Recents Results in Power System Damping Control and RLC Network Model Order Reduction

A talk by Nelson Martins, CEPEL

Department of Electrical & Computer Engineering
University of Maryland, October 6, 2015

N. Martins Talk - Part 1

A Modal Stabilizer for the Independent Damping Control of Aggregate Generator and Intraplant Modes in Multigenerator Power Plants

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Outline of Part 1

1. INTRODUCTION

2. PROOF OF CONCEPT

- Multigenerator Plant with Classical Machines against Infinite Bus (MPIB)
- The Modal 2-channel PSS (PSS-2ch): Basic Concepts and Structure
- Analytical results for MPIB with 2-channel PSSs or with standard PSSs

3. LINEAR SIMULATIONS

- The MPIB Test System
- MPIB Results with No PSS , with PSS-std or with PSS-2ch
- Eigenanalysis, Root Locus, Step Response, Sensitivity Analysis
- Balanced and Imbalanced Operating Conditions
- Symmetric or Asymmetric Impacts

4. NONLINEAR SIMULATIONS

- The MPIB Test System and the Applied 1Ø Faults
- PSS Performances Compared for Different Disturbances

5. CONCLUSIONS

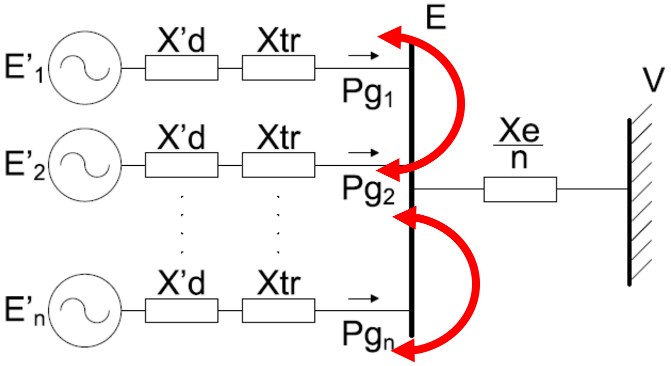
1. INTRODUCTION

Oscillation damping control in multigenerator power plants

•Types of Electromechanical Oscillations in a symmetric MPIB system:

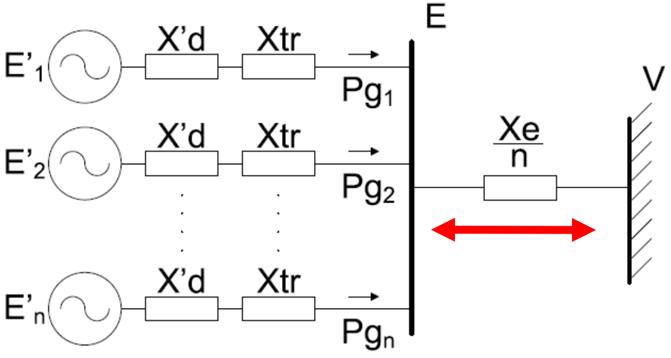
Intraplant:

- •(n-1) identical modes;
- •dynamic activity between plant generators
- •confined to the plant;



Aggregate:

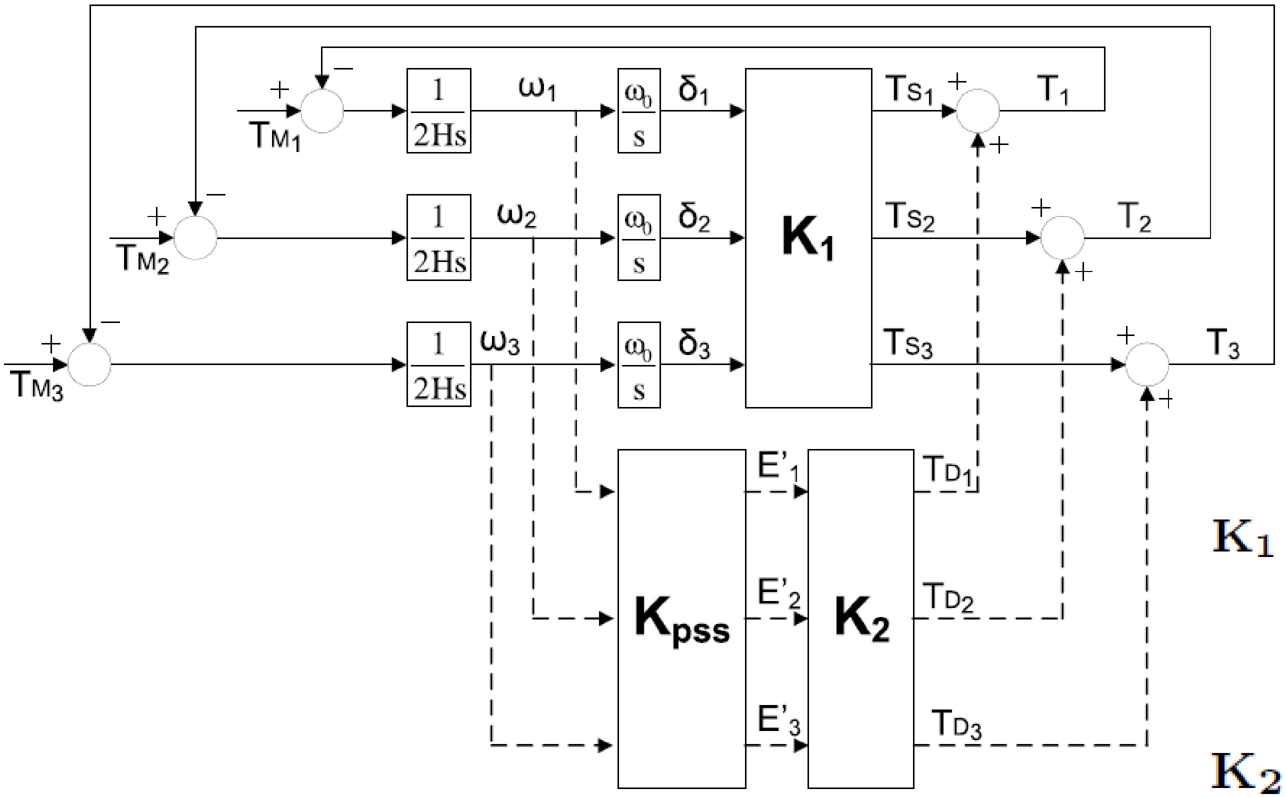
- •1 mode
- •all (n) units oscillate coherently, behaving like a single generator n times larger.
- •Related to the all external dynamics (external modes)



•PSS must damp adequately these oscillations

2. PROOF OF CONCEPT

Linear control diagram of MPIB system



symmetric ↑

$$\mathbf{K_1} = \begin{bmatrix} k_a & k_b & \cdots & k_b \\ k_b & k_a & \ddots & \vdots \\ \vdots & \ddots & \ddots & k_b \\ k_b & \cdots & k_b & k_a \end{bmatrix}$$

$$\mathbf{K_2} = k_d \mathbf{I}_{n \times n}$$ → diagonal

- Algebraic analysis described for **n=3**, but results extend to the **n**-machine case
- Assumptions for simplified analytical study
    - Classical machines (2nd order); all units have equal parameters and loadings **(K1)**
    - PSSs are pure gains and induced voltages E' are in phase with own rotor speeds **(K2)**

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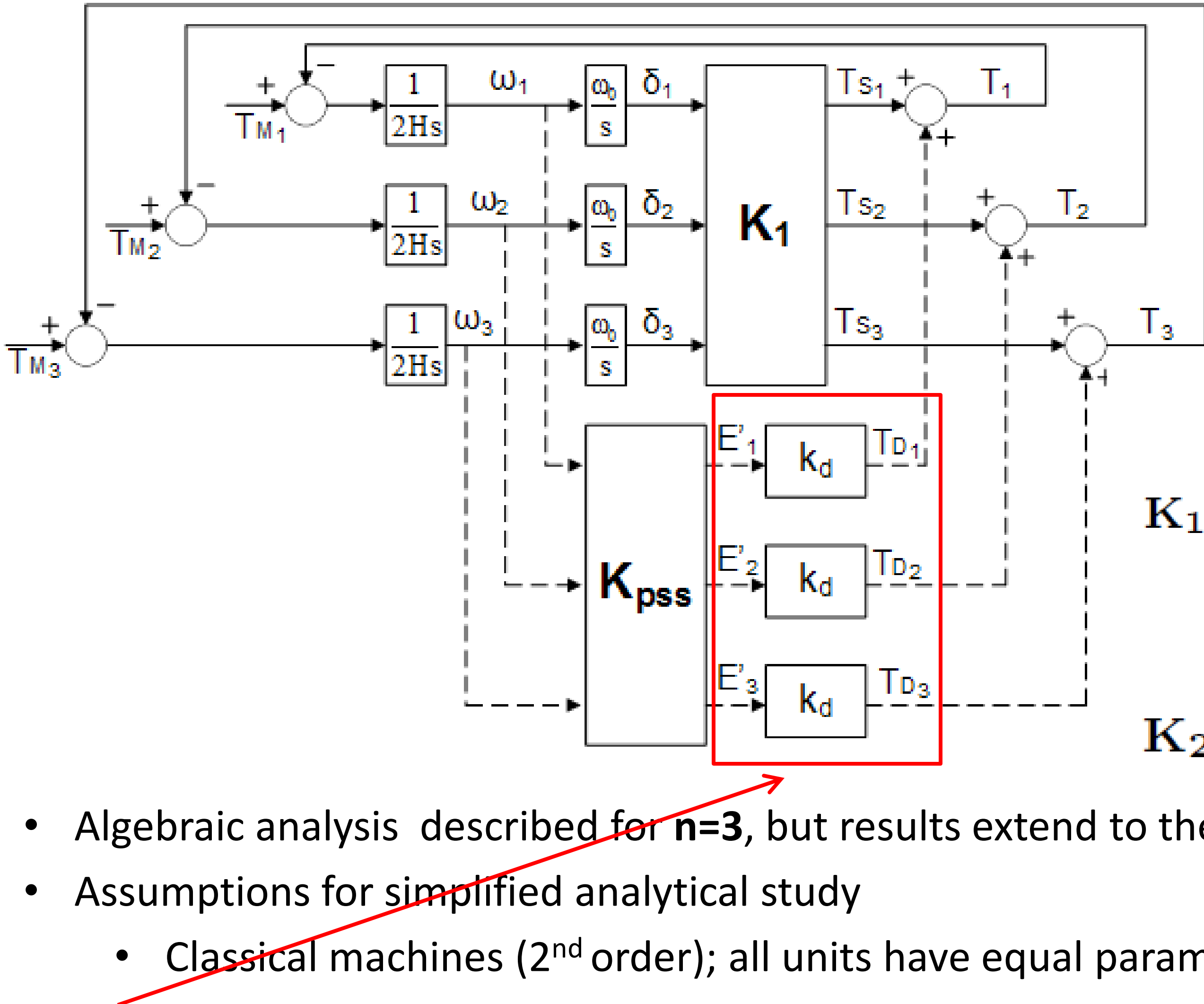
Linear control diagram of MPIB system



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  - PSSs are pure gains and induced voltages E' are in phase with own rotor speeds **(K2)**

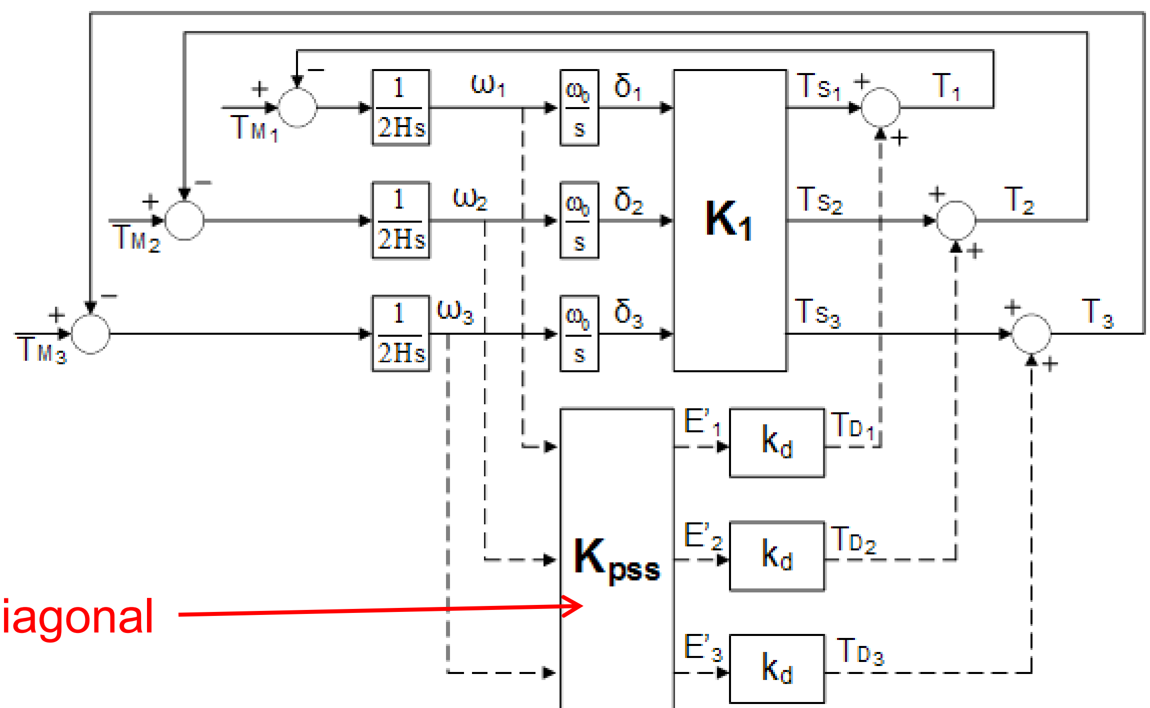
2. PROOF OF CONCEPT

MPIB System with Standard PSSs

- A standard PSS induces voltage changes that are in phase with its own generator speed (single channel)
- Damps both intraplant and aggregate modes through the same dynamic (phase & gain) compensation channel;
- Their frequencies and damping ratios cannot be set independently.

$$\begin{bmatrix} E'_1 \\ E'_2 \\ \vdots \\ E'_n \end{bmatrix} = \underbrace{\begin{bmatrix} k_{std} & 0 & \cdots & 0 \\ 0 & k_{std} & \ddots & \vdots \\ \vdots & \ddots & \ddots & 0 \\ 0 & \cdots & 0 & k_{std} \end{bmatrix}}_{\mathbf{K}^{\mathbf{std}}_{\mathbf{pss}}} \begin{bmatrix} \omega_1 \\ \omega_2 \\ \vdots \\ \omega_n \end{bmatrix}$$

$\mathbf{K}^{\mathbf{std}}_{\mathbf{pss}} = k_{std}\mathbf{I}_{n\times n}$ → diagonal



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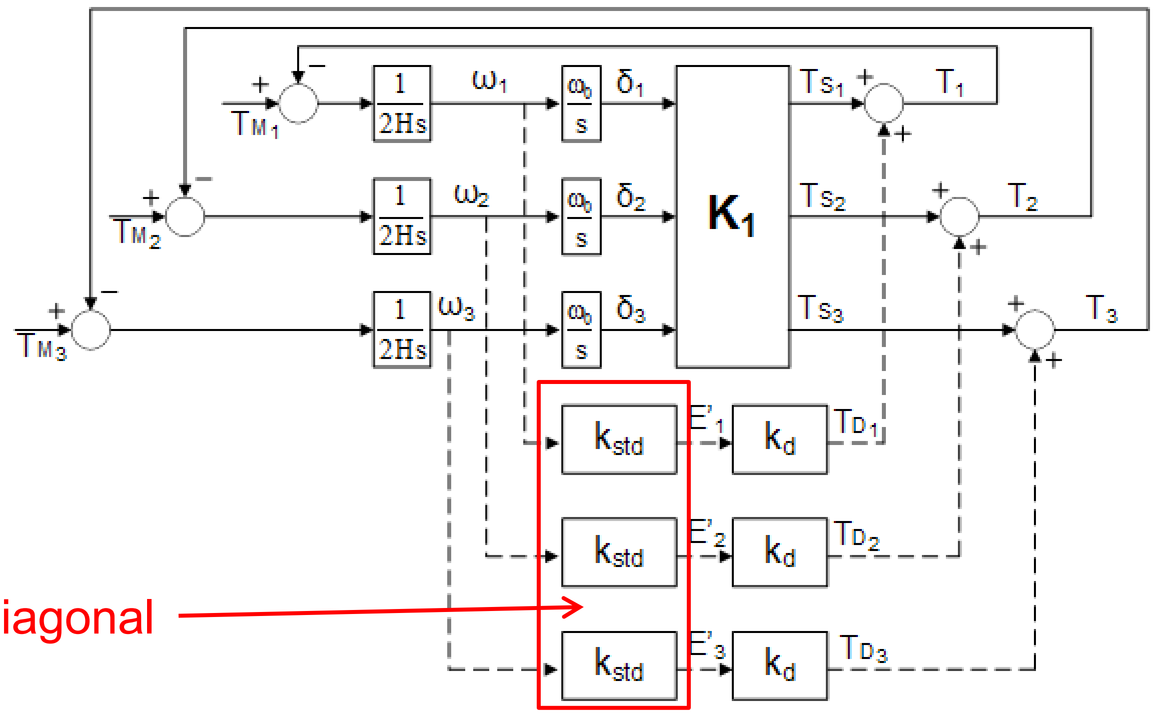


$\mathbf{K}^{\mathbf{std}}_{\mathbf{pss}} = k_{std}\mathbf{I}_{n\times n} \rightarrow$ diagonal

2. PROOF OF CONCEPT

MPIB System with Standard PSSs

- State matrix (A^{std}) for the MPIB system equipped with standard PSSs, where the state vector is $X=[\omega_1,\delta_1,\omega_2,\delta_2,\omega_3,\delta_3]$

$$\alpha \triangleq \frac{k_a}{2H} \quad , \quad \beta \triangleq \frac{k_b}{2H} \quad , \quad 2\gamma_{std} \triangleq \frac{k_{std}k_d}{2H}$$

$$\mathbf{A^{std}} = \left[\begin{array}{cc:cc:cc} -2\gamma_{std} & -\alpha & 0 & -\beta & 0 & -\beta \\ w_0 & 0 & 0 & 0 & 0 & 0 \\ \hdashline 0 & -\beta & -2\gamma_{std} & -\alpha & 0 & -\beta \\ 0 & 0 & w_0 & 0 & 0 & 0 \\ \hdashline 0 & -\beta & 0 & -\beta & -2\gamma_{std} & -\alpha \\ 0 & 0 & 0 & 0 & w_0 & 0 \end{array}\right]$$

2. PROOF OF CONCEPT

MPIB System with Standard PSSs

- Similarity transformation with matrix P block-diagonalizes the state matrix A

$$\mathbb{P} = \begin{bmatrix} \mathbf{I}_{m\times m} & \mathbf{I}_{m\times m} & \mathbf{I}_{m\times m} & \cdots & \mathbf{I}_{m\times m} \\ \mathbf{I}_{m\times m} & -\mathbf{I}_{m\times m} & \mathbf{0}_{m\times m} & \cdots & \mathbf{0}_{m\times m} \\ \mathbf{I}_{m\times m} & \mathbf{0}_{m\times m} & -\mathbf{I}_{m\times m} & \ddots & \vdots \\ \vdots & \vdots & \ddots & \ddots & \mathbf{0}_{m\times m} \\ \mathbf{I}_{m\times m} & \mathbf{0}_{m\times m} & \cdots & \mathbf{0}_{m\times m} & -\mathbf{I}_{m\times m} \end{bmatrix}$$

$$\bar{\mathbf{A}} = \mathbb{P}^{-1}\mathbf{A}\mathbb{P}$$

$$\bar{\mathbf{A}}^{\mathbf{std}} = \begin{bmatrix} -2\gamma_{std} & -(\alpha+2\beta) & 0 & 0 & 0 & 0 \\ w_0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -2\gamma_{std} & -(\alpha-\beta) & 0 & 0 \\ 0 & 0 & w_0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -2\gamma_{std} & -(\alpha-\beta) \\ 0 & 0 & 0 & 0 & w_0 & 0 \end{bmatrix}$$

$$\lambda_{ag} = \lambda_{1,2} = -\gamma_{std} \pm j\sqrt{(\alpha+2\beta)w_0 - \gamma_{std}^2}$$

$$\lambda_{ip} = \lambda_{3,4} = \lambda_{5,6} = -\gamma_{std} \pm j\sqrt{(\alpha-\beta)w_0 - \gamma_{std}^2}$$

- Changes in gain of standard PSS impact the dampings of both *ip* and *ag* modes

2. PROOF OF CONCEPT

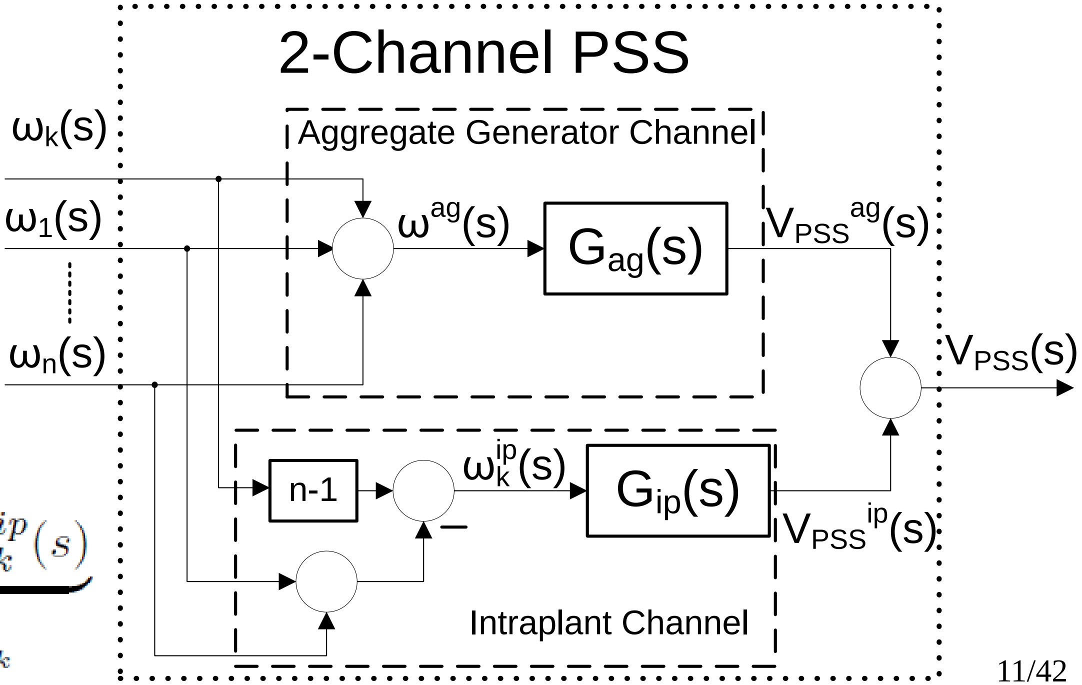
The proposed PSS-2ch

- Damps both oscillation modes with a differential: the intraplant dynamics is kept decoupled from the aggregate dynamics;
- Their frequencies and damping ratios can be independently set
- Output Signal of PSS-2ch has two orthogonal components
  - Agreggate component is equal to the average rotor speed of all (n) units
  - Intraplant: amplified local speed subtracted from speeds of (n-1) parallel units

$$\omega^{ag} = \sum_{i=1}^{n} \omega_i$$

$$\omega_k^{ip} = (n-1)\omega_k - \sum_{i=1, i\neq k}^{n} \omega_i$$

$$V_{PSS_k}(s) = \underbrace{G_{ag}(s)\omega^{ag}(s)}_{V_{PSS}^{ag}} + \underbrace{G_{ip}(s)\omega_k^{ip}(s)}_{V_{PSS_k}^{ip}}$$

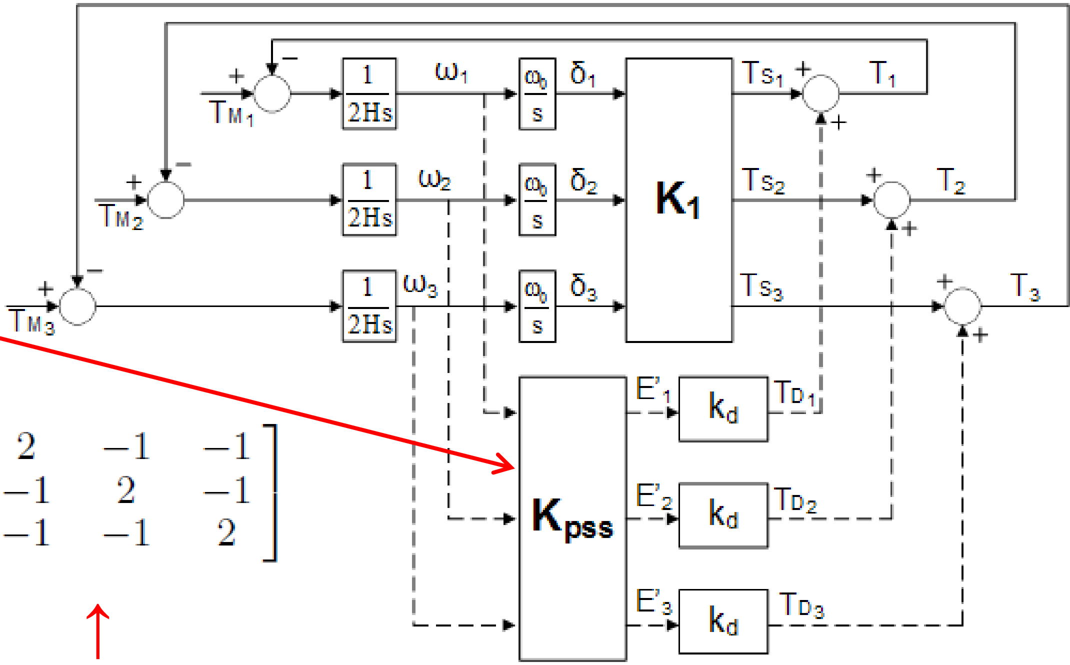


2. PROOF OF CONCEPT

MPIB System with proposed 2-channel PSSs

- A 2-channel PSS induces voltage changes that are a smart mix of the speeds from all generator units

$$\begin{bmatrix} E'_1 \\ E'_2 \\ E'_3 \end{bmatrix} = \underbrace{\mathbf{K}_{\mathbf{ag_{3x3}}} + \mathbf{K}_{\mathbf{ip_{3x3}}}}_{\mathbf{K}_{\mathbf{pss}}^{\mathbf{2ch}}} \begin{bmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \end{bmatrix}$$



$$\mathbf{K}_{\mathbf{ag_{3\times3}}} = \frac{k_{ag}}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix} \quad \mathbf{K}_{\mathbf{ip_{3\times3}}} = \frac{k_{ip}}{3}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}$$

↑ n-generator case ↑

$$\mathbf{K}_{\mathbf{ag}} = \frac{k_{ag}}{n}\begin{bmatrix} 1 & 1 & \cdots & 1 \\ 1 & 1 & \ddots & \vdots \\ \vdots & \ddots & \ddots & 1 \\ 1 & \cdots & 1 & 1 \end{bmatrix} \quad \mathbf{K}_{\mathbf{ip}} = \frac{k_{ip}}{n}\begin{bmatrix} n-1 & -1 & \cdots & -1 \\ -1 & n-1 & \ddots & \vdots \\ \vdots & \ddots & \ddots & -1 \\ -1 & \cdots & -1 & n-1 \end{bmatrix}$$

2. PROOF OF CONCEPT

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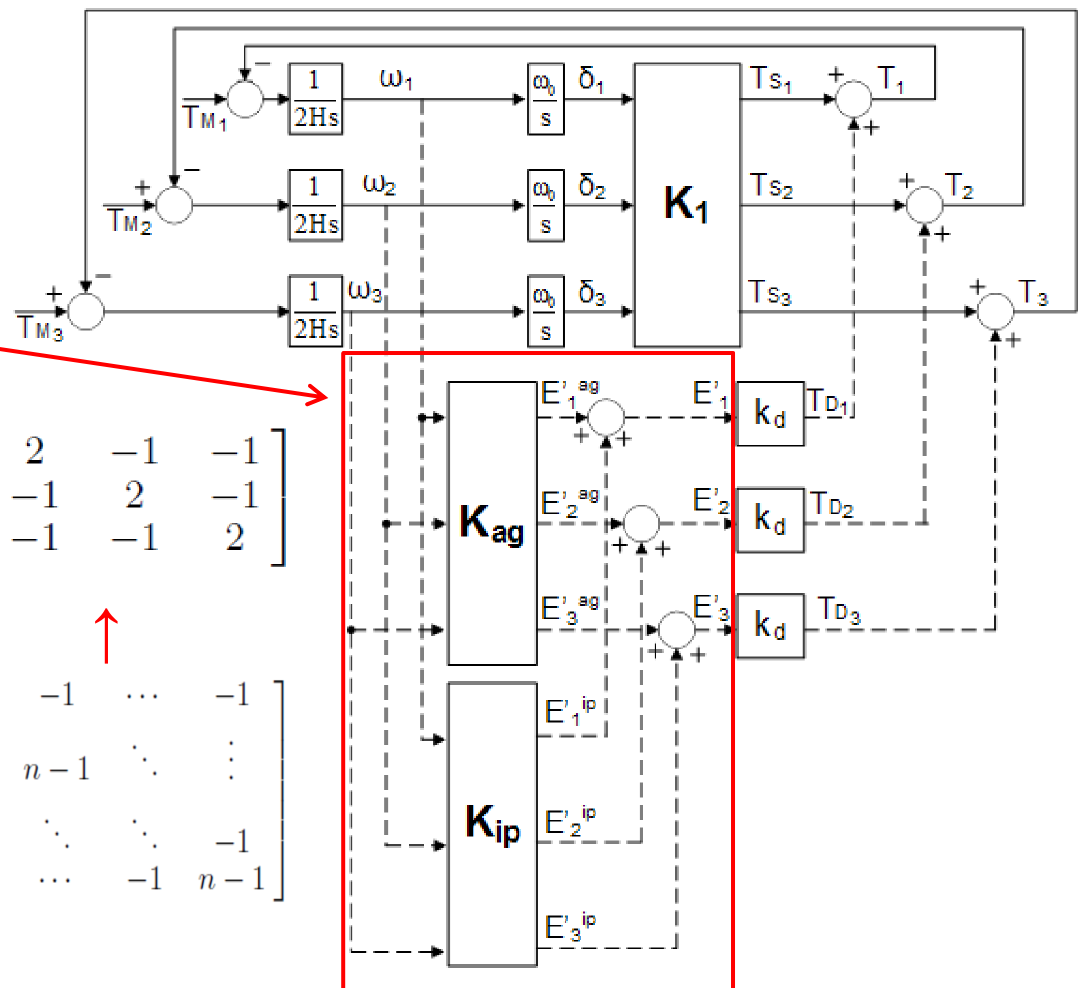
$$\mathbf{K}_{\mathbf{ag}_{3\times 3}} = \frac{k_{ag}}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix} \quad \mathbf{K}_{\mathbf{ip}_{3\times 3}} = \frac{k_{ip}}{3}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}$$

↑ n-generator case ↑

$$\mathbf{K}_{\mathbf{ag}} = \frac{k_{ag}}{n}\begin{bmatrix} 1 & 1 & \cdots & 1 \\ 1 & 1 & \ddots & \vdots \\ \vdots & \ddots & \ddots & 1 \\ 1 & \cdots & 1 & 1 \end{bmatrix} \quad \mathbf{K}_{\mathbf{ip}} = \frac{k_{ip}}{n}\begin{bmatrix} n-1 & -1 & \cdots & -1 \\ -1 & n-1 & \ddots & \vdots \\ \vdots & \ddots & \ddots & -1 \\ -1 & \cdots & -1 & n-1 \end{bmatrix}$$



2. PROOF OF CONCEPT

MPIB System with proposed 2-channel PSSs

- State matrix (A^{2ch}) for the MPIB system equipped with 2-channel PSSs, where the state vector is X=[ω_1,δ_1,ω_2,δ_2, ω_3,δ_3]

$$\gamma_1 \triangleq \gamma_{ag} + 2\gamma_{ip} \quad , \quad \gamma_2 \triangleq \gamma_{ag} - \gamma_{ip}$$

$$2\gamma_{ag} \triangleq \frac{k_d}{3}\frac{k_{ag}}{2H} \quad , \quad 2\gamma_{ip} \triangleq \frac{k_d}{3}\frac{k_{ip}}{2H}$$

$$\mathbf{A^{2ch}} = \left[\begin{array}{cc|cc|cc} -2\gamma_1 & -\alpha & -2\gamma_2 & -\beta & -2\gamma_2 & -\beta \\ w_0 & 0 & 0 & 0 & 0 & 0 \\ \hline -2\gamma_2 & -\beta & -2\gamma_1 & -\alpha & -2\gamma_2 & -\beta \\ 0 & 0 & w_0 & 0 & 0 & 0 \\ \hline -2\gamma_2 & -\beta & -2\gamma_2 & -\beta & -2\gamma_1 & -\alpha \\ 0 & 0 & 0 & 0 & w_0 & 0 \end{array}\right]$$

2. PROOF OF CONCEPT

MPIB System with proposed 2-channel PSSs

- Similarity transformation with matrix P block-diagonalizes the state matrix A

$$\bar{\mathbf{A}}^{\mathbf{2ch}} = \begin{bmatrix} -2\gamma_{ag} & -(\alpha+2\beta) & 0 & 0 & 0 & 0 \\ w_0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -2\gamma_{ip} & -(\alpha-\beta) & 0 & 0 \\ 0 & 0 & w_0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -2\gamma_{ip} & -(\alpha-\beta) \\ 0 & 0 & 0 & 0 & w_0 & 0 \end{bmatrix}$$

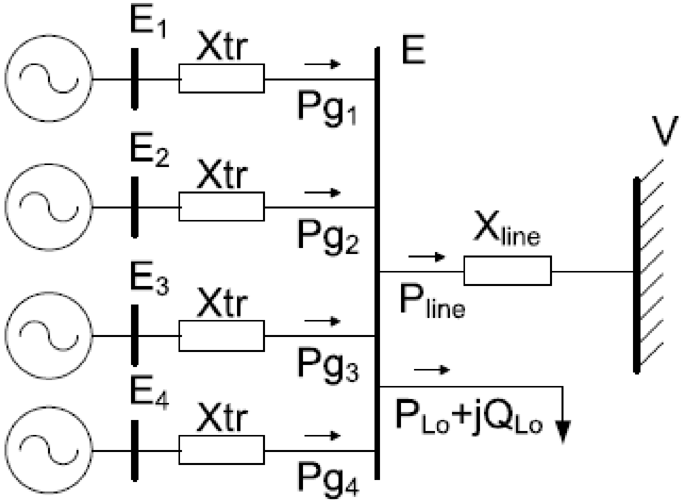
$$\lambda_{ag} = -\gamma_{ag} \pm j\sqrt{(\alpha+2\beta)w_0 - \gamma_{ag}^2}$$
$$\lambda_{ip} = -\gamma_{ip} \pm j\sqrt{(\alpha-\beta)w_0 - \gamma_{ip}^2}$$

- The damping ratios for the intraplant and aggregate modes can be independently set by adjusting the gains, either *Kip* or *Kag,* of the PSS–2ch.

3. LINEAR SIMULATIONS

MPIB Test System with Slow Response Exciter

- Test system has 4-generator plant and unstable, low frequency "interarea" mode
  - Large const-P load at high-side bus & high impedance transmission line
- Round rotor generator (detailed 6th-order model);
- Slow response excitation system → hinders effective damping role of standard PSSs
- All values are given in pu on the MVA base of a single generating unit



$$G_{exc}(s) = \frac{K_A}{(1 + sT_A)}$$

$$K_A = 10,\ T_A = 0.8$$

- Sn=250 MVA , H=3.53 pu
- Xl=0.16 , Ra=0.0023 , Xd=1.81 , Xq=1.76
- X'd=0.3 , X'q=0.61 , X"d=0.217 , X"q=0.217
- T'd0=7.8 , T'q0=0.9 , T"d0=0.022 , T"q0=0.074
- System base: 250MVA
- Impedances: X_{tr}=0.1 pu, X_{line}=8 pu
- Voltages: E_i=1.0 pu, E=0.974 pu, V=1.0 pu
- Power Flow: Pg_i=0.96 pu, P_{lo}=3.76 pu (constant P), Q_{lo}=0.80 pu (constant Z), P_{line}=0.08 pu

3. LINEAR SIMULATIONS

Root Locus for MPIB System with Standard PSSs

$$G^{std}(s) = k_{std} \frac{10s}{(1+10s)} \frac{1+0.8s}{(1+0.2s)} \frac{1+0.8s}{(1+0.2s)}$$

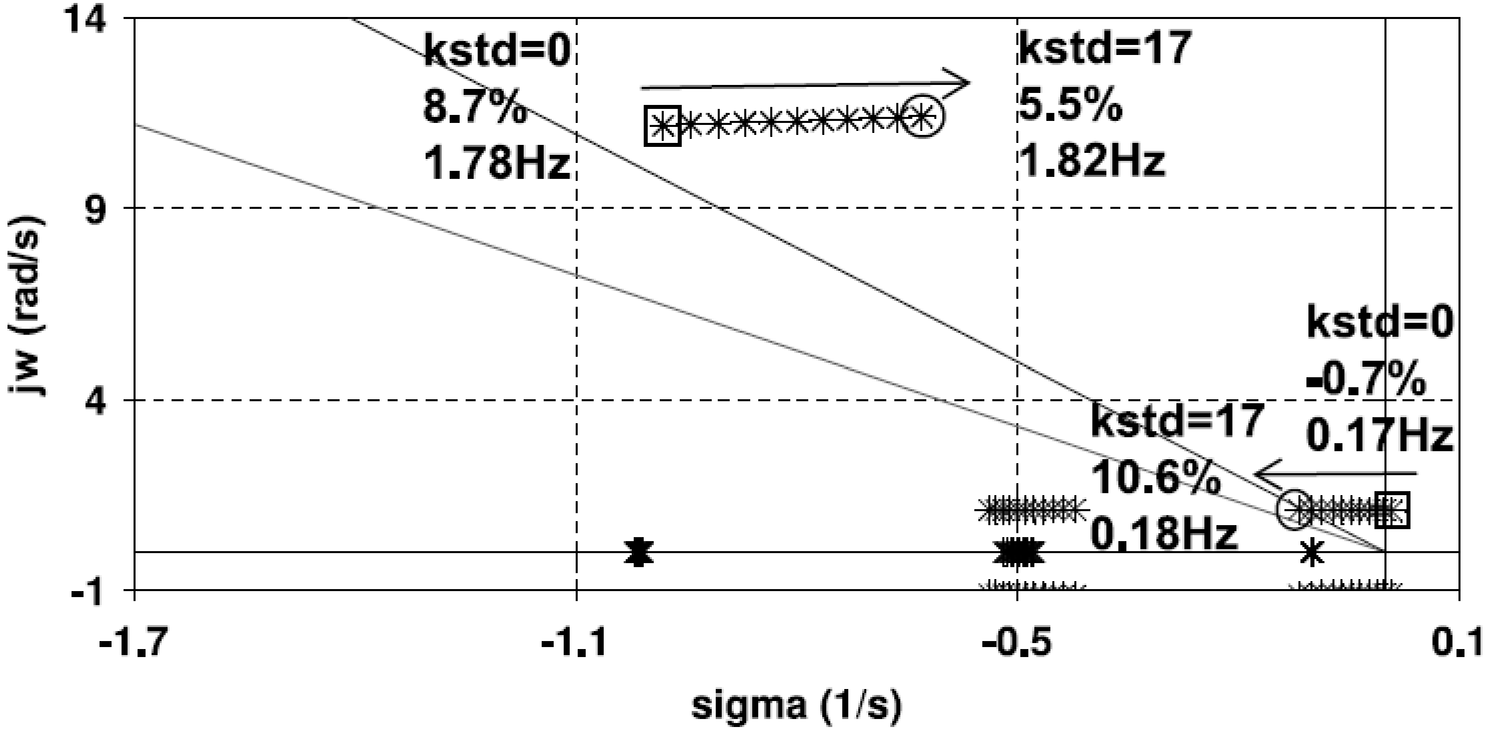


Fig. 21: RL plot for the MPIB Slow-exc system, with the four (standard) PSSs having their gains (k_{std}) varying from 0 up to 17 in steps of 1.7.

3. LINEAR SIMULATIONS

Root Locus for 2-ch PSSs

$$G_{ag}^{2ch}(s) = k_{ag} \frac{10s}{(1+10s)} \frac{1+0.8s}{(1+0.2s)} \frac{1+0.8s}{(1+0.2s)}$$

$$G_{ip}^{2ch}(s) = k_{ip} \frac{2s}{(1+2s)} \frac{1+0.2s}{(1+0.05s)}$$

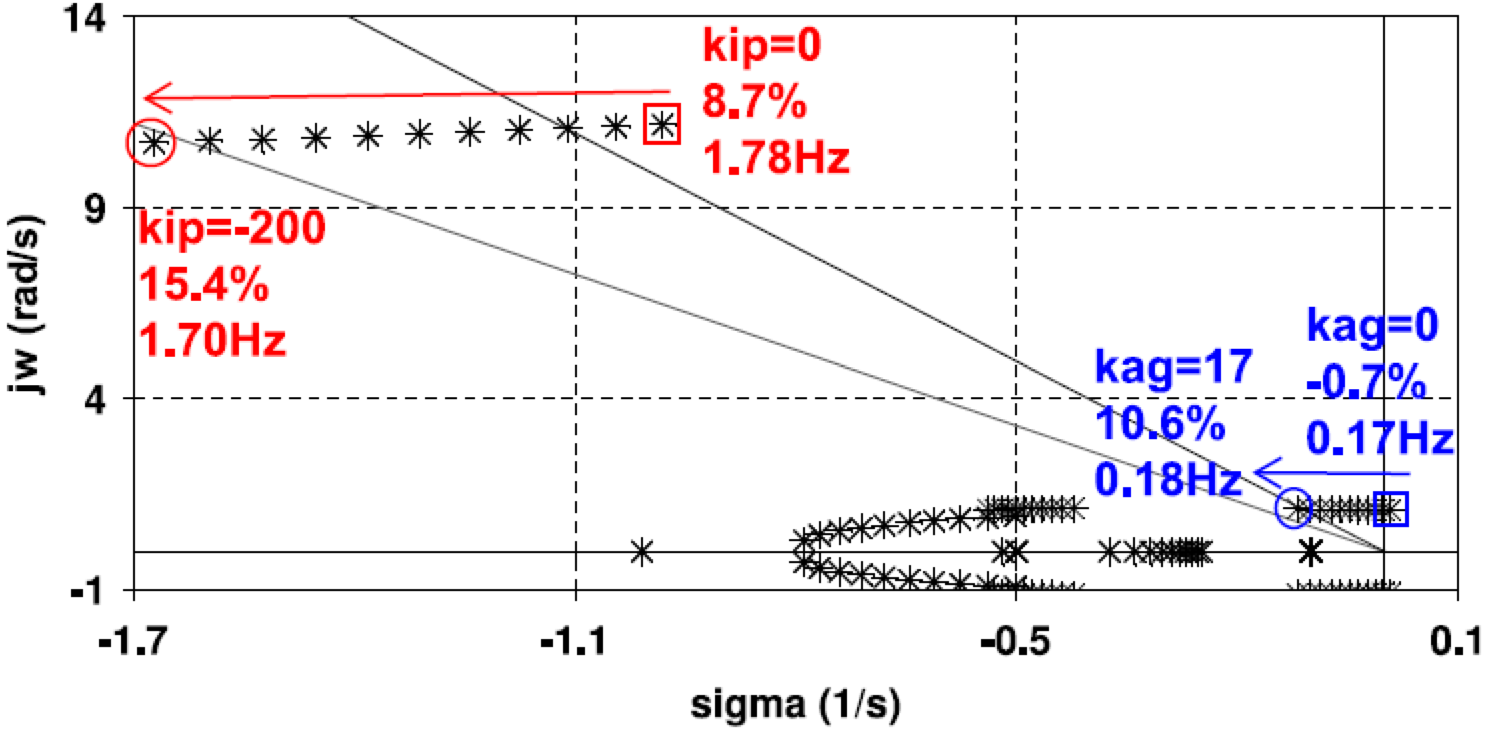


Fig. 20: RL plot of the MPIB Slow-Exc system for the simultaneous variation of the gains of the four 2-channel PSSs. Gain ranges are 0 to 17 for *Kag* and 0 to -200 for *Kip*, which vary in steps of 1.7 and -20, respectively.

3. LINEAR SIMULATIONS

Eigenvalue Results for the Standard and 2-channel PSSs

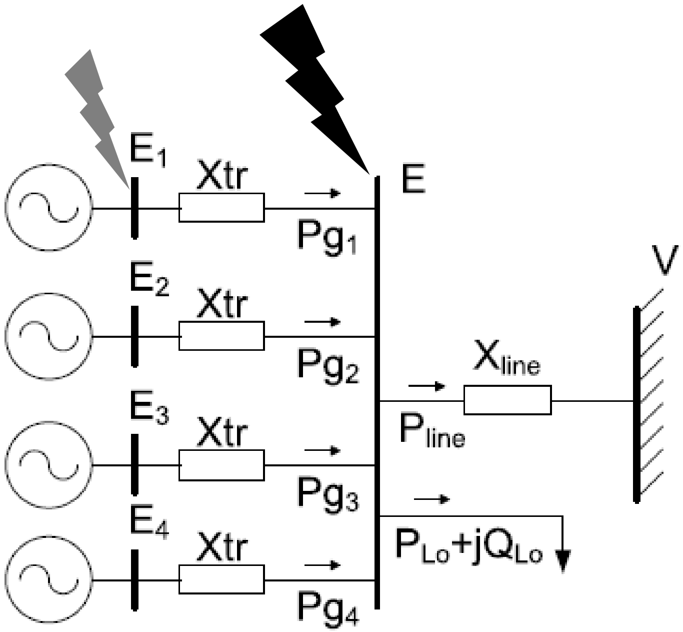
PSS type	Gains
Standard PSS	$k_{std} = 17$
2-channel PSS	$k_{ag} = 17$ & $k_{ip} = -200$

- k_{ag}: confers a damping ratio of 10% to the aggregate mode
- k_{ip}: confers a damping ratio of 15% to the intraplant mode

Modes	Standard PSS	2-Channel PSS	Without PSS
Aggregate Mode	$\omega_d = 0.18Hz$ $\zeta = 10.6\%$	$\omega_d = 0.18Hz$ $\zeta = 10.6\%$	$\omega_d = 0.17Hz$ $\zeta = -0.7\%$
Intraplant Modes	$\omega_d = 1.82Hz$ $\zeta = 5.5\%$	$\omega_d = 1.70Hz$ $\zeta = 15.4\%$	$\omega_d = 1.78Hz$ $\zeta = 8.7\%$

3. LINEAR SIMULATIONS

Types of Disturbance applied to the MPIB System



Symmetric - A disturbance which is applied to bus E, equally impacts all four units, and only excites the aggregate modes.

Asymmetric – A disturbance which is applied to an internal bus (E1, ..., E4) and excites both the aggregate and intraplant modes.

3. LINEAR SIMULATIONS

MPIB System Time Response for Symmetric Disturbance

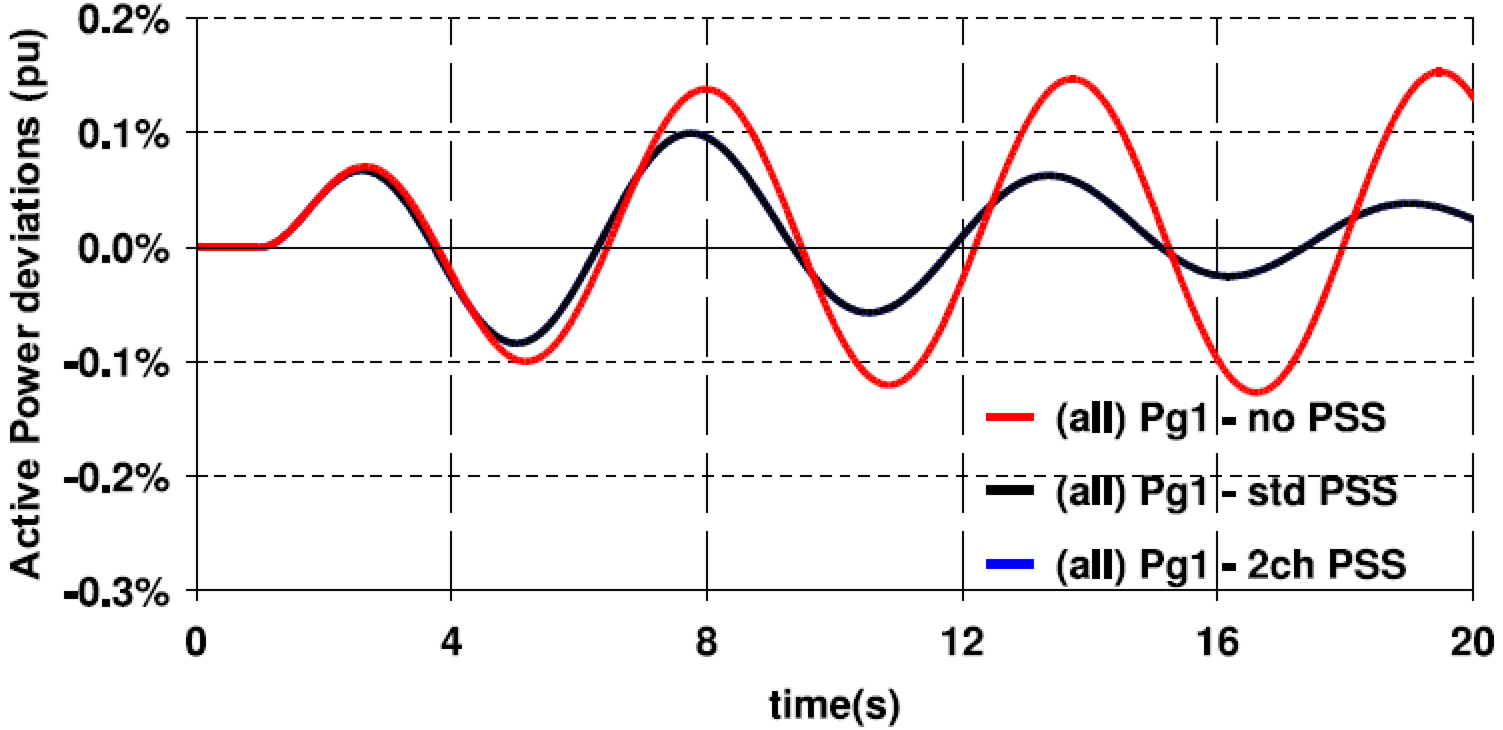


Fig. 22: MPIB Slow-exc system with Small Symmetric disturbance - Active Power responses of one unit.

3. LINEAR SIMULATIONS

MPIB System Time Response for Asymmetric Disturbance

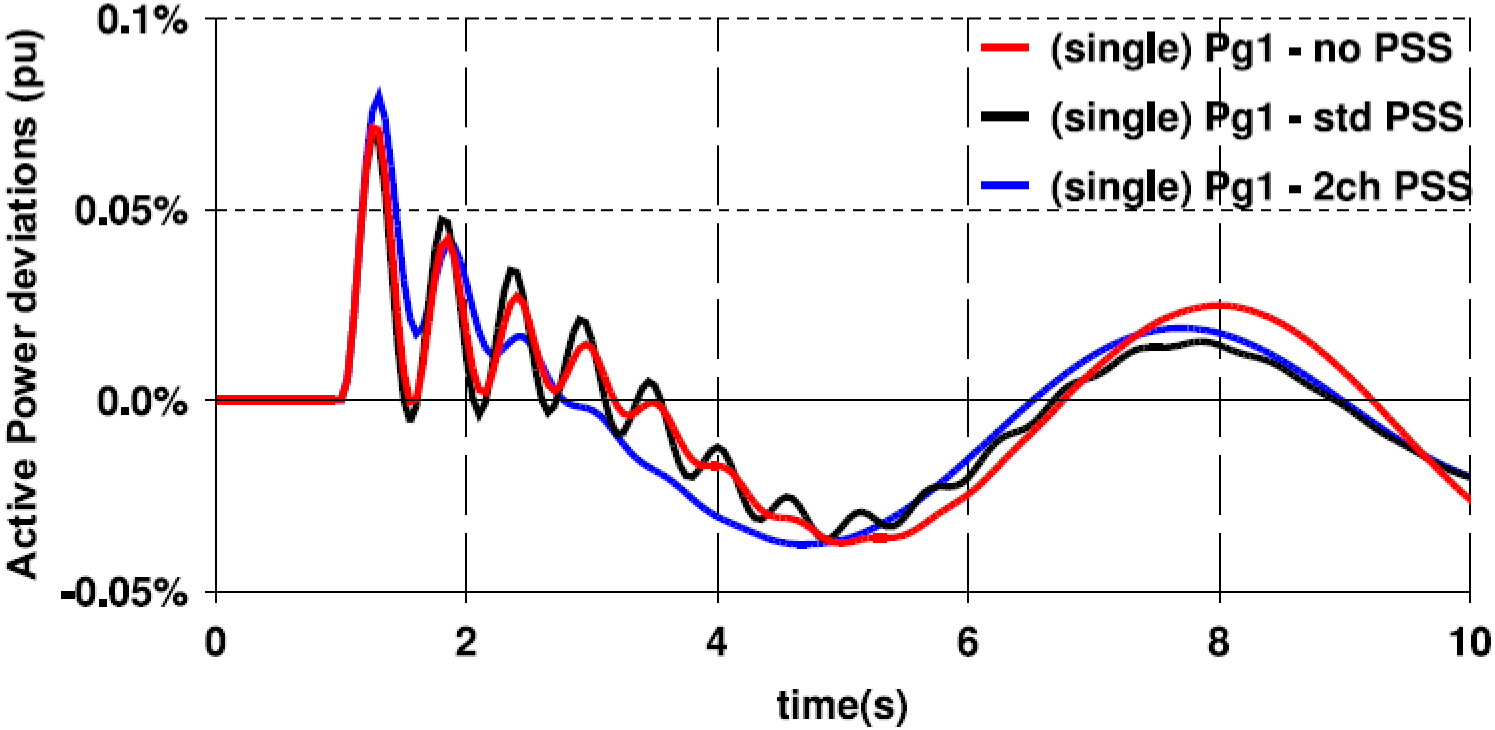


Fig. 23: MPIB Slow-exc system with Small Asymmetric disturbance - Active Power responses of one unit.

3. LINEAR SIMULATIONS

Power Flow and Parameter Data for the Imbalanced MPIB System

- Generator Powers: Pg_1=1.00 pu, Pg_2=0.88 pu, Pg_3=0.76 pu, Pg_4=0.64 pu
- Generator Voltages: E_1=0.97 pu, E_2=0.99 pu, E_3=1.01 pu, E_4=1.03 pu
- System: P_{lo}=3.2 pu (constant P), Q_{lo}=0.80 pu (constant Z), P_{line}=0.08 pu
- Slow-exciter gains: K_{A_1}=10, K_{A_2}=11, K_{A_3}=9, K_{A_4}=8
- Slow-exciter time constants: T_{A_1}=0.8s, T_{A_2}=0.7s, T_{A_3}=0.9s, T_{A_4}=1.0s

3. LINEAR SIMULATIONS

Root Locus for Std PSSs in Imbalanced MPIB System

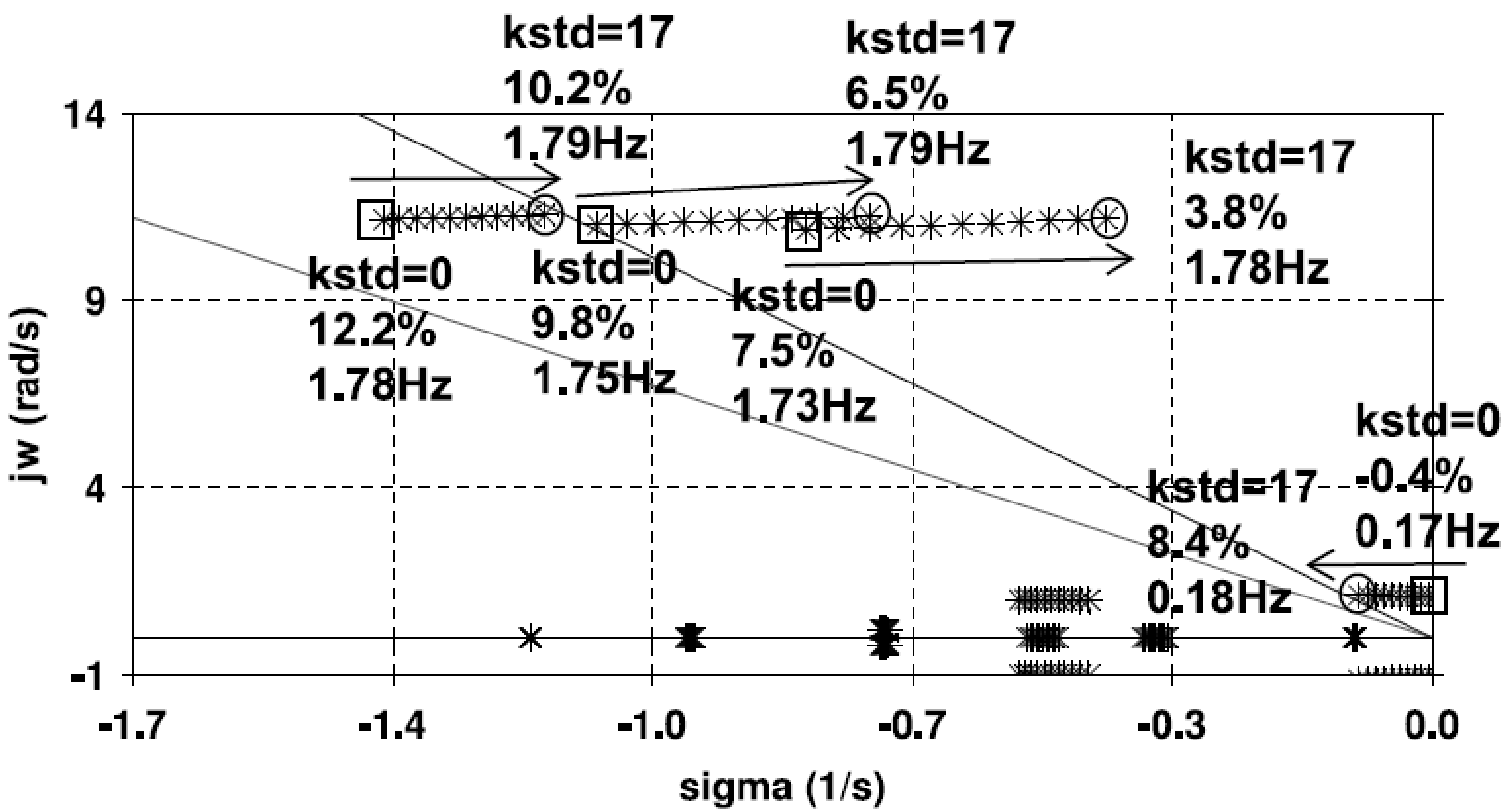


Fig. 24: RL plot for the Unbalanced MPIB Slow-exc system, with the four (standard) PSSs having their gains (k_{std}) varying from 0 up to 17 in steps of 1.7.

3. LINEAR SIMULATIONS

Root Locus for 2-ch PSSs in Imbalanced MPIB System

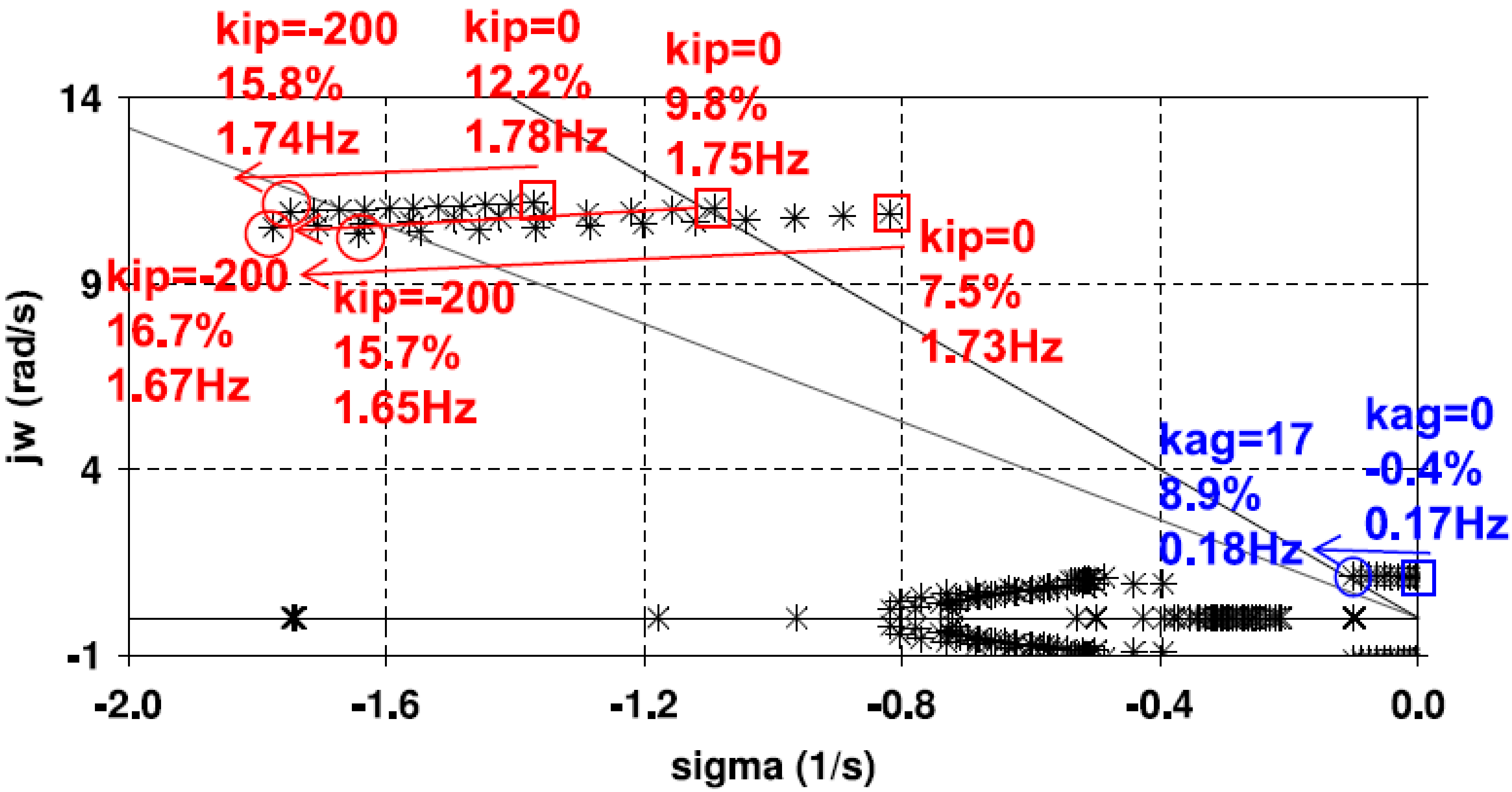


Fig. 25: RL plot for the Unbalanced MPIB Slow-exc system, with the simultaneous variation in the gains of the four 2-channel PSSs Gain ranges are 0 to 17 for k_{ag} and 0 to -200 for k_{ip}, which vary in steps of 1.7 and -20, respectively.

3. LINEAR SIMULATIONS

Eigenvalue Results for Imbalanced MPIB System

Modes	Standard PSS	2-Channel PSS	Without PSS
Aggregate Mode	$\omega_d = 0.18Hz$ $\zeta = 8.4\%$	$\omega_d = 0.18Hz$ $\zeta = 8.9\%$	$\omega_d = 0.17Hz$ $\zeta = -0.4\%$
Intraplant Mode 1	$\omega_d = 1.78Hz$ $\zeta = 3.8\%$	$\omega_d = 1.65Hz$ $\zeta = 15.7\%$	$\omega_d = 1.73Hz$ $\zeta = 7.5\%$
Intraplant Mode 2	$\omega_d = 1.79Hz$ $\zeta = 6.5\%$	$\omega_d = 1.67Hz$ $\zeta = 16.7\%$	$\omega_d = 1.75Hz$ $\zeta = 9.8\%$
Intraplant Mode 3	$\omega_d = 1.79Hz$ $\zeta = 10.2\%$	$\omega_d = 1.74Hz$ $\zeta = 15.8\%$	$\omega_d = 1.78Hz$ $\zeta = 12.2\%$

3. LINEAR SIMULATIONS

Imbalanced MPIB System with Small Symmetric Disturbance

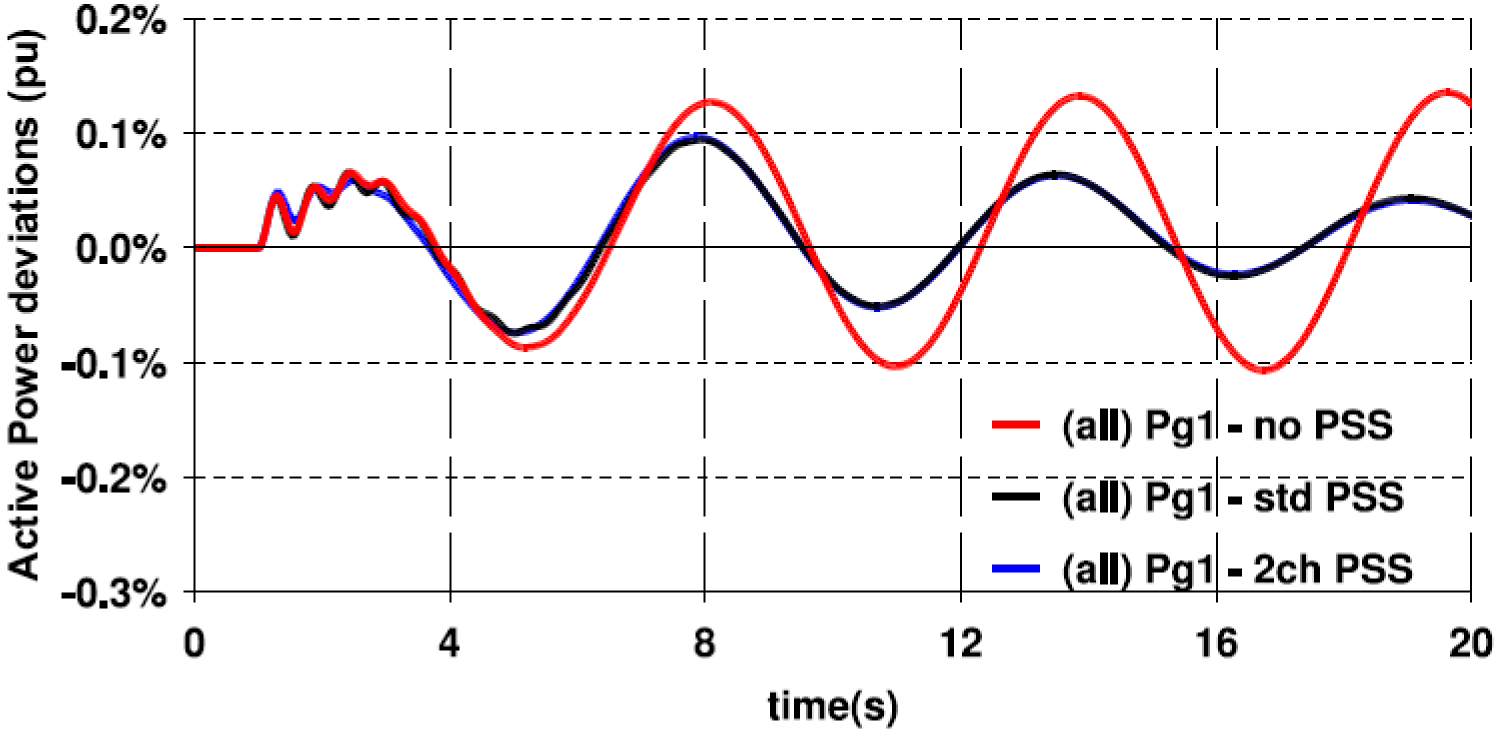


Fig. 26: Unbalanced MPIB Slow-exc system with Small Symmetric disturbance - Active Power responses of one unit.

3. LINEAR SIMULATIONS

Imbalanced MPIB System with Small Asymmetric Disturbance

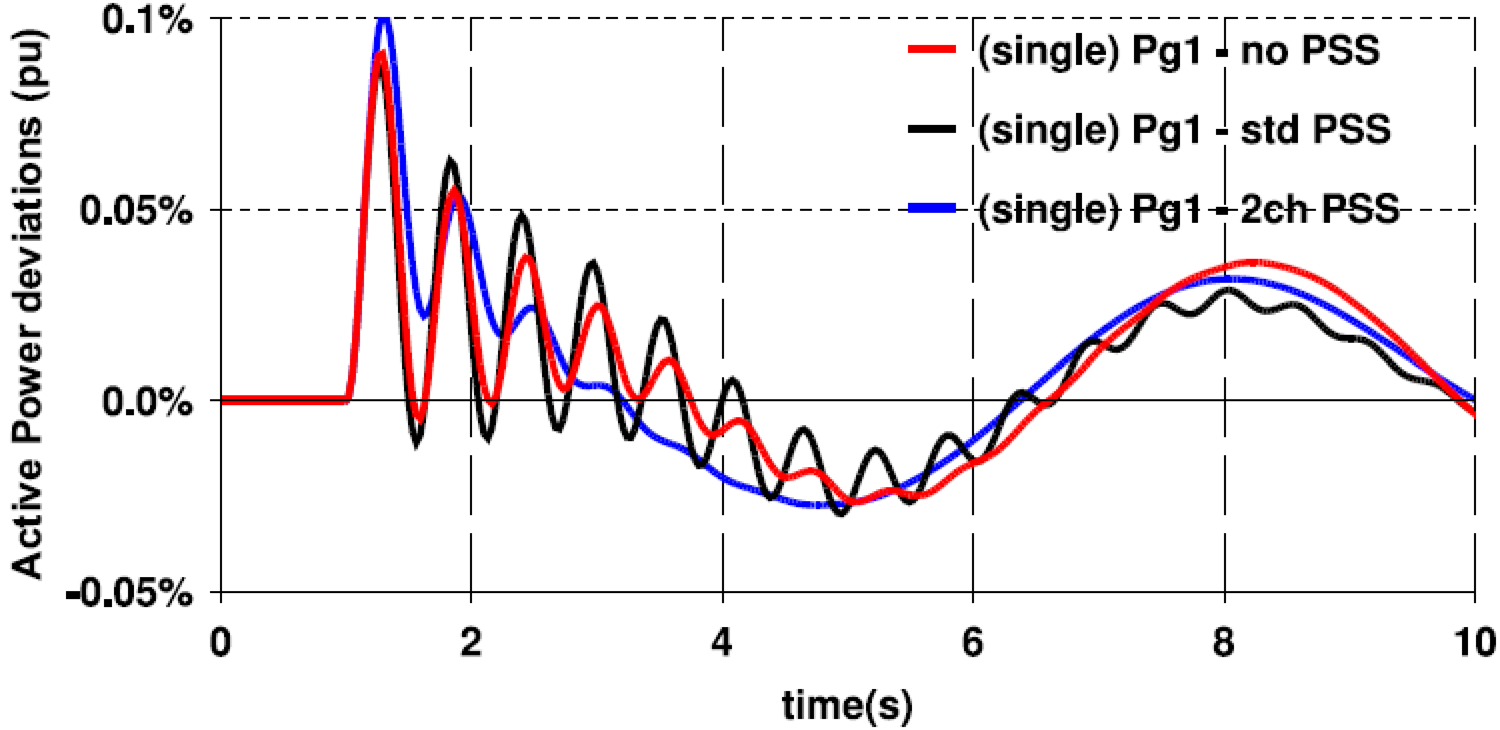


Fig. 27: Unbalanced MPIB Slow-exc system with Small Asymmetric disturbance - Active Power responses of one unit.

4. NONLINEAR (TransStab) SIMULATIONS

MPIB Test System with Slow Response Exciters

Nonlinear Simulation Parameters

- Total simulation time: 20s or 30s, when studying Large Exogenous Faults
- Total simulation time: 6s, when studying Large Internal Faults
- Integration time step: 0.005s
- Fault inception: 1.00s
- Fault duration: 100ms
- Fault at the generator terminals simulated by switching a 800 MVAr reactor at the E_1 (generator #1) bus
- Fault at the plant high-side bus simulated by switching a 1080 MVAr reactor at the E (high-side) bus

4. NONLINEAR SIMULATIONS

Balanced MPIB System following an External Fault

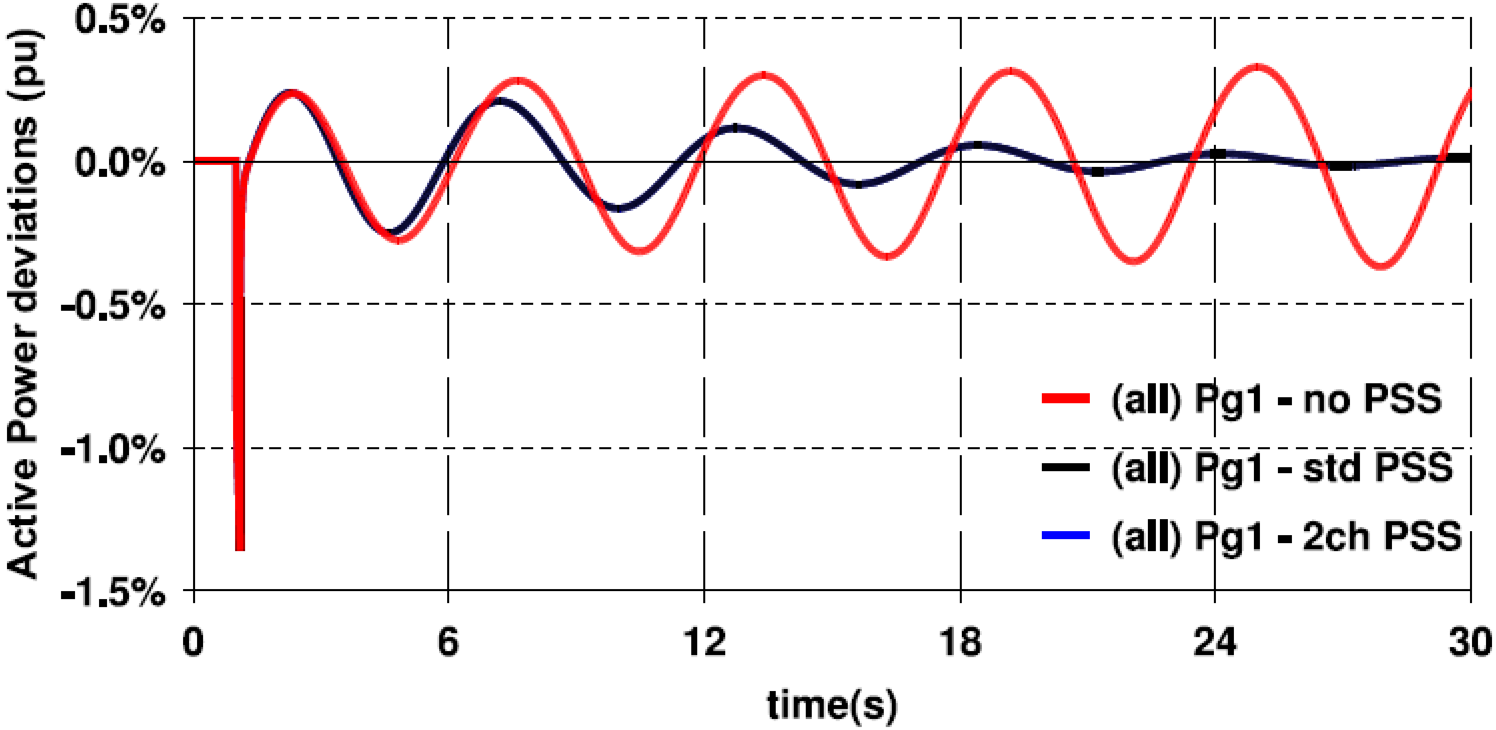


Fig. 28: MPIB Slow-exc system with Large Exogenous Fault - Active Power responses of unit #1.

4. NONLINEAR SIMULATIONS

Balanced MPIB System Following an External Fault

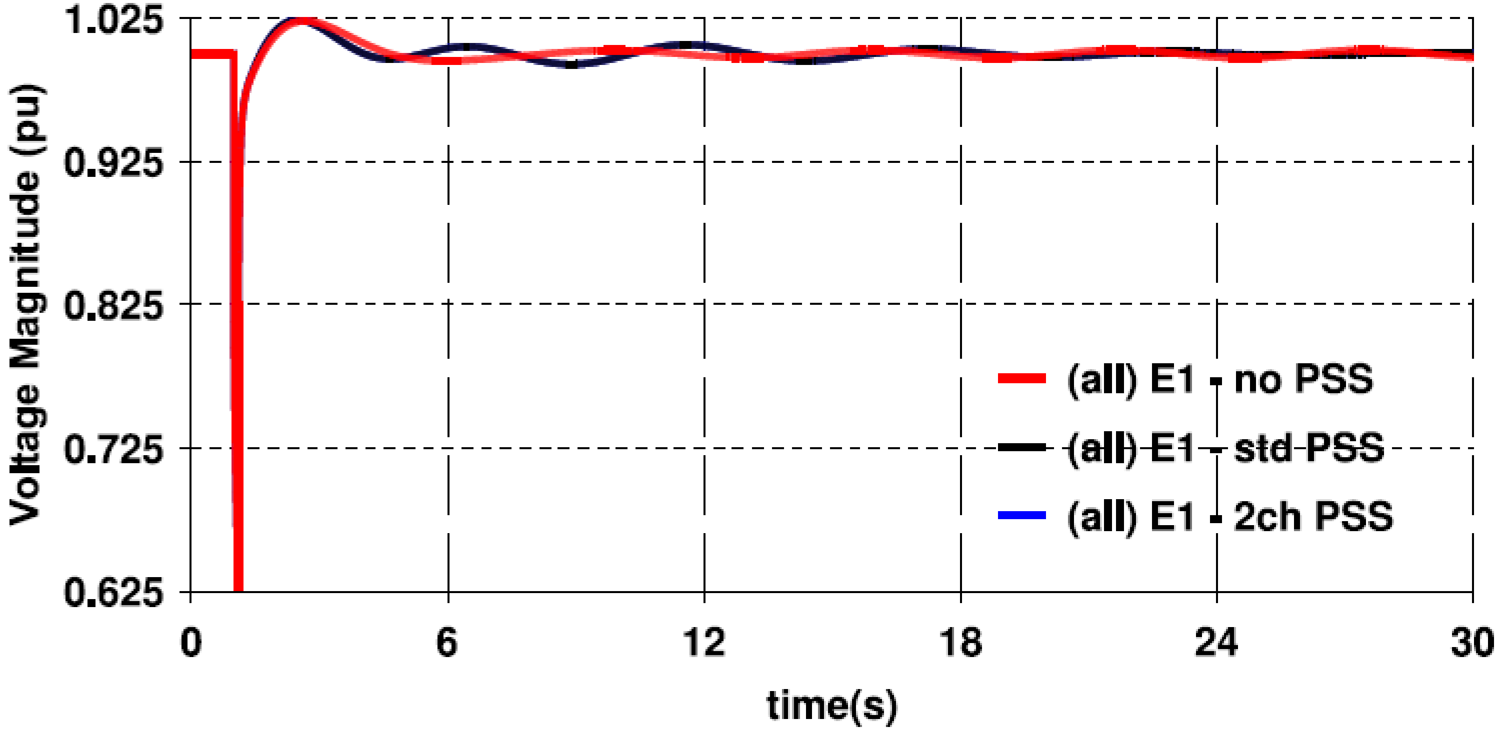


Fig. 29: MPIB Slow-exc system with Large Exogenous Fault - Terminal Voltage responses of unit #1.

4. NONLINEAR SIMULATIONS

Balanced MPIB System following an External Fault

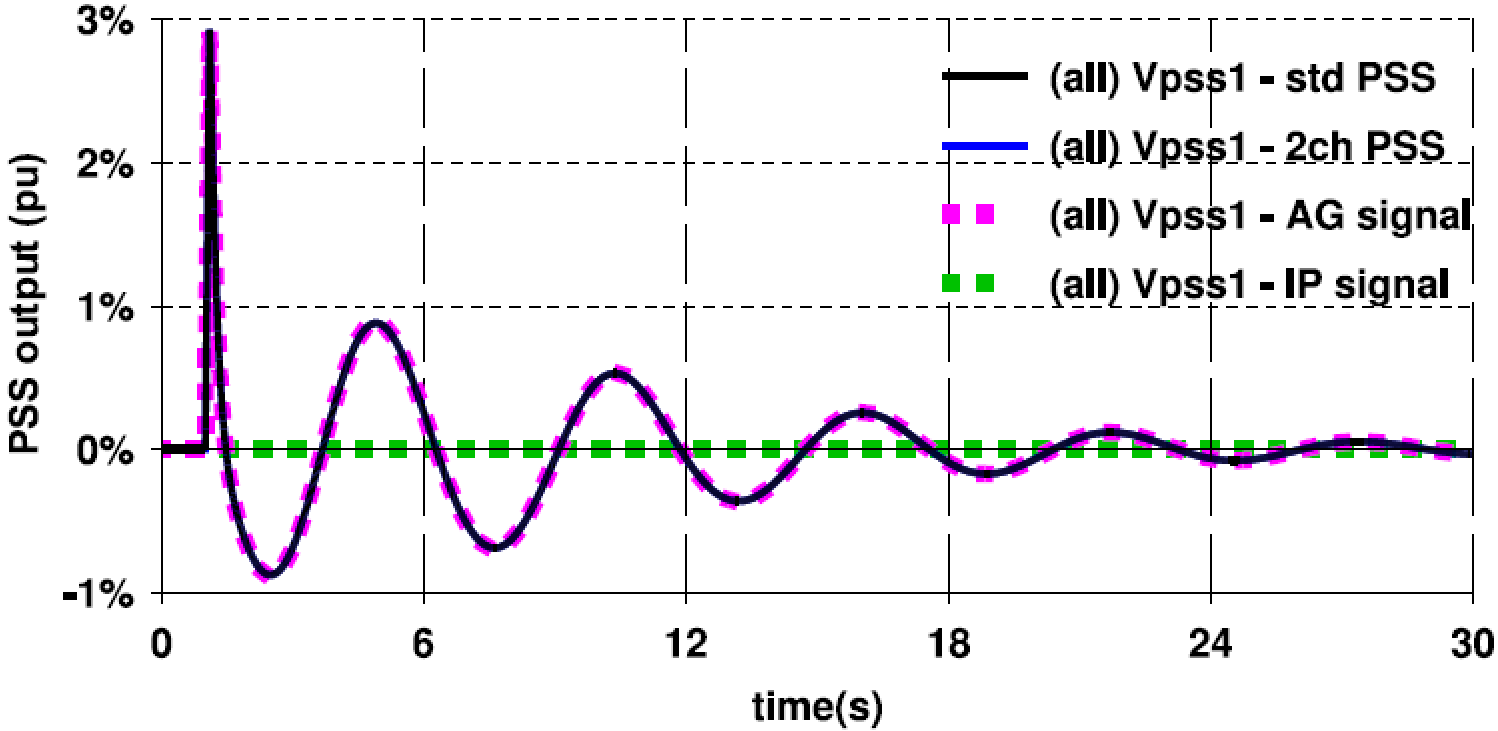


Fig. 30: MPIB Slow-exc system with Large Exogenous Fault - PSS Output responses of unit #1.

4. NONLINEAR SIMULATIONS

Balanced MPIB System following an Internal Fault

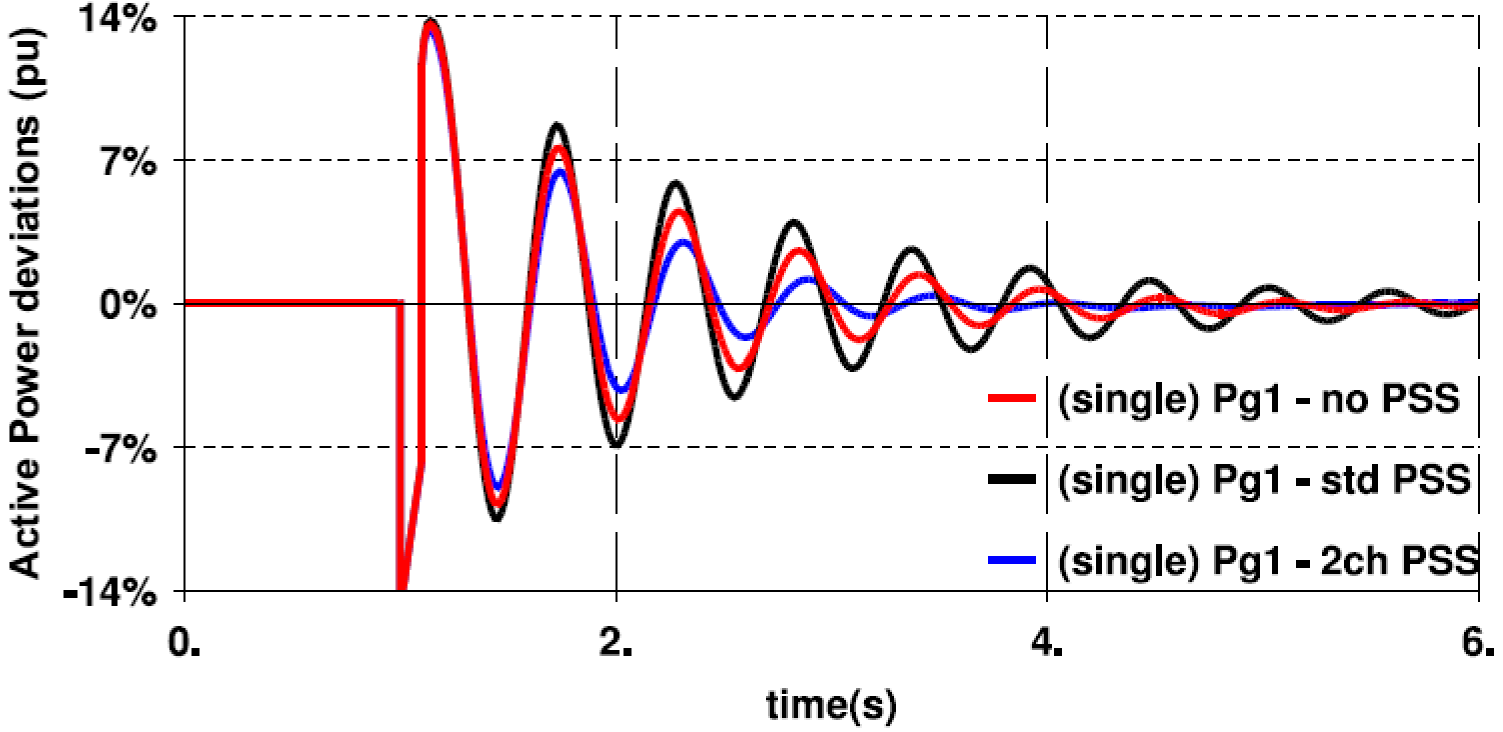


Fig. 31: MPIB Slow-exc system with Large Internal Fault - Active Power responses of unit #1.

4. NONLINEAR SIMULATIONS

Balanced MPIB System following an Internal Fault

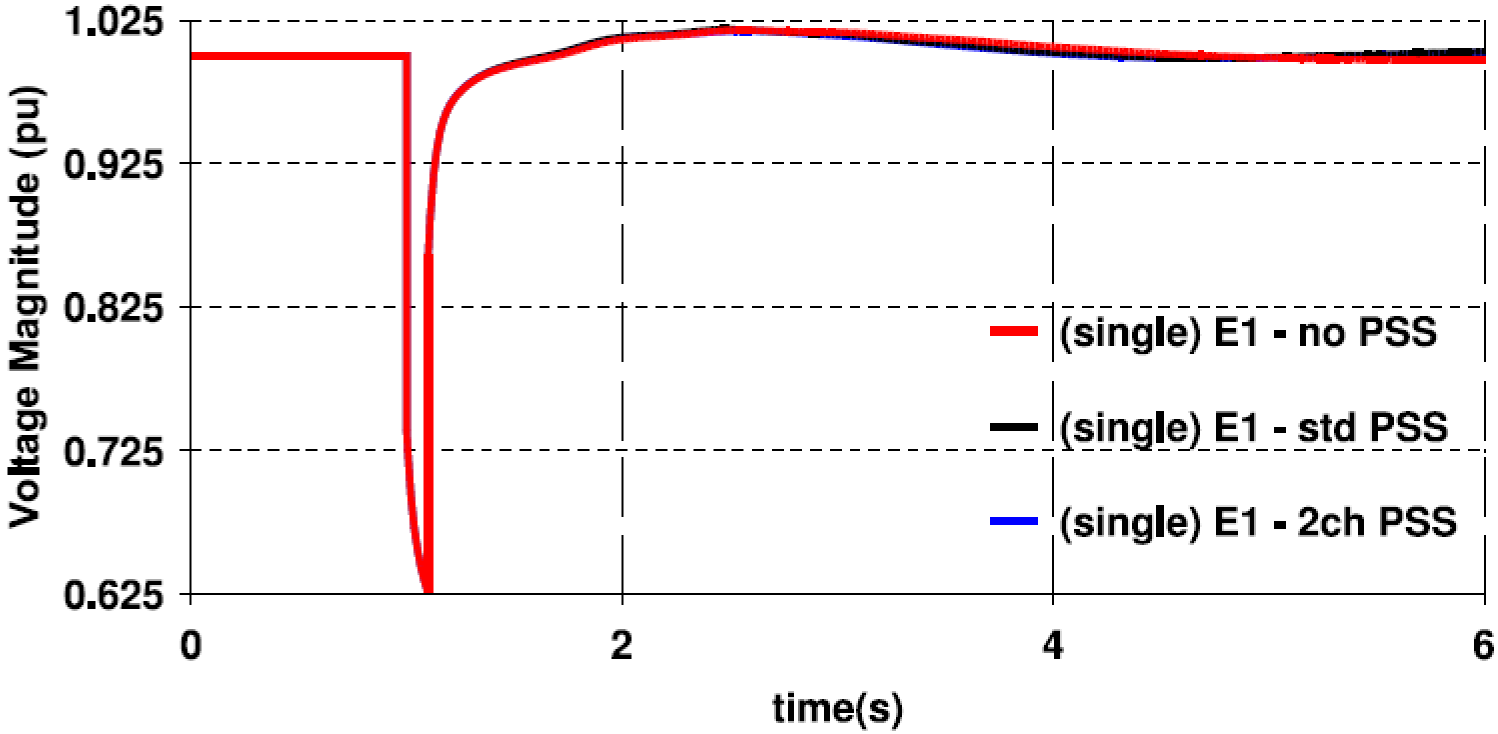


Fig. 32: MPIB Slow-exc system with Large Internal Fault - Terminal Voltage responses of unit #1.

4. NONLINEAR SIMULATIONS

Balanced MPIB System following an Internal Fault

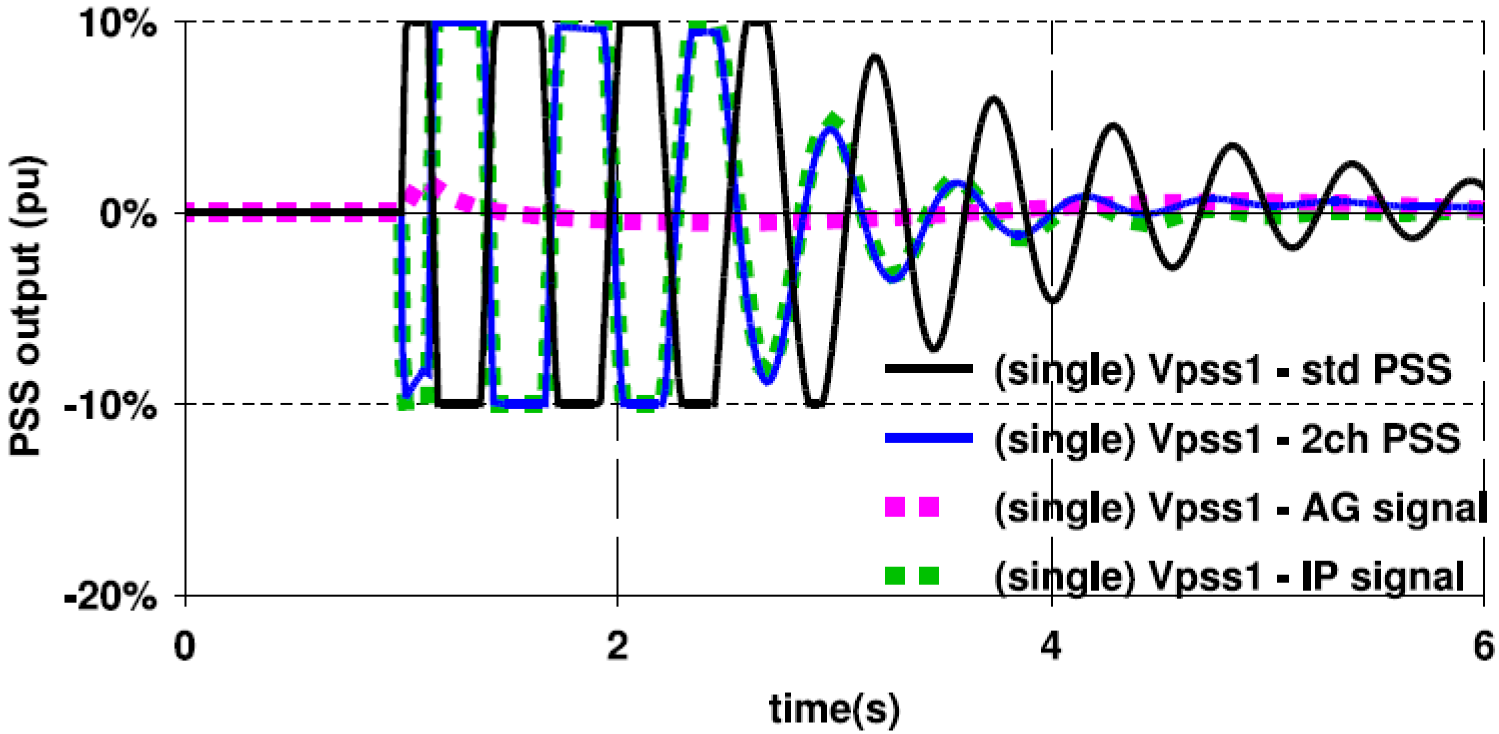


Fig. 33: MPIB Slow-exc system with Large Internal Fault - PSS Output responses of unit #1.

4. NONLINEAR SIMULATIONS

Imbalanced MPIB System following an External Fault (1/2)

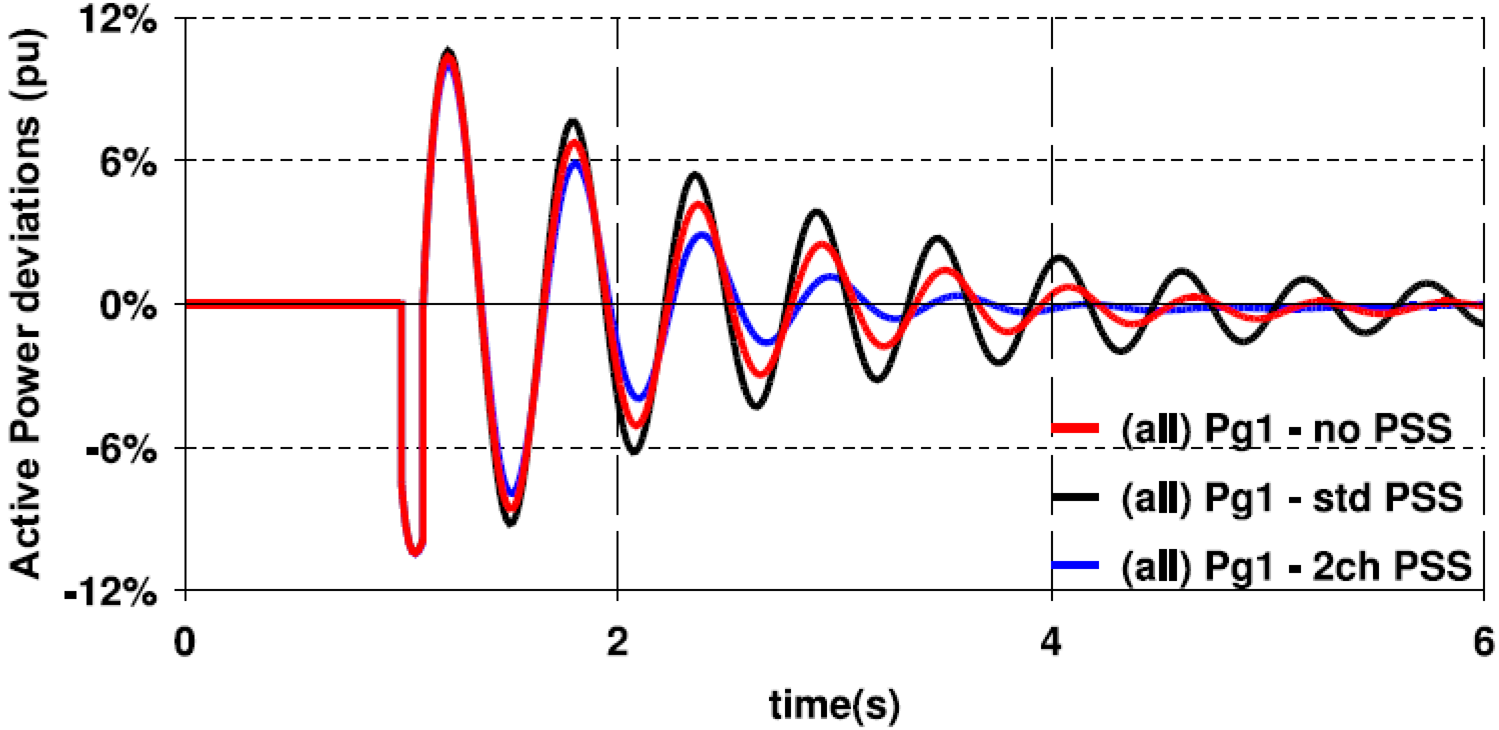


Fig. 34: Unbalanced MPIB Slow-exc system with Large Exogenous Fault - Active Power responses of unit #1. Part I - first 6s of the nonlinear simulation.

4. NONLINEAR SIMULATIONS

Imbalanced MPIB System following an External Fault (2/2)

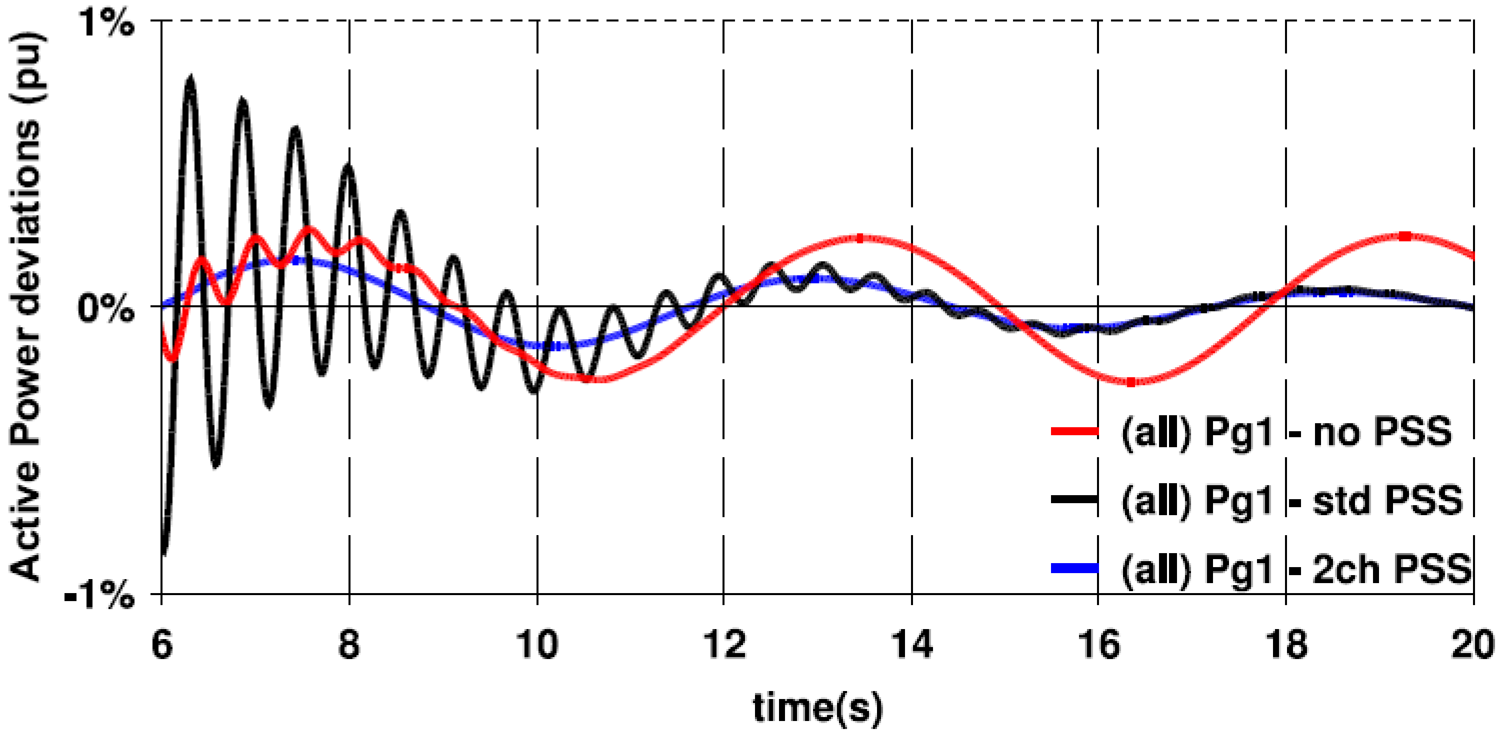


Fig. 35: Unbalanced MPIB Slow-exc system with Large Exogenous Fault - Active Power responses of unit #1. Part II - last 14s of the nonlinear simulation.

5. CONCLUSIONS

Benefits of 2-channel PSS in multigenerator plants

- The intraplant and aggregate components of the Vpss signal are orthogonal and maintain the subspace orthogonality that exists in the original system
- Damping ratios for intraplant and aggregate modes can be set as desired by the independent tuning of the two control channels of the 2ch PSS
- Robust damping performance for fairly large levels of plant imbalance
- Helps solving difficult damping control problems in multigenerator plants
- The 2ch PSS solution may prevent discarding rotating exciters when upgrading vintage plants that shall take part in the damping control of interarea modes
- These concepts equally apply to the vibration damping control of light flexible mechanical structures.

7. SIMILARITY TRANSFORMATION

- **A** has a block-symmetric structure
- Similarity transformation with matrix **P** turns the state matrix **A** block-diagonal

$$\mathbf{A} = \left[\begin{array}{c:c:c:c} \mathbf{a} & \mathbf{b} & \cdots & \mathbf{b} \\ \hdashline \mathbf{b} & \mathbf{a} & \ddots & \vdots \\ \hdashline \vdots & \ddots & \ddots & \mathbf{b} \\ \hdashline \mathbf{b} & \cdots & \mathbf{b} & \mathbf{a} \end{array}\right]$$

$$\mathbb{P} = \begin{bmatrix} \mathbf{I}_{m\times m} & \mathbf{I}_{m\times m} & \mathbf{I}_{m\times m} & \cdots & \mathbf{I}_{m\times m} \\ \mathbf{I}_{m\times m} & -\mathbf{I}_{m\times m} & \mathbf{0}_{m\times m} & \cdots & \mathbf{0}_{m\times m} \\ \mathbf{I}_{m\times m} & \mathbf{0}_{m\times m} & -\mathbf{I}_{m\times m} & \ddots & \vdots \\ \vdots & \vdots & \ddots & \ddots & \mathbf{0}_{m\times m} \\ \mathbf{I}_{m\times m} & \mathbf{0}_{m\times m} & \cdots & \mathbf{0}_{m\times m} & -\mathbf{I}_{m\times m} \end{bmatrix}$$

$$\bar{\mathbf{A}} = \mathbb{P}^{-1}\mathbf{A}\mathbb{P}$$

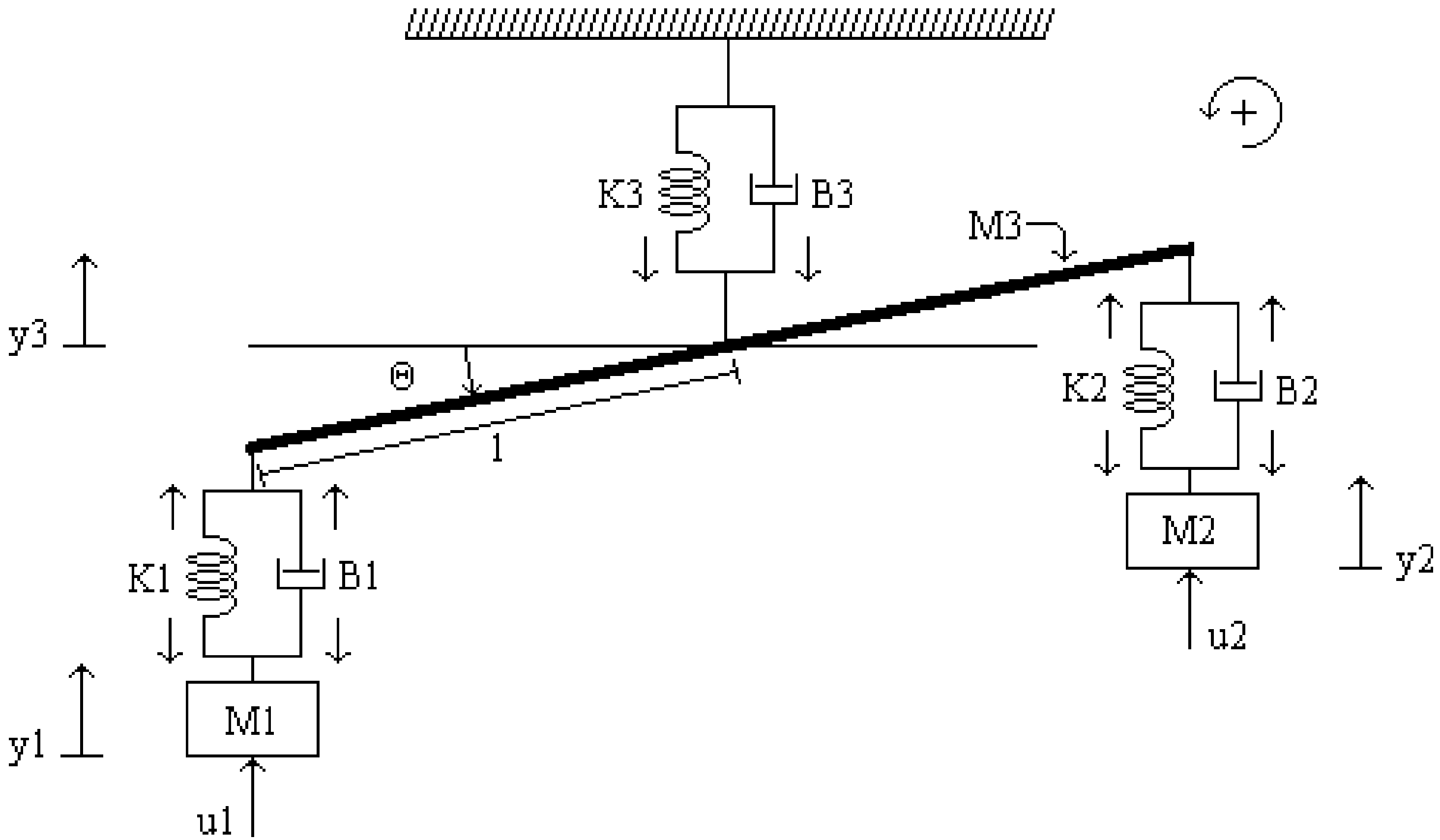
$$\bar{\mathbf{A}} = \begin{bmatrix} \boxed{\mathbf{a} + (n-1)\mathbf{b}} & \mathbf{0} & \cdots & \mathbf{0} \\ \mathbf{0} & \boxed{\mathbf{a} - \mathbf{b}} & \ddots & \vdots \\ \vdots & \ddots & \ddots & \mathbf{0} \\ \mathbf{0} & \cdots & \mathbf{0} & \boxed{\mathbf{a} - \mathbf{b}} \end{bmatrix}$$

T. H. S. Bossa, N. Martins, P. C. Pellanda, and R. J. G. C. da Silva, “A field test to determine PSS effectiveness at multigenerator power plants,” IEEE Trans. Power Syst., vol. 26, no. 3, pp. 1522–1533, Aug. 2011.

7. MODAL DECOMPOSITION

Mechanical analog

- Spring – Mass System is an analog to the 2-unit Power Plant
  - translational mode (*θ=0*) is the aggregate mode
  - Rotational mode (*y3=0*) is the intraplant mode



7. MODAL DECOMPOSITION

Symmetrical Components Analogy

- Impedance of a balanced 3-phase load Z_{bal}:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \underbrace{\begin{bmatrix} Z_s & Z_m & Z_m \\ Z_m & Z_s & Z_m \\ Z_m & Z_m & Z_s \end{bmatrix}}_{\mathbf{Z}_{\text{bal}}} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}$$

$$\mathcal{T} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1\angle 120 & 1\angle -120 \\ 1 & 1\angle -120 & 1\angle 120 \end{bmatrix}$$

- Load is decomposed into its sequence components:

$$\mathbf{Z}'_{\text{bal}} = \mathcal{T}^{-1} \mathbf{Z}_{\text{bal}} \mathcal{T}$$

$$\begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} = \underbrace{\begin{bmatrix} Z_s + 2Z_m & 0 & 0 \\ 0 & Z_s - Z_m & 0 \\ 0 & 0 & Z_s - Z_m \end{bmatrix}}_{\mathbf{Z}'_{\text{bal}}} \begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix}$$

THANK YOU!