ADVANCED TOOL FOR HARMONIC ANALYSIS OF POWER SYSTEMS

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Objectives (1/1)

- Description of some features of the HarmZs program for analysis of harmonic problems in power systems.

- Review of some basic concepts of the conventional and modal analysis needed for understanding the methodologies computationally implemented in the program.
Network Modeling Techniques (1/2)

- The HarmZs program utilizes two recent electrical network-modeling techniques, named Descriptor Systems and $\mathbf{Y}(s)$ matrix.

- These techniques allow electrical network analyses over all the complex plane $s$ instead of just over the imaginary “$j\omega$” axis.

- In this expanded domain modal and conventional analyses can be performed.

- Modal analysis provides an important set of dynamic system information that is hard to obtain using the two conventional methods: time simulation and frequency response.
Network Modeling Techniques (2/2)

- This information includes the natural oscillation modes, identification of equipment that more heavily participate in these modes, modal sensitivities with respect to parameters changes, etc.

- May be effectively used to improve the harmonic performance of electrical networks.
Descriptor System (1/1)

- **Main Characteristic**
  - The equations are written in the time-domain.

- **Main Advantage**
  - The complete set of poles and zeros can be simultaneously calculated using the QZ decomposition or one at a time using iterative methods.

- **Main Disadvantage**
  - Difficulties in modeling frequency dependent parameters.
Matrix $Y(s)$ (1/1)

- **Main Characteristic**
  - The equations are written in the $s$-domain.

- **Main Advantage**
  - Modeling of frequency dependent parameters is very easy.

- **Main Disadvantage**
  - The poles and zeros can only be calculated one at a time using iterative methods.
Test System (1/3)

Fundamental frequency = 50 Hz

- HV System Equivalent
- $V_{th}$
- $L_{cc}$
- T1 (HV/MV)
- TL 1-2
- TL 1-3
- $I_{h1}$
- $C_1$
- $I_{h2}$
- $Z_2$
- $C_2$
- $I_{h3}$
- $Z_3$
- $C_3$
Test System (2/3)

System Modeling

![Diagram of a test system with labeled components: v1, C1, L1, iL4, i1, i10, i12, R12, L12, bus 1, bus 2, bus 3, v2, C2, R2, L2, iL2, i2, i20, i3, v3, C3, R3, L3, iL3, i30.](image-url)
Test System (3/3)

- Test system parameter values referred to 20 kV

<table>
<thead>
<tr>
<th>Inductance (mH)</th>
<th>Resistance (Ω)</th>
<th>Capacitance (µF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_1$</td>
<td>8.0</td>
<td>$R_2$ 80.0</td>
</tr>
<tr>
<td>$L_2$</td>
<td>424.0</td>
<td>$R_3$ 133.0</td>
</tr>
<tr>
<td>$L_3$</td>
<td>531.0</td>
<td>$R_{12}$ 0.46</td>
</tr>
<tr>
<td>$L_{12}$</td>
<td>9.7</td>
<td>$R_{13}$ 0.55</td>
</tr>
<tr>
<td>$L_{13}$</td>
<td>11.9</td>
<td></td>
</tr>
</tbody>
</table>
Properties

- If $s_k = \sigma_k + j\omega_k$ is a system pole or a zero of the transfer function $G(s)$, then $G(\sigma_k + j\omega_k)$ tends to $\infty$ or is equal to 0, respectively. However, $G(j\omega_k)$ does not approach $\infty$ or is equal to 0.

- $|G(j\omega_k)|$ has a high value (very close to a local maximum) or a low value (very close to a local minimum) depending on whether $s_k$ is a pole or a zero.
Test system poles and zeros of the self-impedances

<table>
<thead>
<tr>
<th></th>
<th>Poles</th>
<th>Zeros</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Bus 1</td>
</tr>
<tr>
<td>1</td>
<td>-2.90.08 ± j 1583.6</td>
<td>-338.52 ± j 2670.9</td>
</tr>
<tr>
<td>2</td>
<td>-507.00 ± j 3069.1</td>
<td>-804.43 ± j 3550.6</td>
</tr>
<tr>
<td>3</td>
<td>-345.88 ± j 4535.7</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>-0.98914</td>
<td>-1.0091</td>
</tr>
<tr>
<td>5</td>
<td>-1.0419</td>
<td>-1.0549</td>
</tr>
</tbody>
</table>
Poles, Zeros and Frequency Response Plot (3/6)

- Pole and zero frequencies in Hz

\[
Pole \text{ or zero frequency in Hz} = \frac{\text{Im}(s_k)}{2 \pi}
\]

Test System

<table>
<thead>
<tr>
<th>Poles</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f(\text{Hz}) )</td>
<td>252</td>
<td>488</td>
<td>722</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Zeros</th>
<th>1</th>
<th>2</th>
<th>1</th>
<th>2</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus 1</td>
<td>425</td>
<td>565</td>
<td>332</td>
<td>633</td>
<td>382</td>
<td>704</td>
</tr>
</tbody>
</table>

Bus 2

Bus 3
Self-impedance of bus 1
Self-impedance of bus 2

Poles, Zeros and Frequency Response Plot (5/6)
Self-impedance of bus 3
The poles that have the largest associated residue moduli for a chosen transfer function are defined as dominant poles of that transfer function.

If these transfer function poles are fairly close to the imaginary axis or, in other words, if they have relatively small real parts, they will produce a high peak in the frequency response magnitude plot.
Dominant Poles and Reduced Models (2/4)

- Partial fraction form of a transfer function

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

\( n \rightarrow \text{number of poles} \)

\( R_i = \lim_{s \to \lambda_i} G(s)(s - \lambda_i) \)

\( d = \lim_{s \to \infty} G(s) \)

- Considering only the dominant poles of \( G(s) \)

\[ G(s) \approx \sum_{\Omega} \frac{R_i}{s - \lambda_i} + d \]

\( \Omega \rightarrow \text{Set of dominant poles} \)
Dominant Poles and Reduced Models (3/4)

- Dominant poles and reduced model of the bus 1
- Self-impedances

<table>
<thead>
<tr>
<th></th>
<th>Poles</th>
<th>Residue moduli</th>
<th>Bus 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-2.90.08 ± j 1583.6 (252 Hz)</td>
<td>8.1782 × 10^3</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>-507.00 ± j 3069.1 (488 Hz)</td>
<td>2.5161 × 10^3</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>-345.88 ± j 4535.7 (722 Hz)</td>
<td>12.237 × 10^3</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>-0.98914</td>
<td>1.9039 × 10^-4</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>-1.0419</td>
<td>6.5180 × 10^-5</td>
<td></td>
</tr>
</tbody>
</table>
Dominant Poles and Reduced Models (4/4)

Reduced model of bus 3 self-impedance
The sensitivity of an eigenvalue $s_k$ (pole or zero) with respect to a system parameter $p_j$ is defined by $\frac{\partial s_k}{\partial p_j}$.

### Sensitivities of the zeros of the bus 2 self-impedance $(1 + j \text{ rad})(s^{-1}/\mu\text{F})$

<table>
<thead>
<tr>
<th>Capacitor</th>
<th>Zero 1</th>
<th>Zero 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_1$</td>
<td>$4.3708 - j9.9007$</td>
<td>$-4.3708 - j63.708$</td>
</tr>
<tr>
<td>$C_2$</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$C_3$</td>
<td>$11.523 - j67.108$</td>
<td>$15.024 - j37.988$</td>
</tr>
</tbody>
</table>
Self-impedance of bus 2 for three values of $C_2$

- $C_2 = 8 \, \mu\text{F}$
- $C_2 = 12 \, \mu\text{F}$
- $C_2 = 16 \, \mu\text{F}$
Harmonic Problem Definition (1/1)

Harmonic order | Voltage distortion (%) |
---|---|
11 | 9.09 |
13 | 7.69 |
15 | 4.35 |
17 | 4.00 |
19 | 2.86 |
21 | 2.70 |
23 | 2.70 |
25 | 2.70 |
27 | 2.70 |
29 | 2.70 |
31 | 2.70 |
33 | 2.70 |
35 | 2.70 |
37 | 2.70 |

Frequency (Hz) | Voltage distortion (%) |
---|---|
550 | 9.09 |
650 | 7.69 |
1150 | 4.35 |
1250 | 4.00 |
1750 | 2.86 |
1850 | 2.70 |

Harmonic order | Voltage distortion (%) |
---|---|
11 | 9.09 |
13 | 7.69 |
15 | 4.35 |
17 | 4.00 |
19 | 2.86 |
21 | 2.70 |
23 | 2.70 |
25 | 2.70 |
27 | 2.70 |
29 | 2.70 |
31 | 2.70 |
33 | 2.70 |
35 | 2.70 |
37 | 2.70 |
Harmonic Problem Solution (1/2)

Sensitivities of the poles 2 and 3 \((1 + j \text{ rad})(s^{-1}/\mu\text{F})\)

<table>
<thead>
<tr>
<th>Capacitance</th>
<th>Pole 2 ((-507.00 + j 3069.1))</th>
<th>Pole 3 ((-345.88 + j 4535.7))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(C_1)</td>
<td>7.1822 (-j 3.1098)</td>
<td>(-12.8283 (-j 54.1654)</td>
</tr>
<tr>
<td>(C_2)</td>
<td>13.437 (-j 91.449)</td>
<td>81.5907 (-j 87.1324)</td>
</tr>
<tr>
<td>(C_3)</td>
<td>18.926 (-j 60.418)</td>
<td>(-3.6843 (-j 14.9227)</td>
</tr>
</tbody>
</table>
Reduction of 10 \( \mu \)F in \( C_1 \) and increase of 18 \( \mu \)F in \( C_2 \)
Conclusions (1/1)

- Description of some features of the HarmZs program for analysis of harmonic problems in power systems.

- Review of some basic concepts of the conventional and modal analysis needed for understanding the methodologies computationally implemented in the program:
  - Network-modeling methodologies suitable for modal and conventional analysis.
  - Calculations and concepts of poles, zeros and their sensitivities to system parameter changes.
  - Pole residues, dominant poles and reduced models as important concepts to help obtaining low order dynamic network equivalents (modal equivalents) of large scale power system.
  - Formulation of a harmonic problem example using a test system and its solution by modal analysis.
Remarks (1/1)

- Basically, there are three forms of improving the harmonic performance of a system: Filtering harmonic currents, improving the performance of nonlinear loads and system modifications. This paper is a contribution for the third form.

- System modifications seem to be particularly suitable for reducing harmonic distortions in larger systems which have several and spread nonlinear loads.