SOME RECENT DEVELOPMENTS IN SMALL-SIGNAL STABILITY AND CONTROL

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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
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**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 AVR[s, 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

Eigenvalue Spectrum

Real Part (1/s) vs. Imaginary Part (rad/s)
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
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ROOT CONTOUR WHEN INCREASING THE GAINS OF THE 2 TCSCs

- North-South mode
- Adverse control interaction mode

K=1
K=3.6

5%
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DETERMINING SECURITY BOUNDARIES THROUGH HOPF (5%)
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Determining Security Boundaries Through Hopf (5%)
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Determining Security Boundaries Through Hopf (5%)
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Direction:
- North-South mode
- Adverse control Interaction mode

K=1

Determining Security Boundaries Through Hopf (5%)

Graph showing the relationship between security boundaries and Hopf (5%) with two modes: North-South and Adverse control Interaction.
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DETERMINING SECURITY BOUNDARIES THROUGH HOPF (5%)

- North-South mode
- Adverse control interaction mode
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DETERMINING SECURITY BOUNDARIES THROUGH HOPF (5%)
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)
An \( m \times m \) transfer function \( G(s) \) may be expanded in terms of the system poles and associated residue matrices:

\[
G(s) = \sum_{i=1}^{n} \frac{R_i}{s - \lambda_i}
\]

The truncated sum below is the modal equivalent:

\[
G(s) \approx \sum_{i=1}^{p} \frac{R_i}{s - \lambda_i} , \text{ where } p \ll n
\]
MODAL EQUIVALENTS OF MULTIVARIABLE TRANSFER FUNCTIONS

- Sigma-plot for 8 x 8 G(s), $\zeta = 15\%$
- 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
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.
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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.
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Modal Analysis in Harmonic Studies

Test System

HV System Equivalent

\[ V_{th} \]

\[ L_{cc} \]

\[ T1 (HV/MV) \]

Bus 1

Bus 2

Bus 3

\[ T2 (MV/LV) \]

\[ T3 (MV/LV) \]

\[ I_{h2} \]

\[ I_{h3} \]

\[ C_1 \]

\[ C_2 \]

\[ C_3 \]
MODAL ANALYSIS IN HARMONIC STUDIES

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

![Diagram of RLC system with harmonic sources and capacitors.](image-url)
### Modal Analysis in Harmonic Studies

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

<table>
<thead>
<tr>
<th>System poles</th>
<th>Zeros seen from</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>f(Hz)</td>
<td>252</td>
</tr>
<tr>
<td>$L_{CC}$</td>
<td>-101</td>
</tr>
<tr>
<td>$L_2$</td>
<td>-3</td>
</tr>
<tr>
<td>$L_3$</td>
<td>-4</td>
</tr>
<tr>
<td>$L_{12}$</td>
<td>-2</td>
</tr>
<tr>
<td>$L_{13}$</td>
<td>-19</td>
</tr>
<tr>
<td>$C_1$</td>
<td>-45</td>
</tr>
<tr>
<td>$C_2$</td>
<td>-25</td>
</tr>
<tr>
<td>$C_3$</td>
<td>-54</td>
</tr>
</tbody>
</table>
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!)

\[
\begin{align*}
C_1^{\text{original}} &= 23.9 \ \mu F \\
C_3^{\text{original}} &= 11.9 \ \mu F \\
C_1^{\text{new}} &= 29.26 \ \mu F \\
C_3^{\text{new}} &= 22.77 \ \mu F
\end{align*}
\]
Y(s) technology may become a common upgrade to conventional harmonic analysis programs - Y(jω)

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
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**Active Power Changes Following \( \Delta P_{mec} \) in SMIB**

![Graph showing active power changes following \( \Delta P_{mec} \) in SMIB](image.png)

- **Axes:**
  - \( \text{Tempo (s)} \) on the x-axis.
  - \( \text{Time (s)} \) on the y-axis.

- **Lines:**
  - \( \text{PSS} \omega \) (black line).
  - \( \text{PSSPT} \) (dashed line).

- **Data Points:**
  - \( \Delta P_{mec} = 0,000 \) to \( \Delta P_{mec} = 0,020 \) on the y-axis.

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Zero near the origin causes bigger overshoot in the step response.
Pole-Zero Map for $\Delta Q_T / \Delta P_{MEC} (PSS_\omega)$
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FINAL REMARKS

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