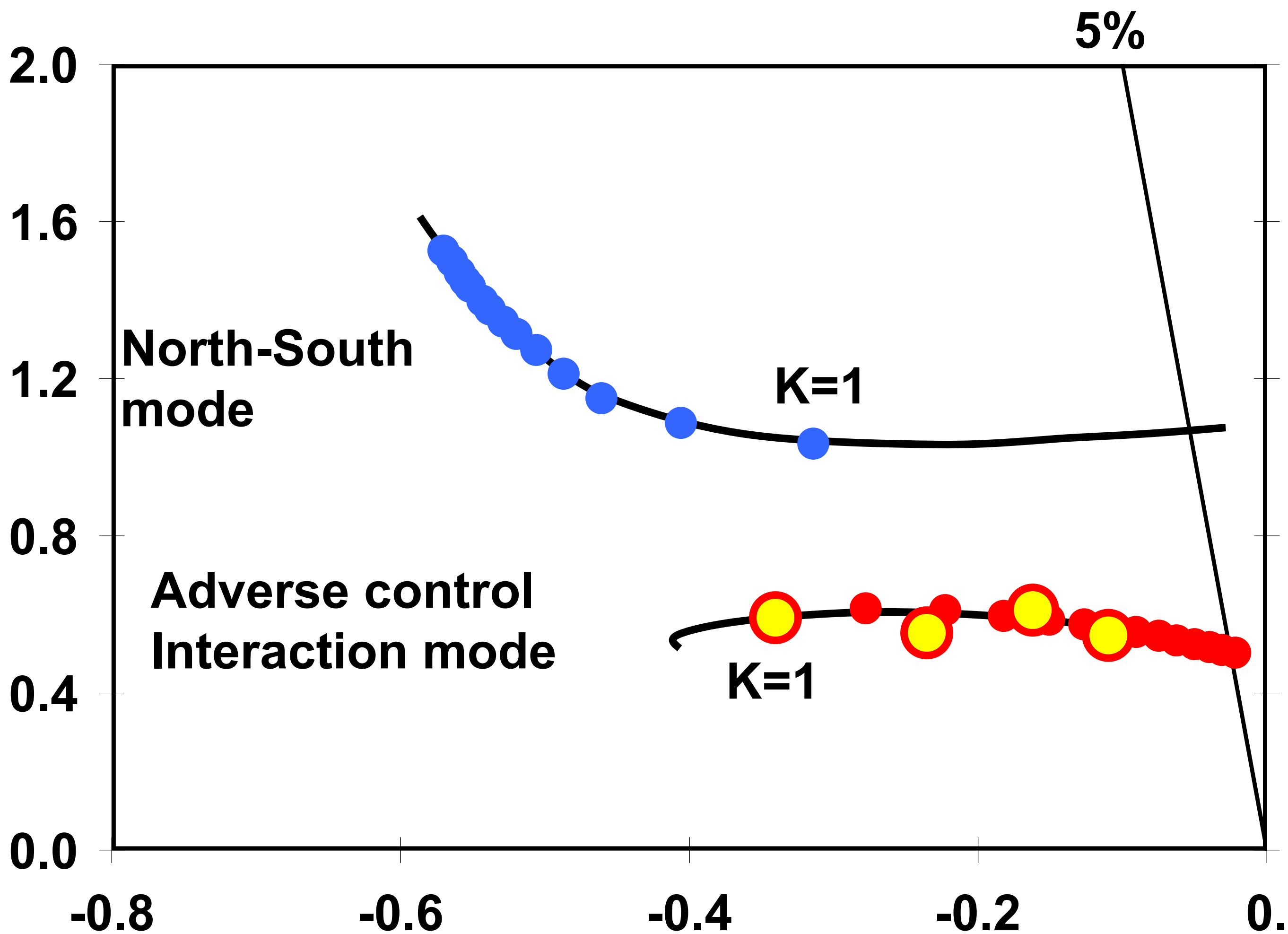

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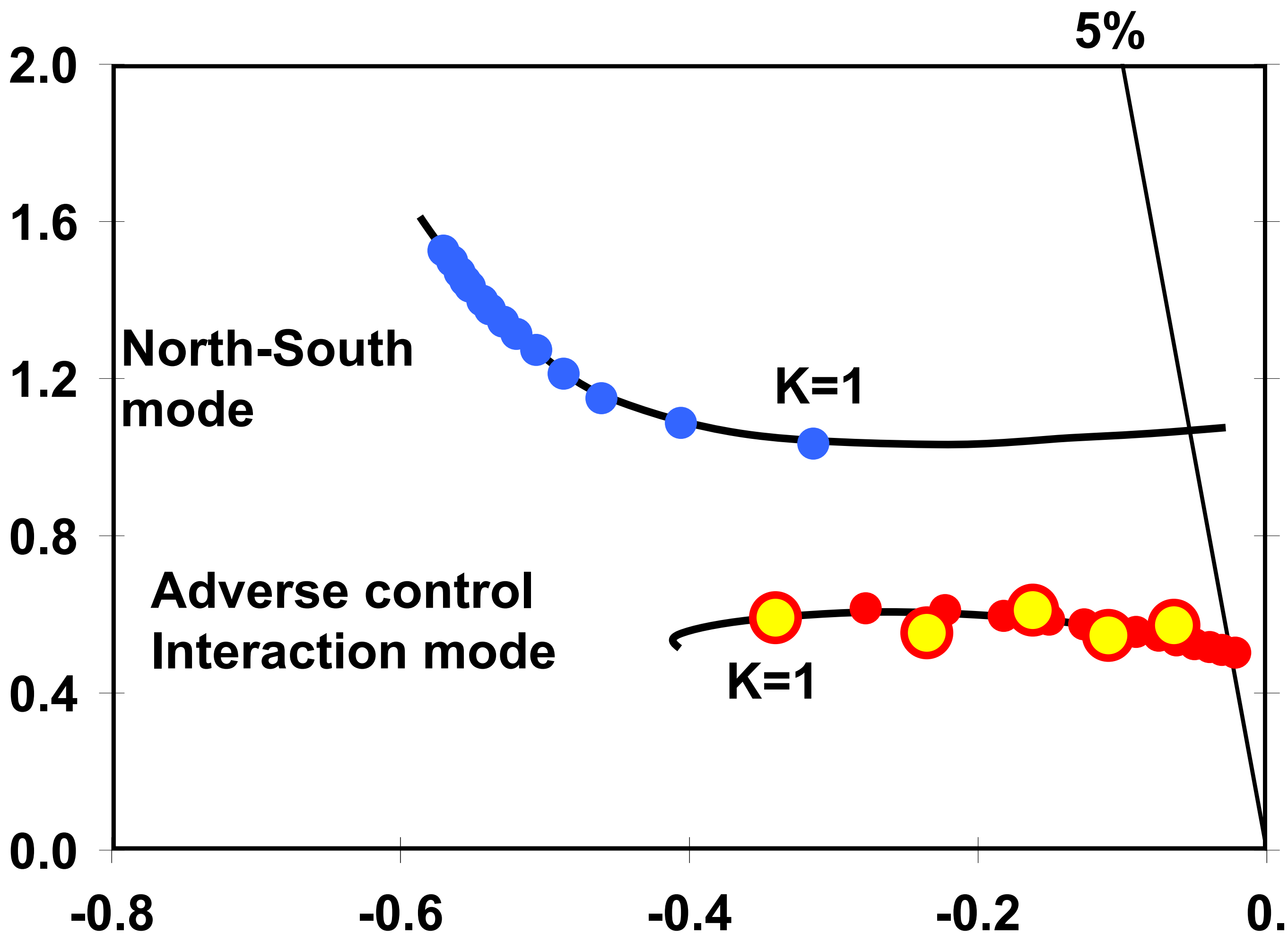

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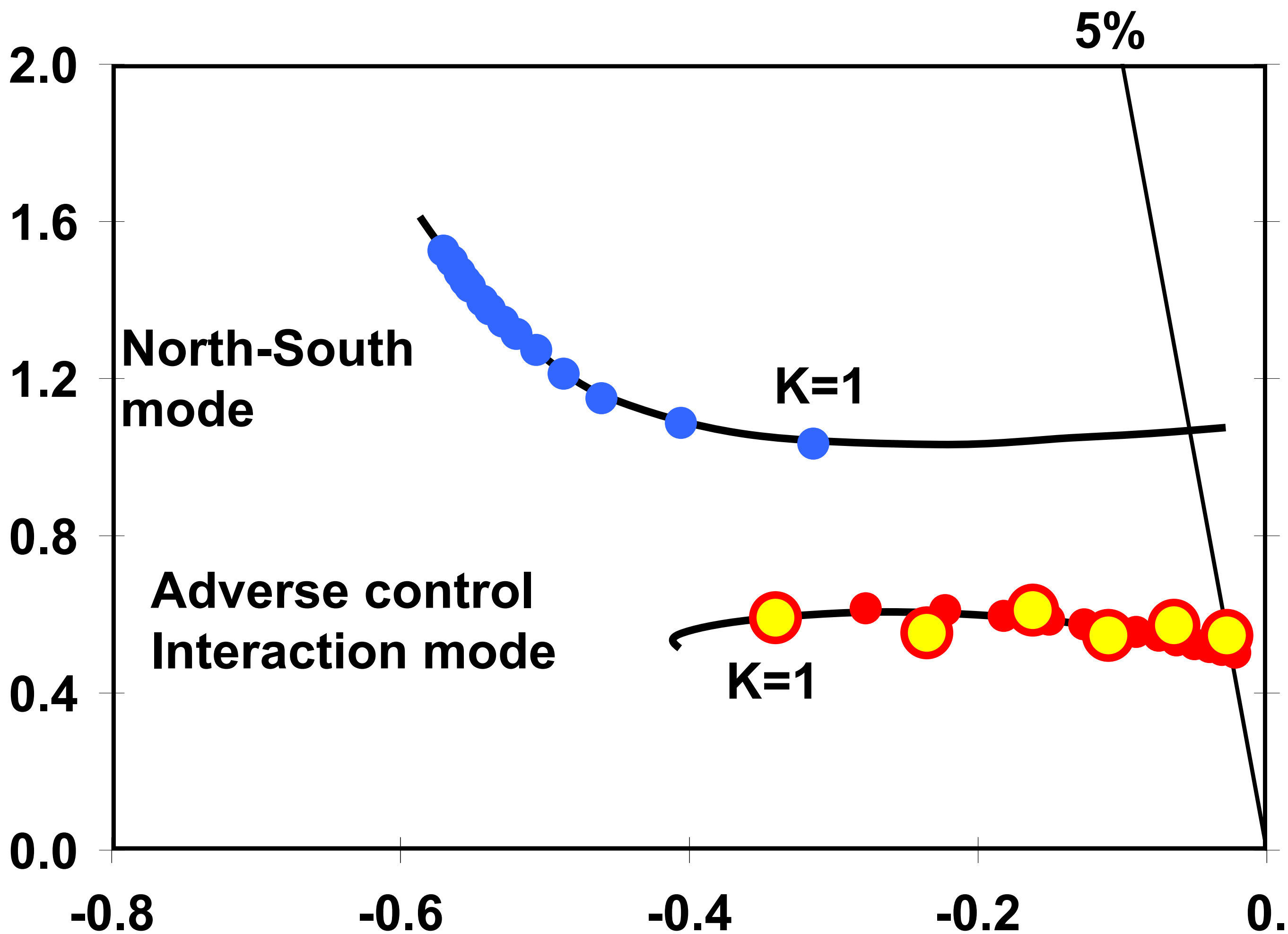

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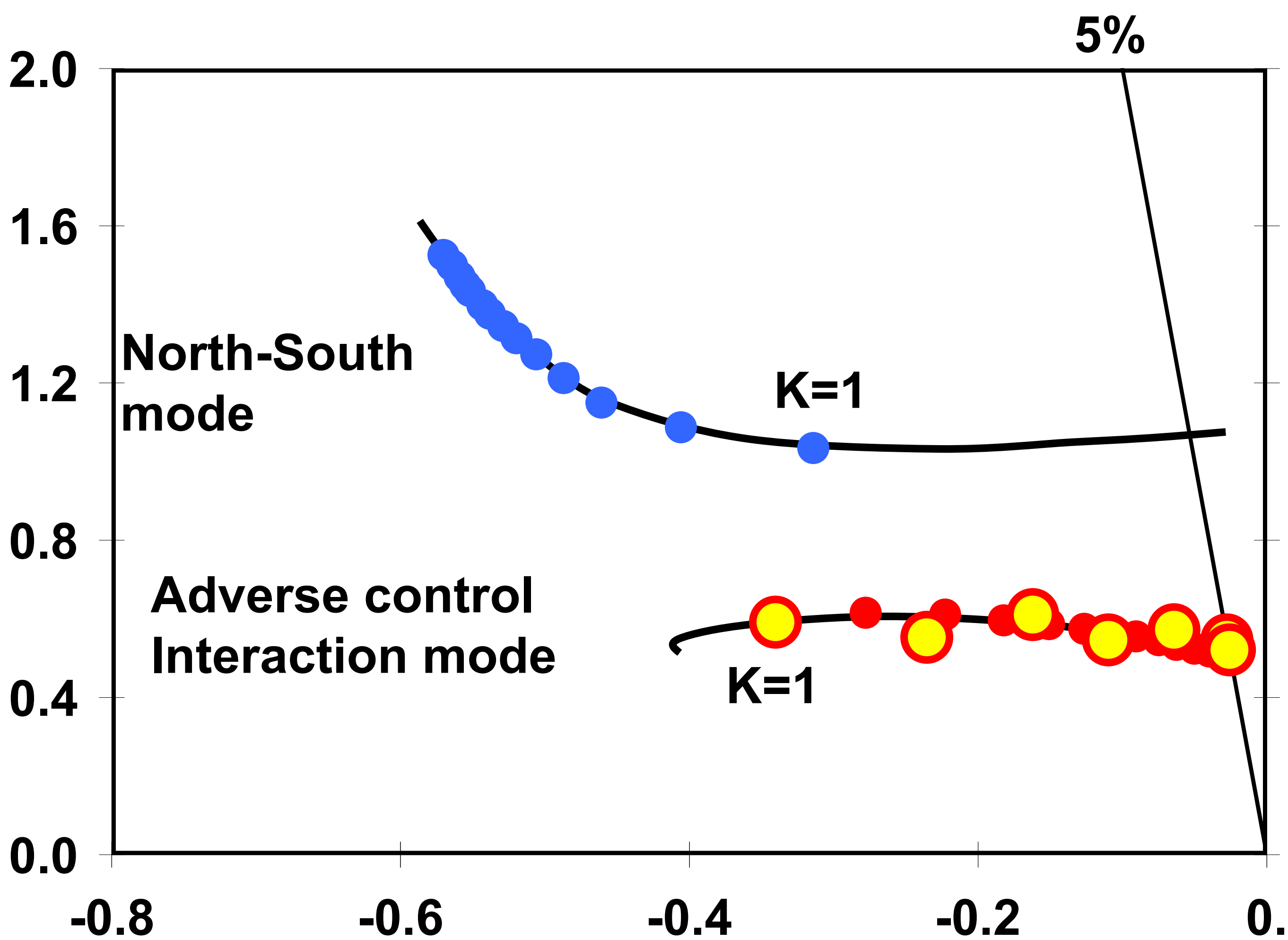

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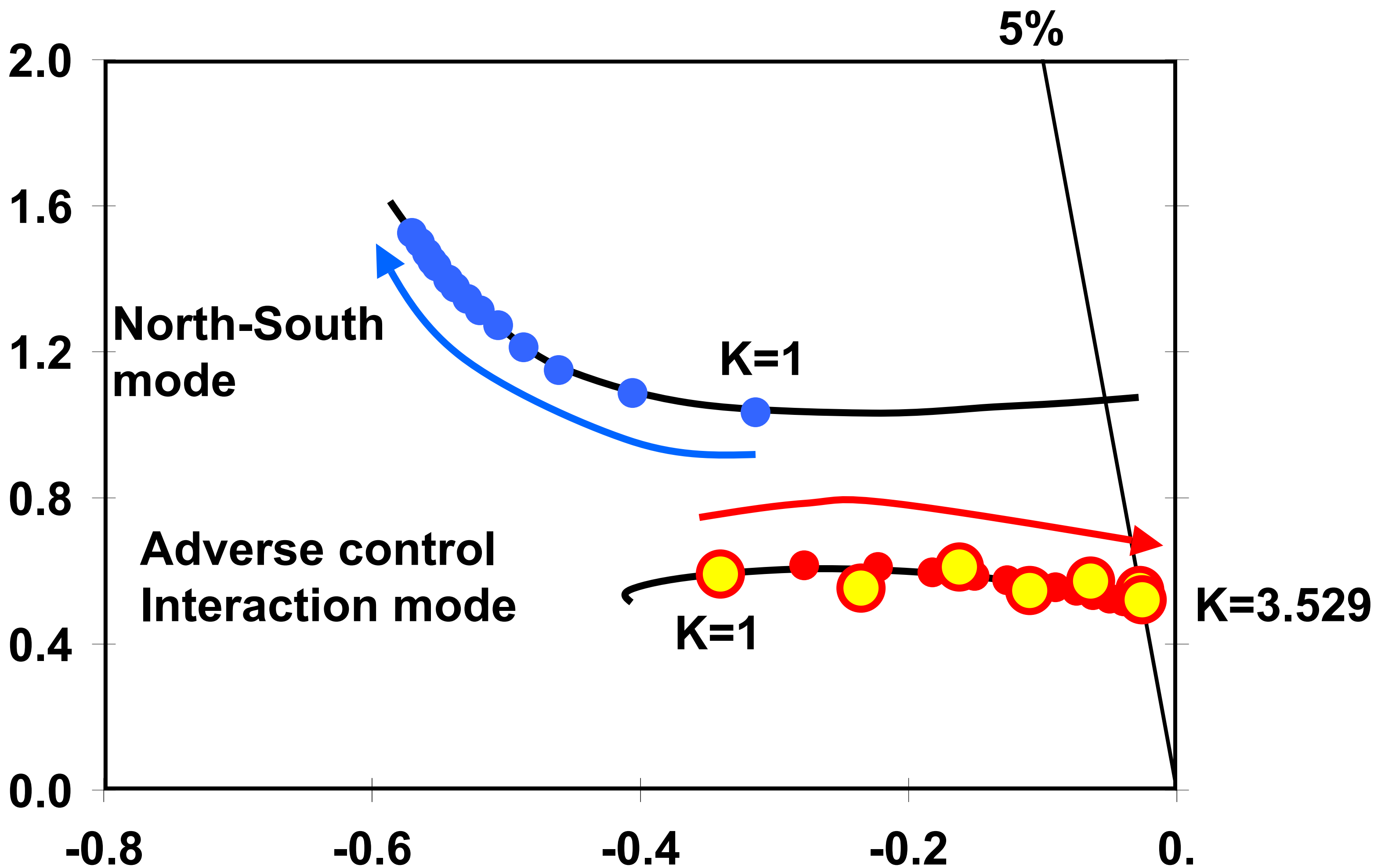


# Hopf Bifurcations - Conclusions

- **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)**

# MODAL EQUIVALENTS OF MULTIVARIABLE TRANSFER FUNCTIONS

- An *m* x *m* transfer function G(*s*) may be expanded in terms of the system poles and associated residue matrices :

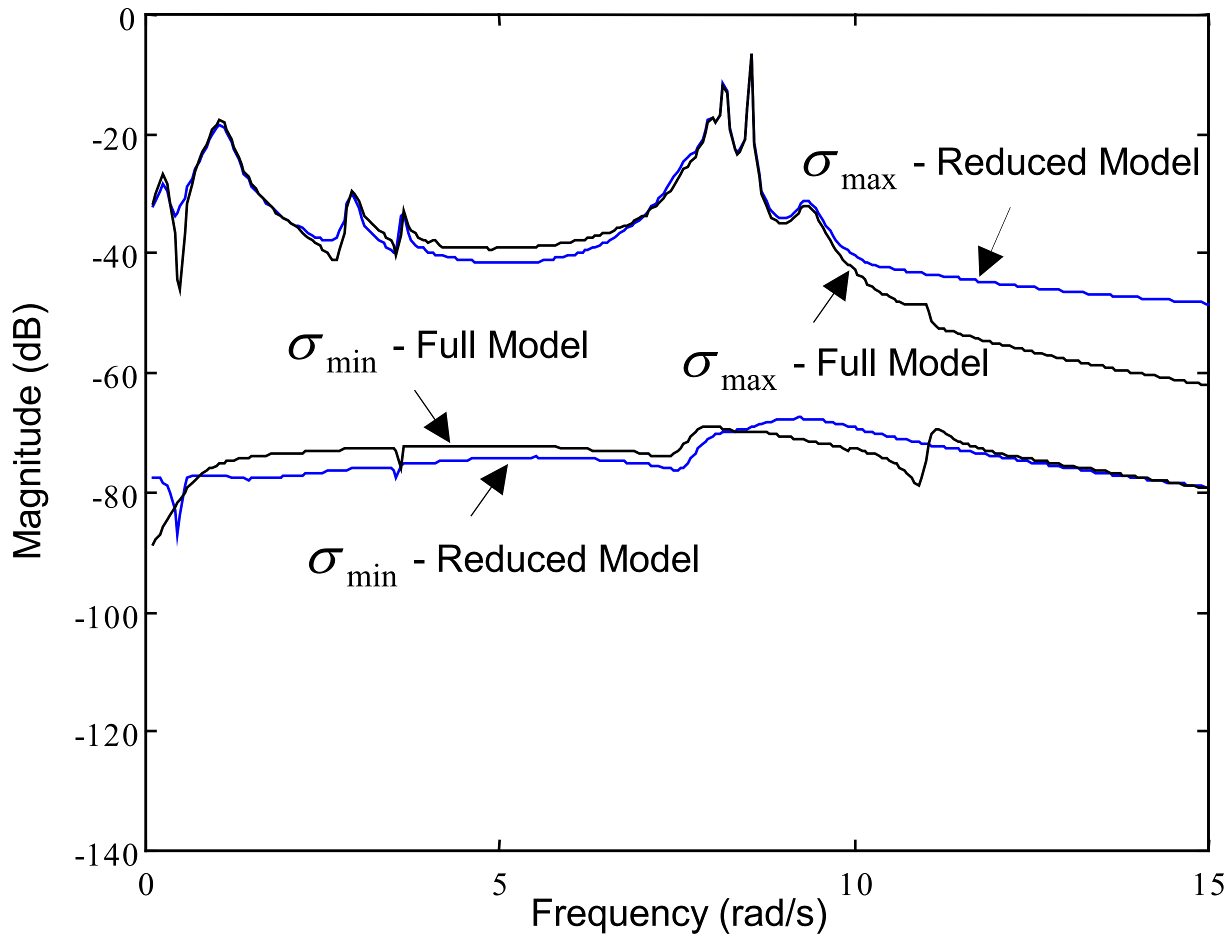
$$\mathbf{G}(s) = \sum_{i=1}^{n} \frac{\mathbf{R}_i}{s - \lambda_i}$$

- The truncated sum below is the modal equivalent:

$$\mathbf{G}(s) \approx \sum_{i=1}^{p} \frac{\mathbf{R}_i}{s - \lambda_i} \text{ , where } p << n$$

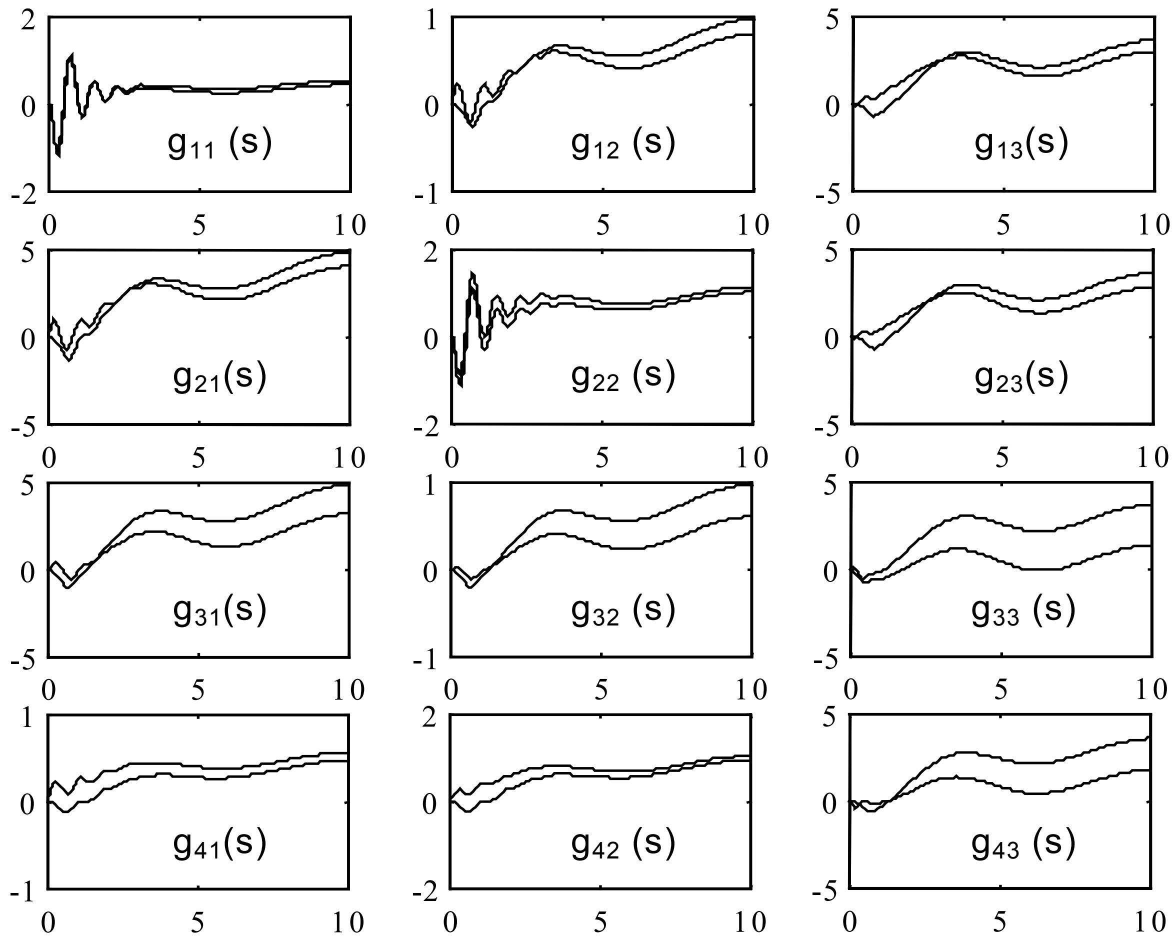
# MODAL EQUIVALENTS OF MULTIVARIABLE TRANSFER FUNCTIONS

- Sigma-plot for 8 x 8 G(*s*), $\xi$ = 15%
- Full Model has order 1,676 while Modal Equivalent has order 41



# MODAL EQUIVALENTS OF MULTIVARIABLE TRANSFER FUNCTIONS

- Step responses for $g_{ij}(s)$ scalar transfer functions for the full model and the 41st-order modal equivalent




- Note: Vertical axes given in rad/s and horizontal axes in seconds

# MODAL ANALYSIS IN HARMONIC STUDIES

## Background

- Harmonic voltage distortions in a system depend on the proximity of its poles and zeros with respect to the characteristic harmonic frequencies
- Modal analysis finds poles, zeros and their respective sensitivities to system parameters
- Determines most effective parameter changes in order to reduce harmonic voltage distortion

# *s*-DOMAIN MODEL Y(*s*) - ADVANTAGES

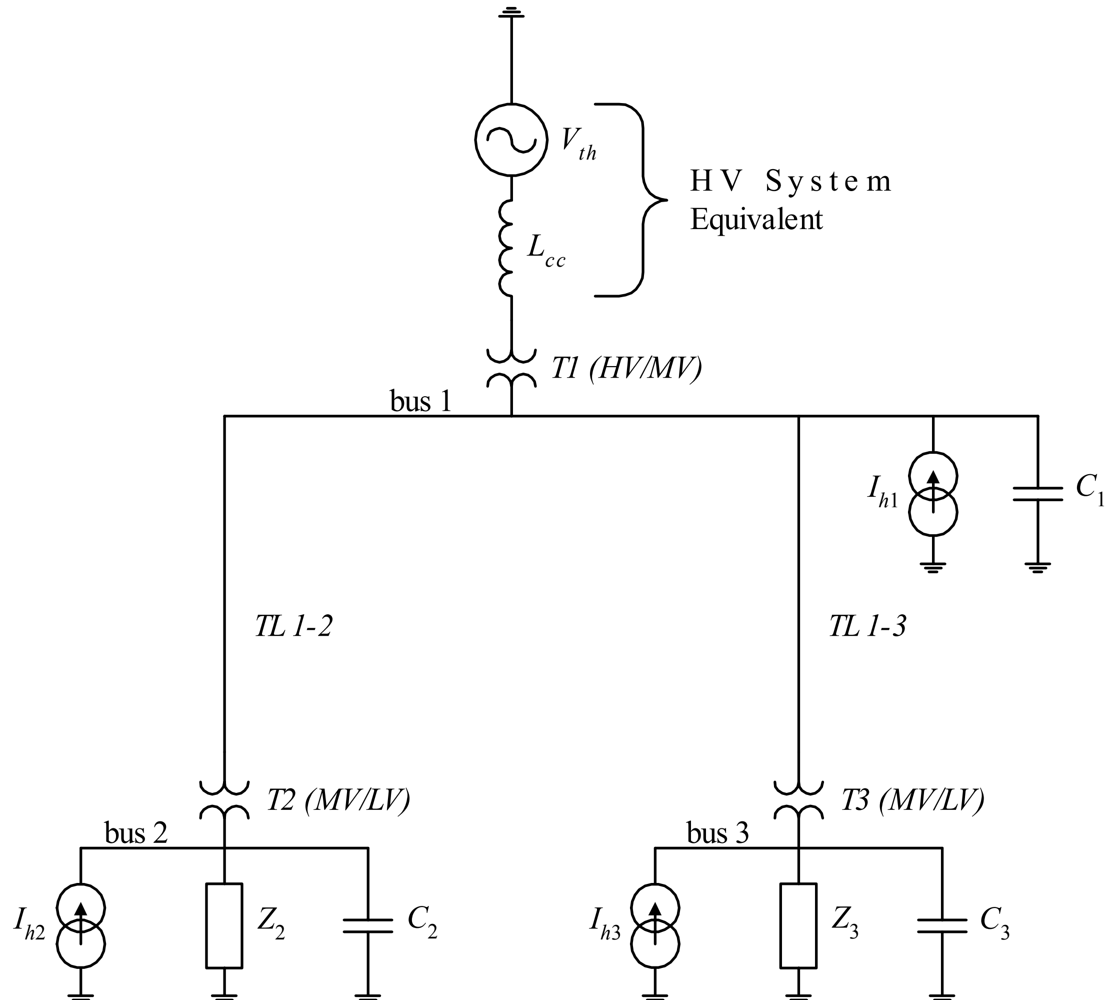
- The Y(*s*) matrix and its derivative can be rapidly built

- Frequency-dependent components and distributed-parameter lines can be efficient and accurately modeled

- Y(s) matrix is always of much lower dimension than state-space or descriptor system models

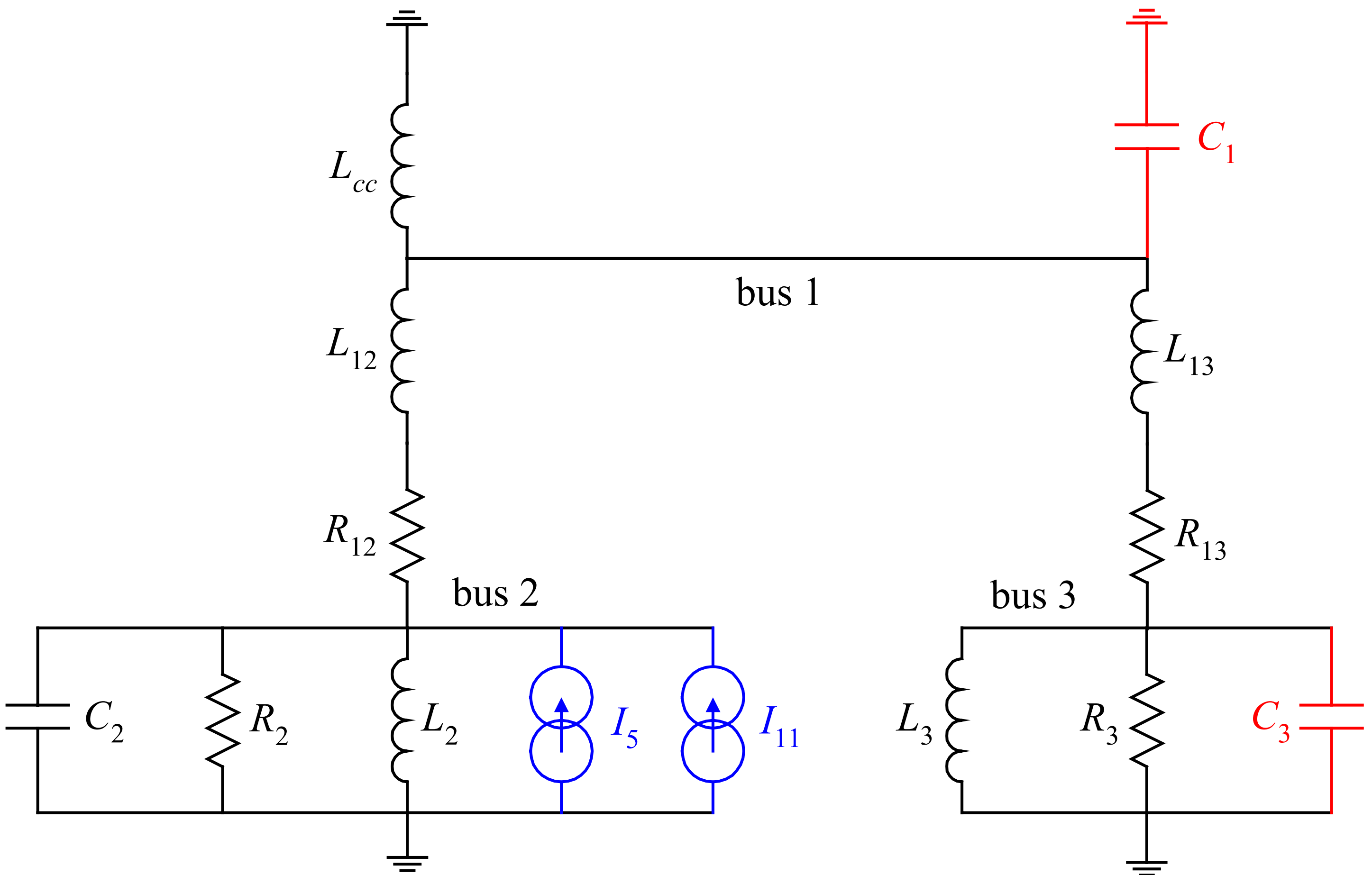
# MODAL ANALYSIS IN HARMONIC STUDIES

## ➢ Test System



# Modal Analysis in Harmonic Studies

- **RLC System Model with Harmonic Current Sources and Capacitors to be Changed**



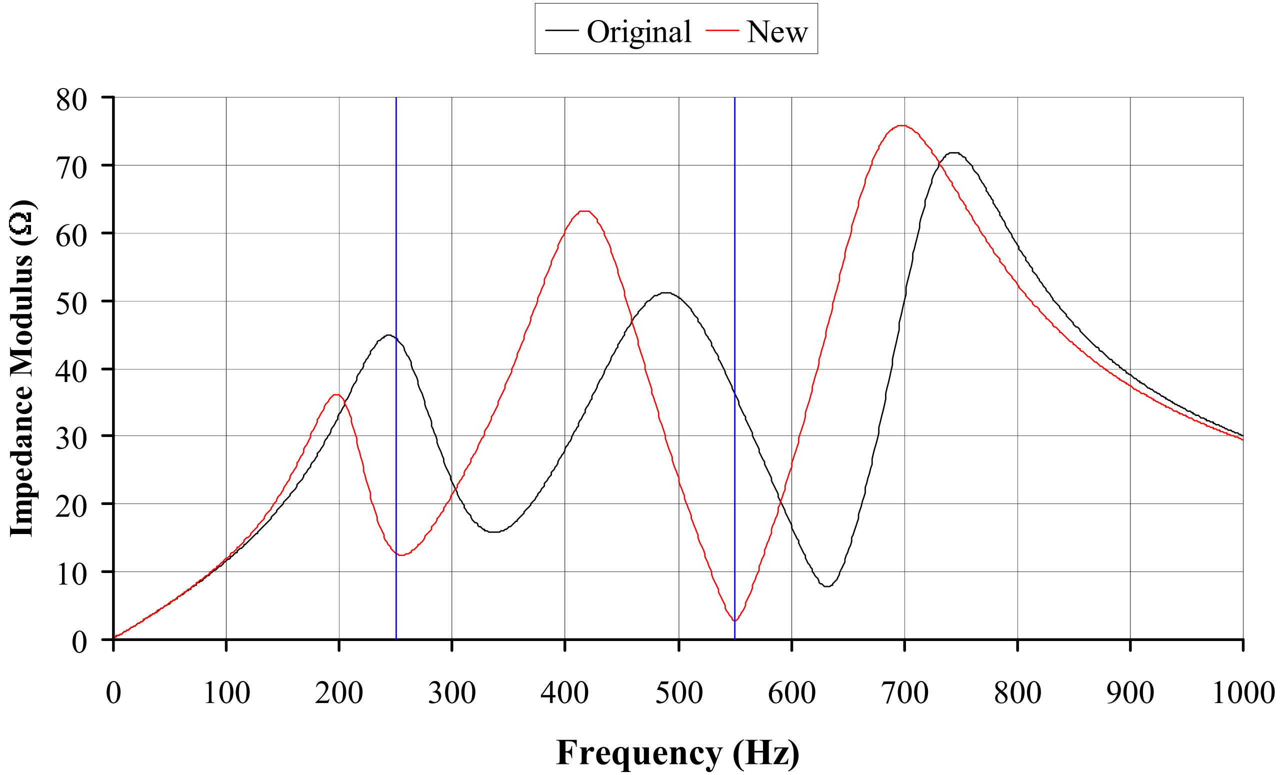
# MODAL ANALYSIS IN HARMONIC STUDIES

- Resonance frequencies and sensitivities (Fundamental freq.: 50 Hz)

| | System poles | | | Zeros seen from | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Bus 1 | | Bus 2 | | Bus 3 | |
| | 1 | 2 | 3 | 1 | 2 | 1 | 2 | 1 | 2 |
| *f(Hz)* | 252 | 489 | 722 | 425 | 565 | 332 | 633 | 382 | 704 |
| $L_{CC}$ | -101 | -11 | -50 | 0 | 0 | -48 | -80 | -88 | -47 |
| $L_2$ | -3 | -4 | -2 | 0 | -7 | 0 | 0 | -5 | -2 |
| $L_3$ | -4 | -2 | 0 | -5 | 0 | -5 | -1 | 0 | 0 |
| $L_{12}$ | -2 | -78 | -247 | 0 | -290 | -40 | -66 | -37 | -289 |
| $L_{13}$ | -19 | -151 | -78 | -211 | 0 | -75 | -172 | -59 | -32 |
| $C_1$ | -45 | -12 | -206 | 0 | 0 | -38 | -242 | -85 | -189 |
| $C_2$ | -25 | -116 | -111 | 0 | -269 | 0 | 0 | -109 | -145 |
| $C_3$ | -54 | -114 | -28 | -210 | 0 | -127 | -72 | 0 | 0 |

# Modal Analysis in Harmonic Studies

- Newton-Raphson Method Used to Shift Poles and/or Zeros Based on Sensitivities
- Reductions of 70% and 90% in the impedance magnitudes at 250Hz and at 550Hz were achieved (notably lower harmonic distortions!)




$C_{1original} = 23.9\ \mu F$

$C_{3original} = 11.9\ \mu F$

$C_{1new} = 29.26\ \mu F$

$C_{3new} = 22.77\ \mu F$

# Modal Analysis in Harmonic Studies

- **Y(*s*) technology may become a common upgrade to conventional harmonic analysis programs - Y(*j*ω)**
- **Efficient eigensolution methods now exist for finding poles of generic Y(*s*) models**
- **Computationally expensive** QR **and** QZ **eigensolution algorithms are no longer needed**

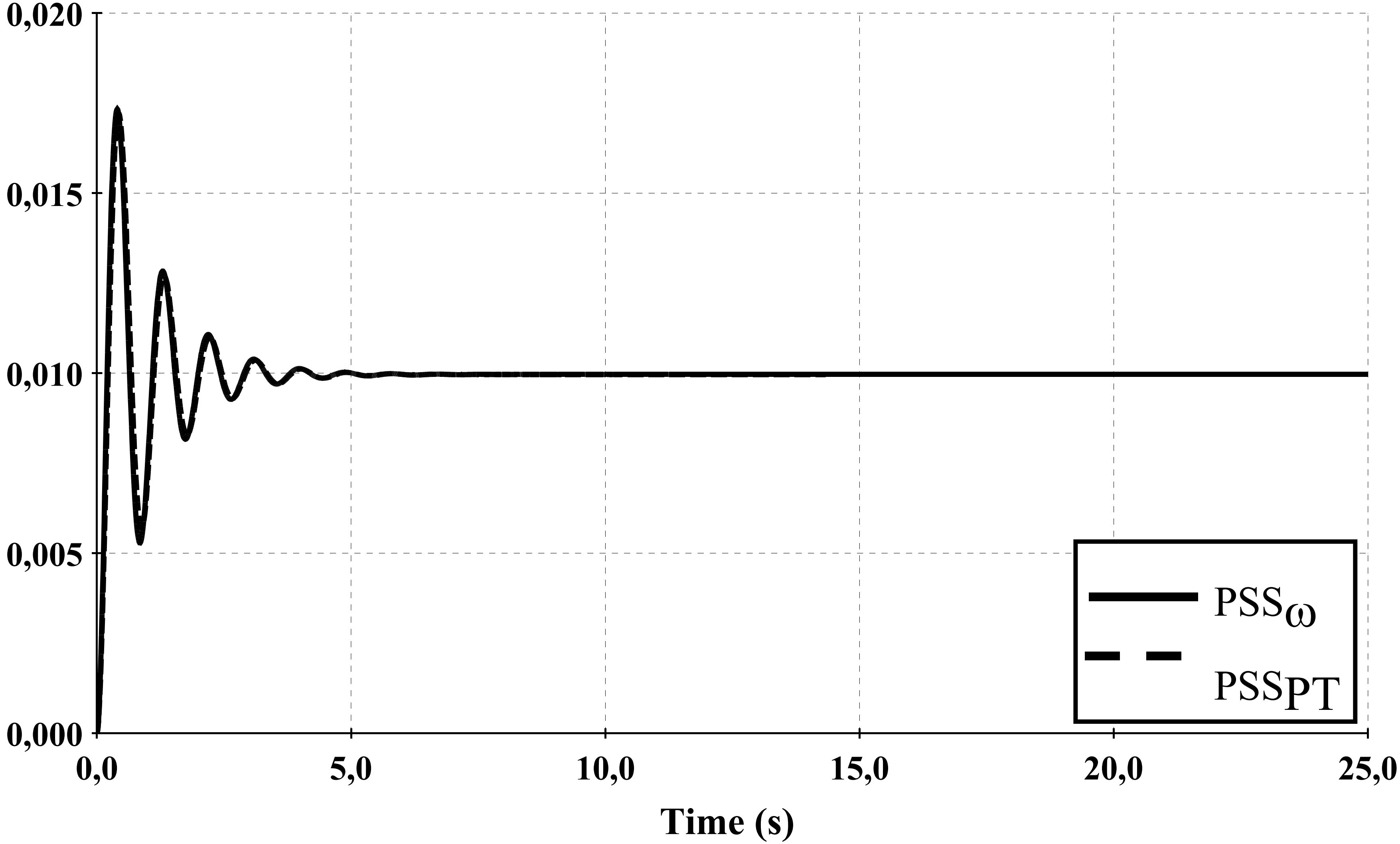
# ADVERSE IMPACTS ON TERMINAL VOLTAGE DUE TO PSSS

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

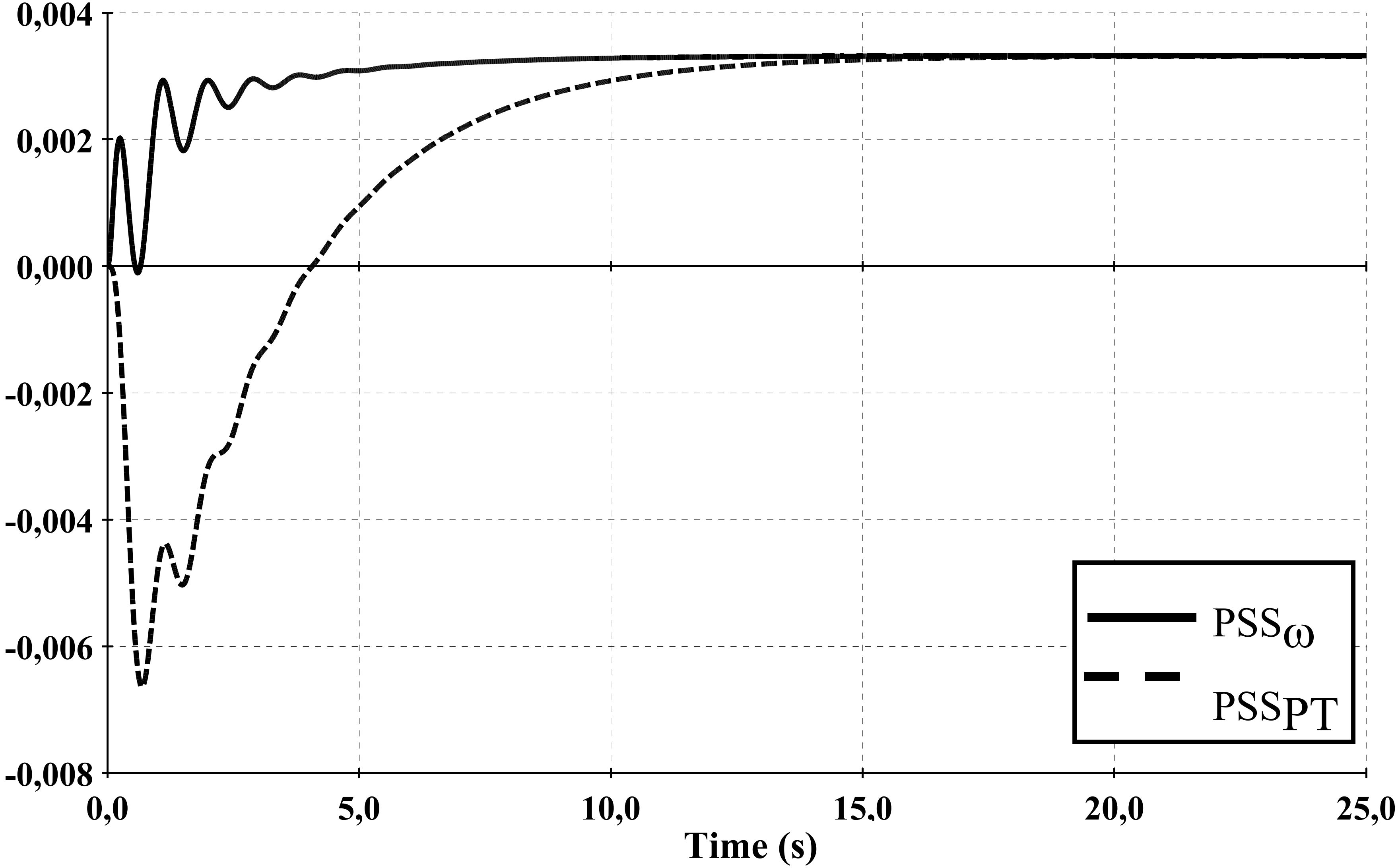
- Comparing the performances of PSSs derived from either rotor speed or terminal power signals

- More detailed presentation on this topic:
  - ➔Power System Stability Controls paper session
  - ➔Tuesday, January 29 – 8h00-12h00 / Regent Parlor

# ACTIVE POWER CHANGES FOLLOWING ΔPMEC IN SMIB

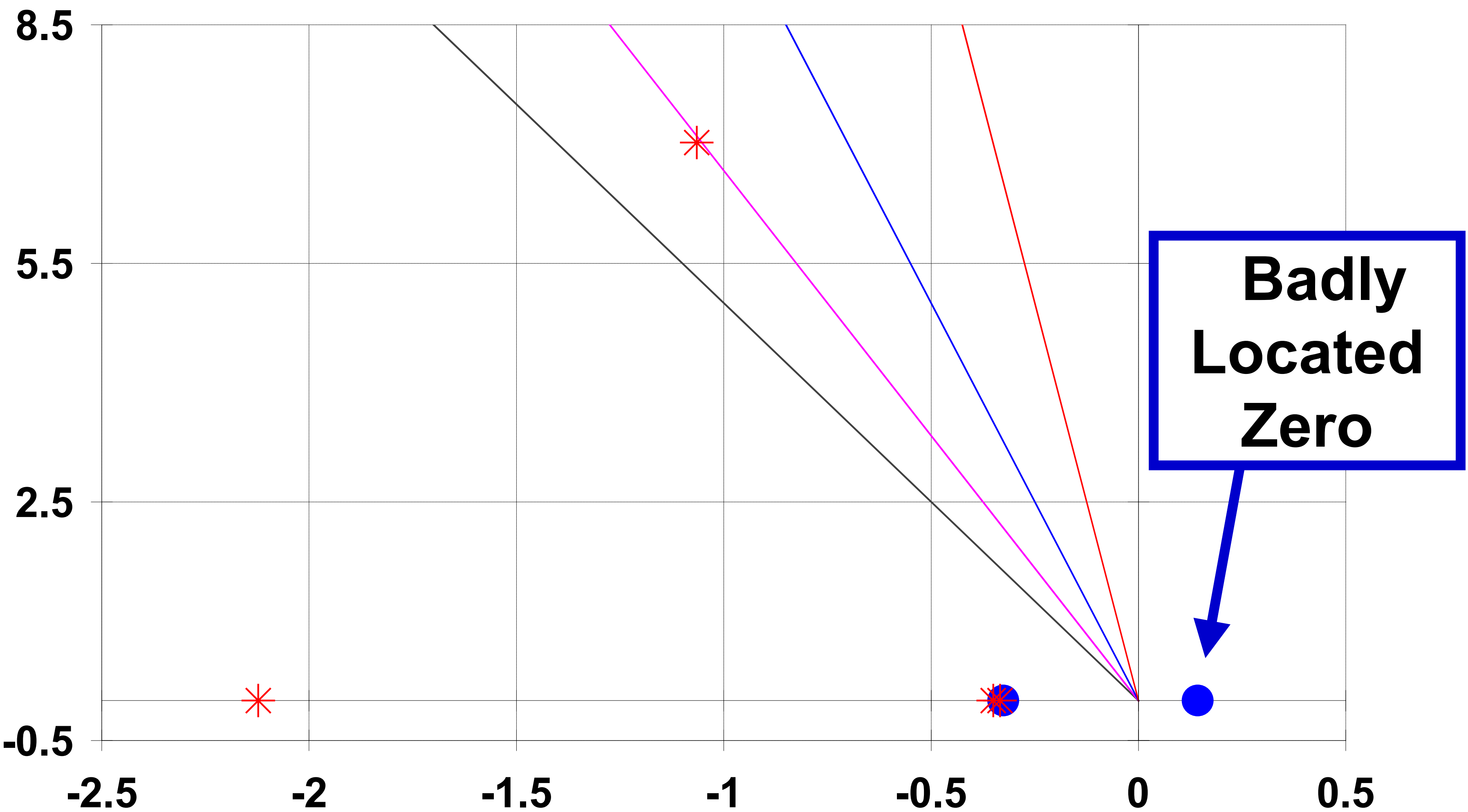


# Reactive Power Changes Following ΔPmec in SMIB



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

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



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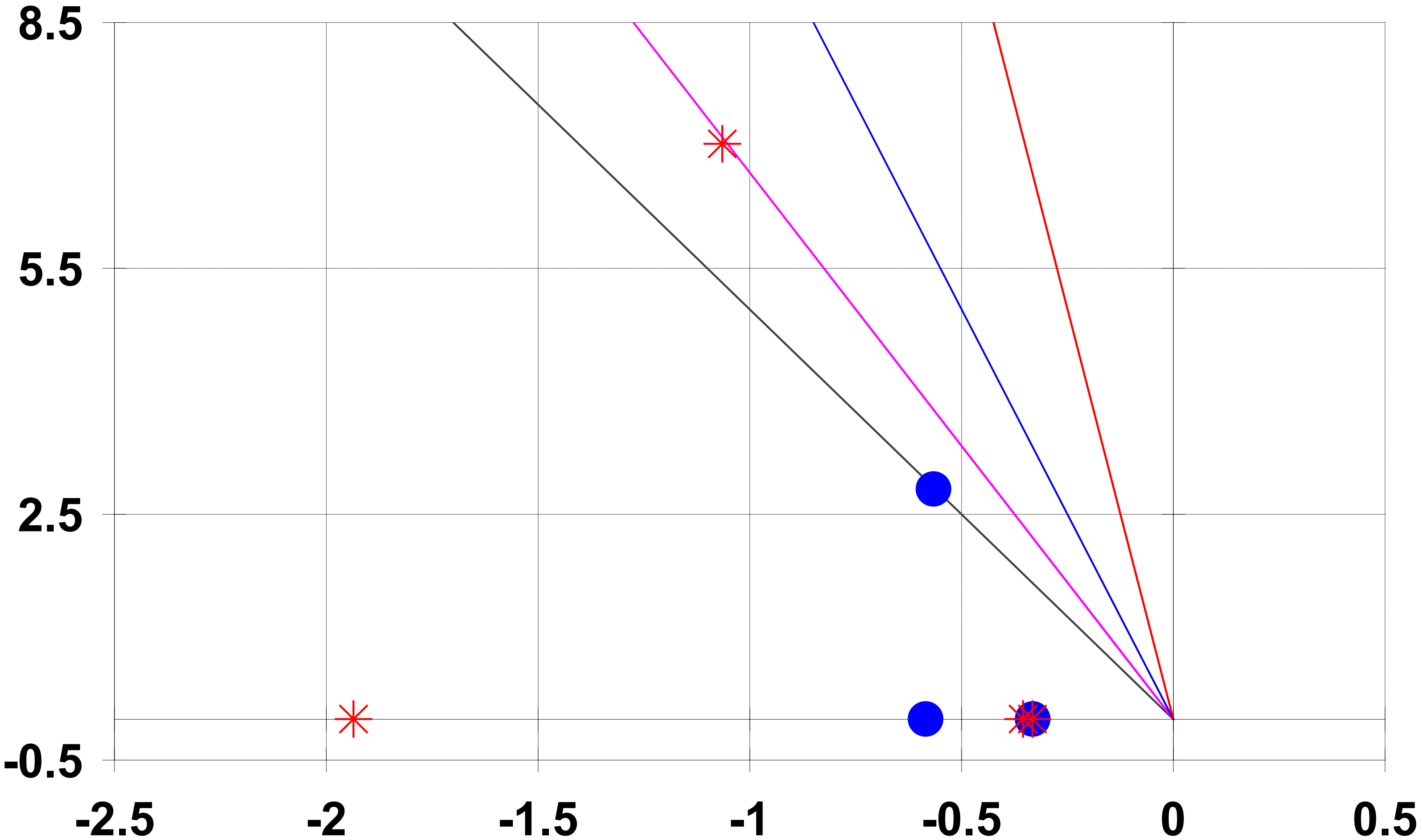

# FINAL REMARKS

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