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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 **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)

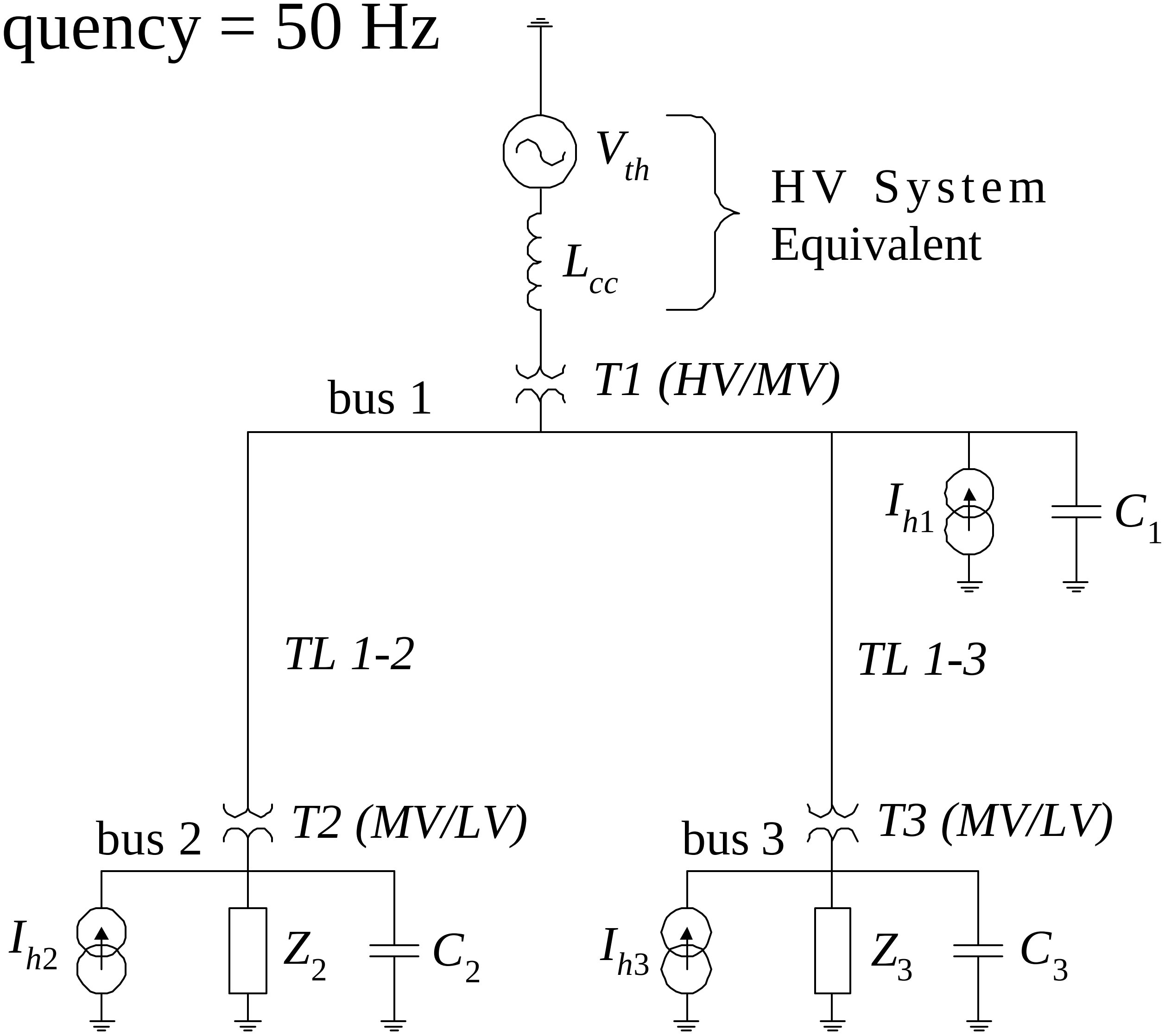
- Main Characteristic
  - The equations are written in the time-domain.
- Main Advantage
  - The complete set of poles and zeros can be simultaneously calculated using the QZ decomposition or one at a time using iterative methods.
- Main Disadvantage
  - Difficulties in modeling frequency dependent parameters.

Matrix $\mathbf{Y}(s)$ (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.

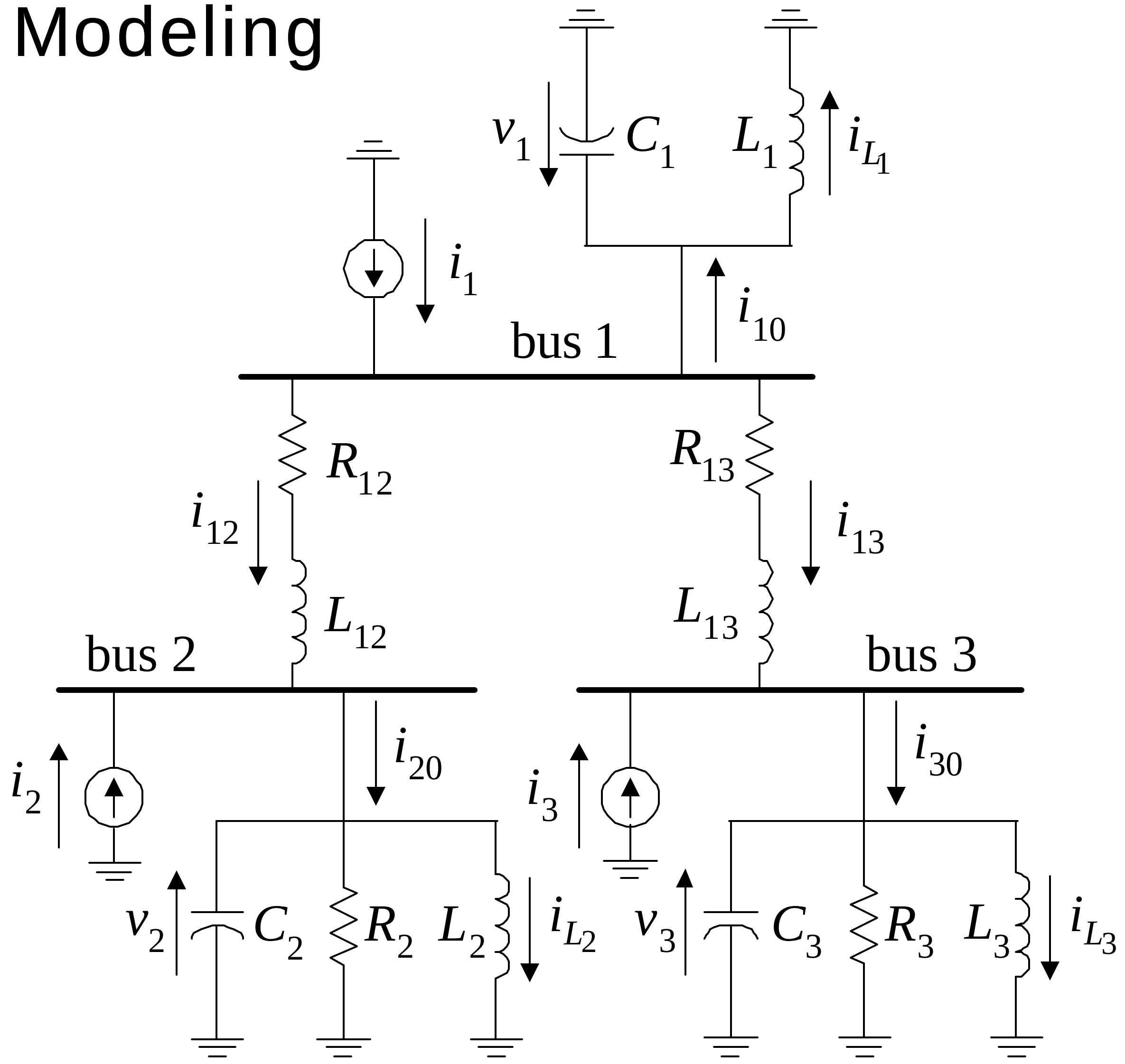
Test System (1/3)

Fundamental frequency = 50 Hz



Test System (2/3)

- System Modeling



Test System (3/3)

- Test system parameter values referred to 20 kV

Inductance (mH)		Resistance (Ω)		Capacitance (μF)	
L_1	8.0	R_2	80.0	C_1	23.9
L_2	424.0	R_3	133.0	C_2	8.0
L_3	531.0	R_{12}	0.46	C_3	11.9
L_{12}	9.7	R_{13}	0.55		
L_{13}	11.9				

Poles, Zeros and Frequency Response Plot (1/6)

- 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 ∞ or is equal to 0, respectively. However, $G(j\omega_k)$ does not approach ∞ 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.

Poles, Zeros and Frequency Response Plot (2/6)

- Test system poles and zeros of the self-impedances

	Poles	Zeros		
		Bus 1	Bus 2	Bus 3
1	-2.90.08 $\pm j$ 1583.6	-338.52 $\pm j$ 2670.9	-255.47 $\pm j$ 2084.9	-415.26 $\pm j$ 2402.1
2	-507.00 $\pm j$ 3069.1	-804.43 $\pm j$ 3550.6	-93.698 $\pm j$ 3975.6	-398.38 $\pm j$ 4424.9
3	-345.88 $\pm j$ 4535.7	0	0	0
4	-0.98914	-1.0091	-0.99428	-1.0357
5	-1.0419	-1.0549	-26.151	-27.820

Poles, Zeros and Frequency Response Plot (3/6)

- Pole and zero frequencies in Hz

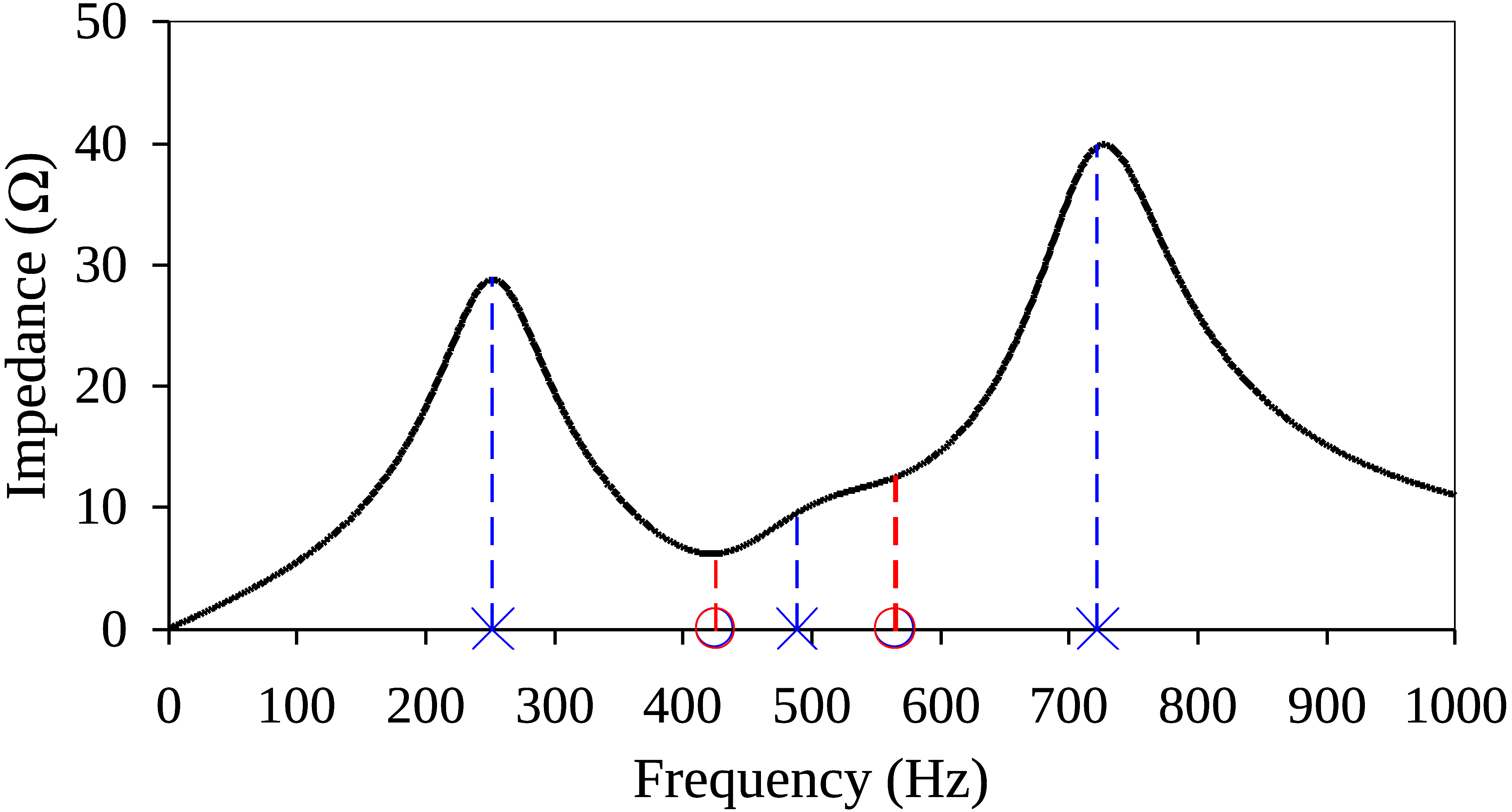
$$\text{Pole or zero frequency in Hz} = \frac{|\mathrm{Im}(s_k)|}{2\pi}$$

Test System

	Poles			Zeros					
				Bus 1		Bus 2		Bus 3	
	1	2	3	1	2	1	2	1	2
f(Hz)	252	488	722	425	565	332	633	382	704

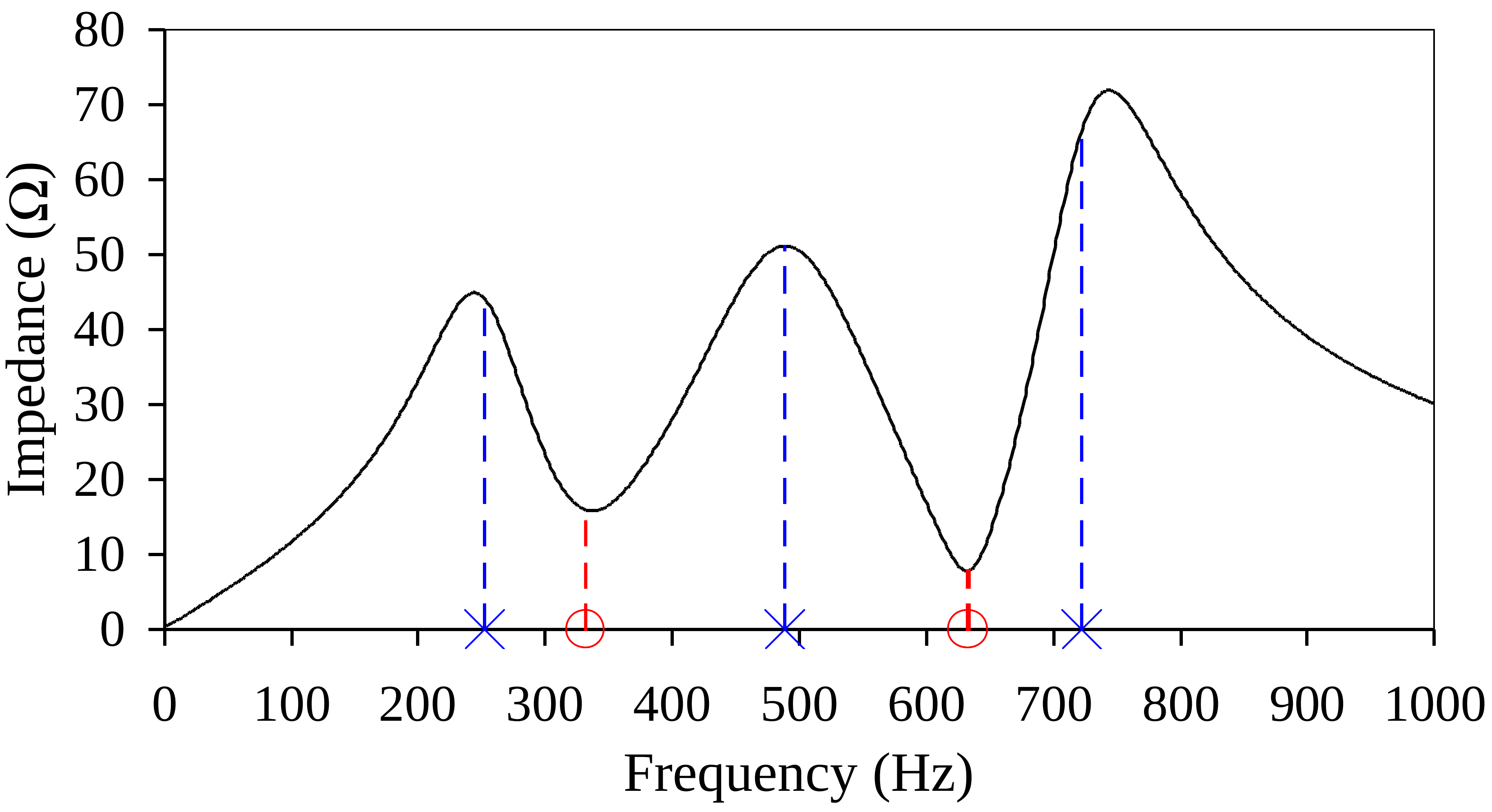
Poles, Zeros and Frequency Response Plot (4/6)

- Self-impedance of bus 1



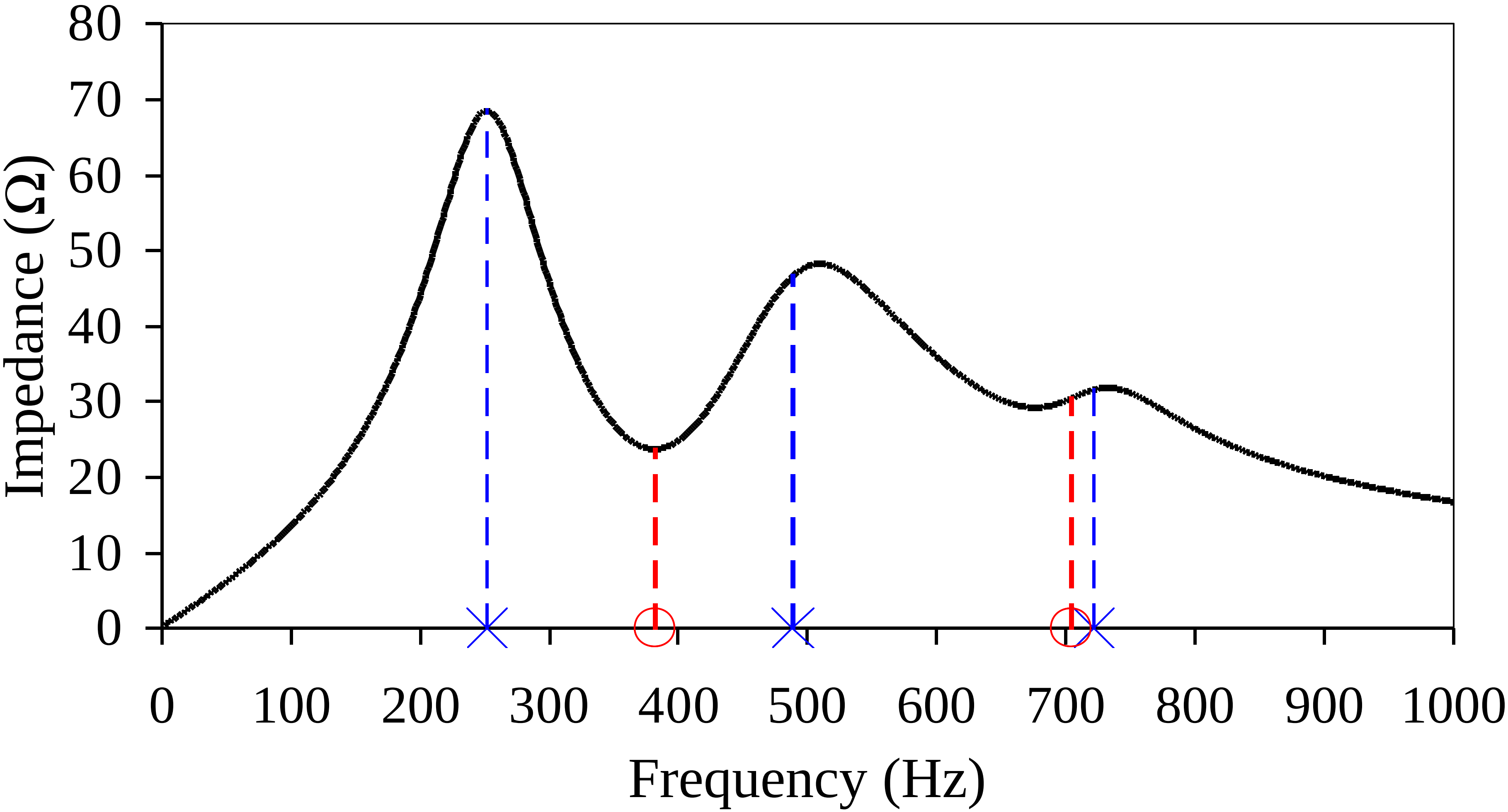
Poles, Zeros and Frequency Response Plot (5/6)

- Self-impedance of bus 2



Poles, Zeros and Frequency Response Plot (6/6)

- Self-impedance of bus 3



Dominant Poles and Reduced Models (1/4)

- 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

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

$n \rightarrow$ number of poles

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

$$d = \lim_{s\rightarrow\infty} G(s)$$

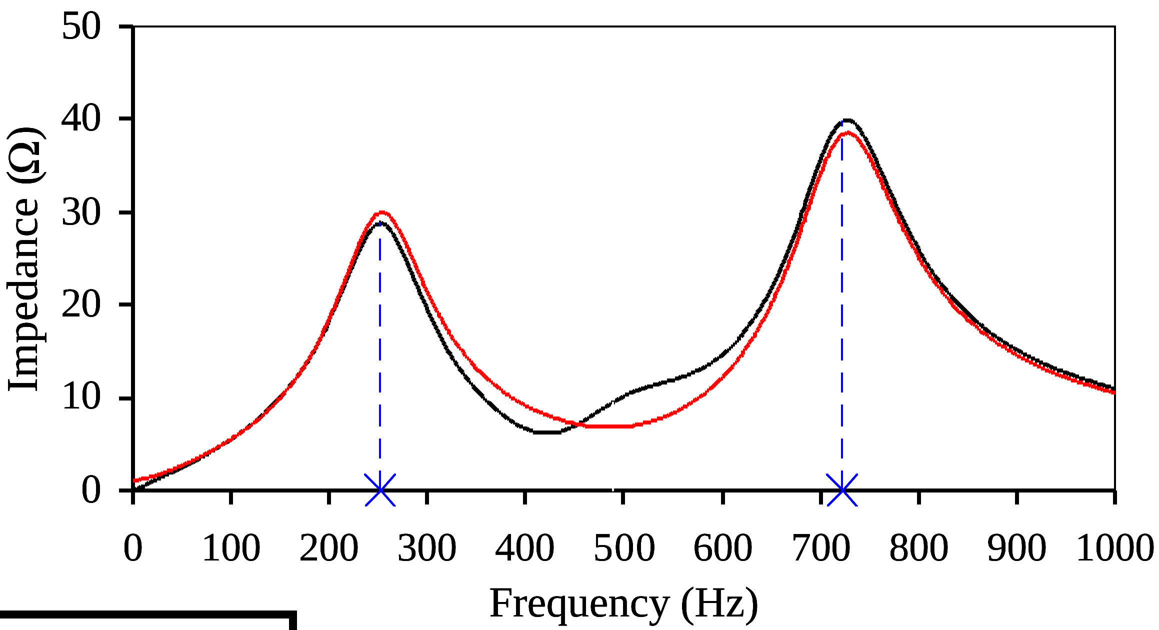
- Considering only the dominant poles of $G(s)$

$$G(s) \cong \sum_{\Omega} \frac{R_i}{s-\lambda_i} + d$$

$\Omega \rightarrow$ Set of dominant poles

Dominant Poles and Reduced Models (3/4)

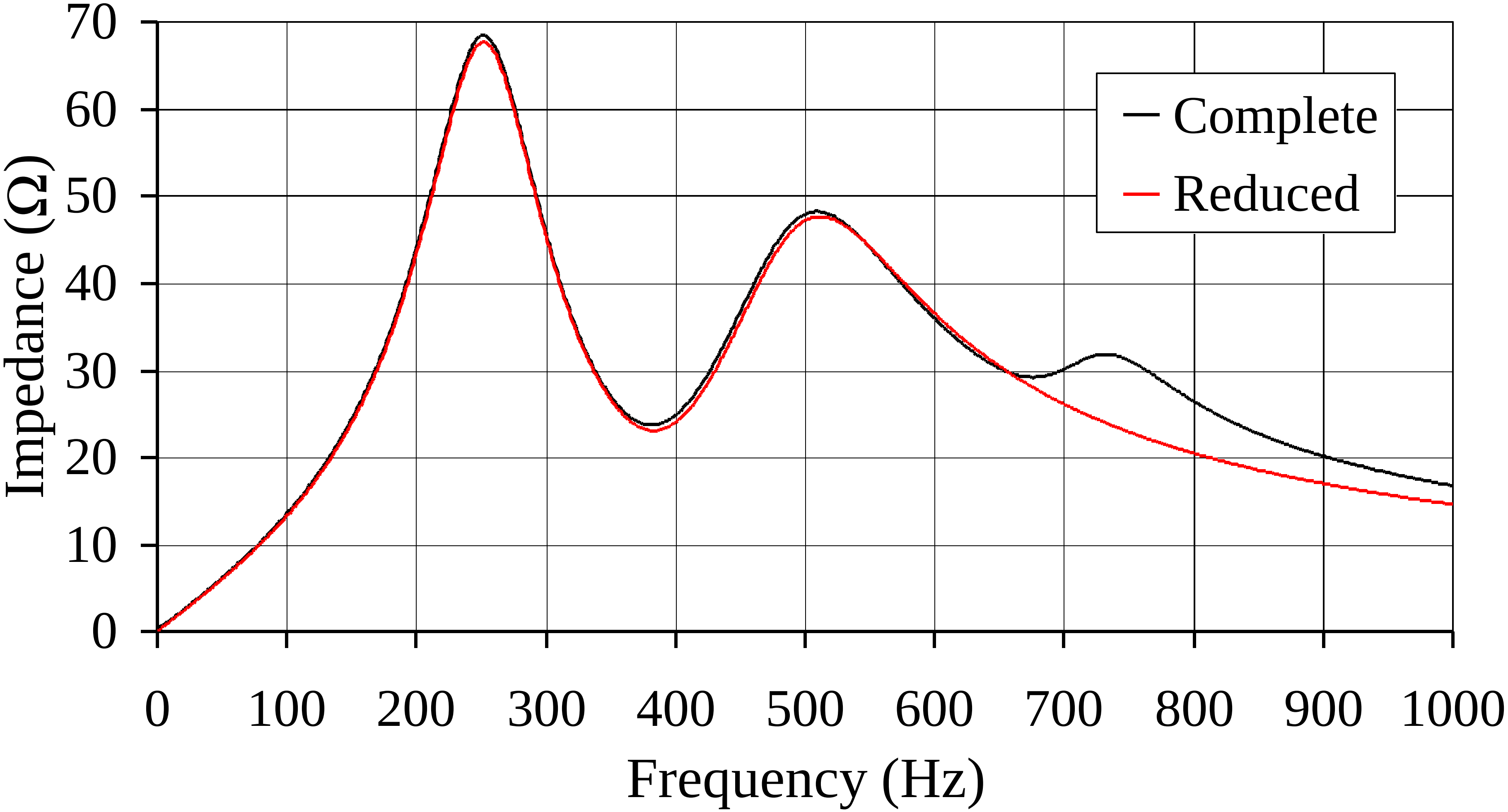
- Dominant poles and reduced model of the bus 1 Self-impedances



	Poles	Residue moduli
		Bus 1
1	$-2.90.08 \pm j\,1583.6$ (252 Hz)	8.1782×10^{3}
2	$-507.00 \pm j\,3069.1$ (488 Hz)	2.5161×10^{3}
3	$-345.88 \pm j\,4535.7$ (722 Hz)	12.237×10^{3}
4	-0.98914	1.9039×10^{-4}
5	-1.0419	6.5180×10^{-5}

Dominant Poles and Reduced Models (4/4)

- Reduced model of bus 3 self-impedance



Pole and Zero Sensitivities (1/2)

- The sensitivity of an eigenvalue s_k (pole or zero) with respect to a system parameter p_j is defined by $\partial s_k / \partial p_j$.

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

Capacitor	Zero 1	Zero 2
C_1	$4.3708 - j\,9.9007$	$-4.3708 - j\,63.708$
C_2	0	0
C_3	$11.523 - j\,67.108$	$15.024 - j\,37.988$

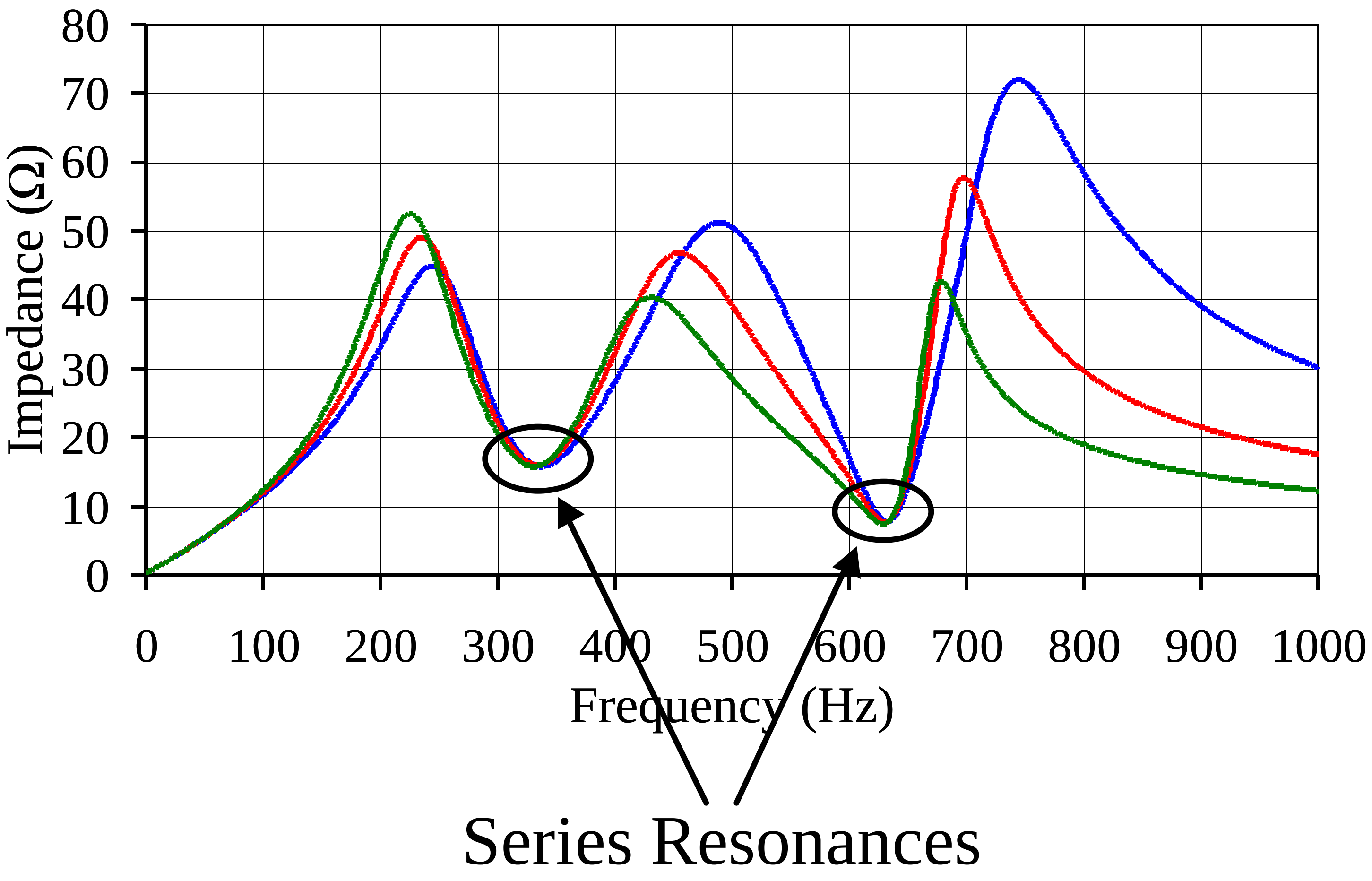
Pole and Zero Sensitivities (2/2)

- Self-impedance of bus 2 for three values of C_2

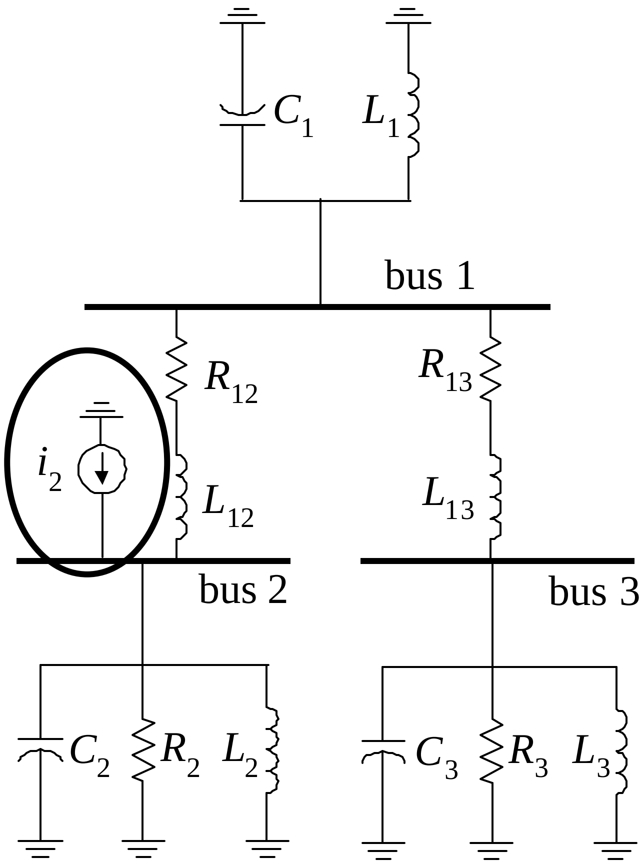
$C_2 = 8\ \mu F$

$C_2 = 12\ \mu F$

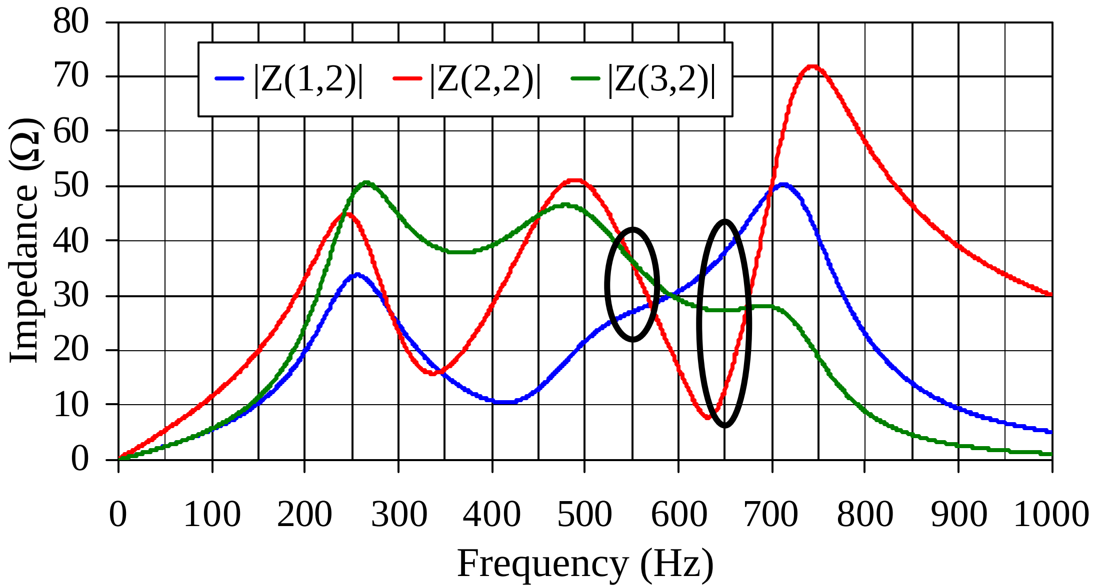
$C_2 = 16\ \mu F$

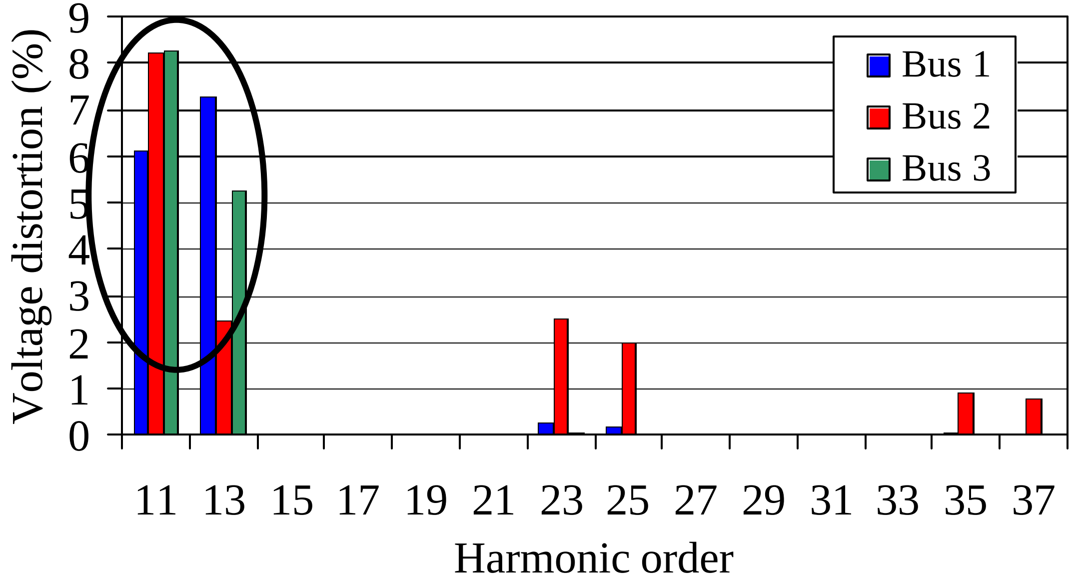


Harmonic Problem Definition (1/1)

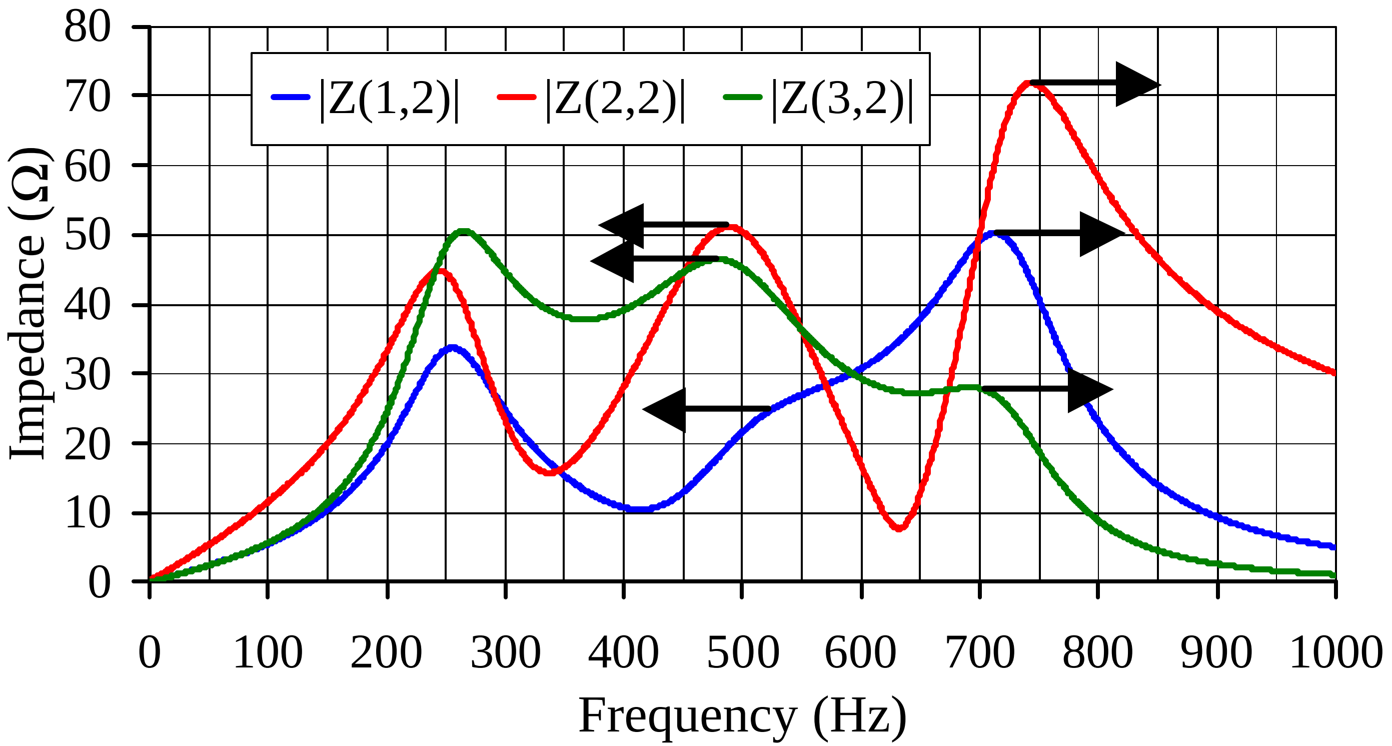


f(Hz)	550	650	1150	1250	1750	1850
h	11	13	23	25	35	37
i_2 (%)	9.09	7.69	4.35	4.00	2.86	2.70





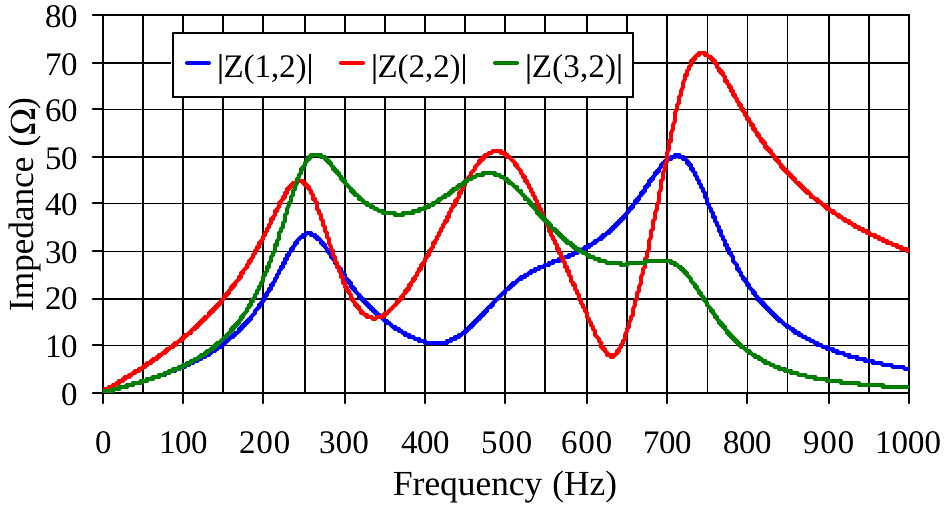
Harmonic Problem Solution (1/2)

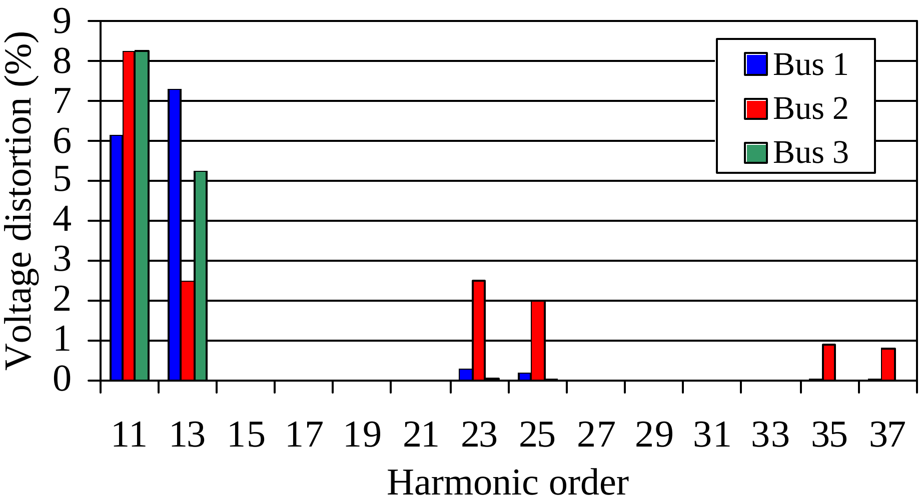


Sensitivities of the poles 2 and 3 (1 + *j* rad)(s^{-1}/μF)

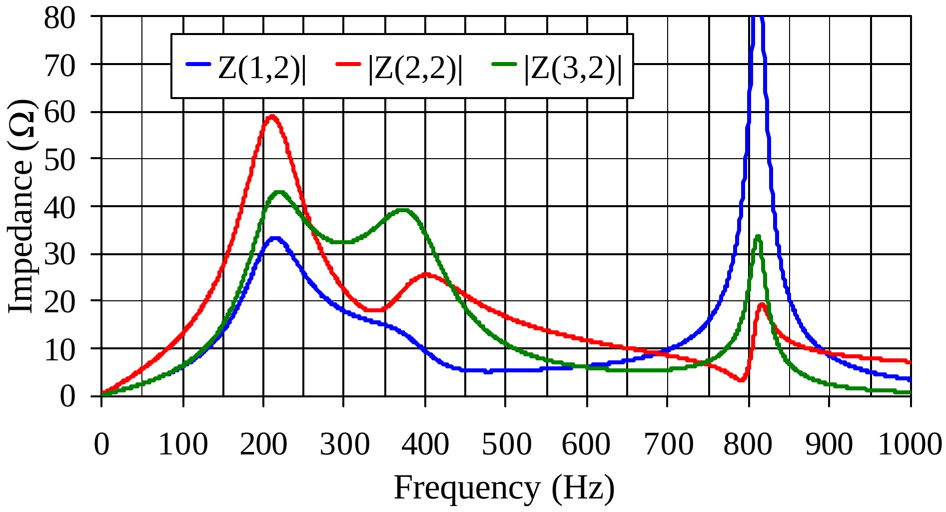
Capacitance	Pole 2 (-507.00 + *j* 3069.1)	Pole 3 (-345.88 + *j* 4535.7)
C_1	7.1822 – *j* 3.1098	–12.8283 – *j* 54.1654
C_2	13.437 – *j* 91.449	81.5907 – *j* 87.1324
C_3	18.926 – *j* 60.418	-3.6843 – *j* 14.9227

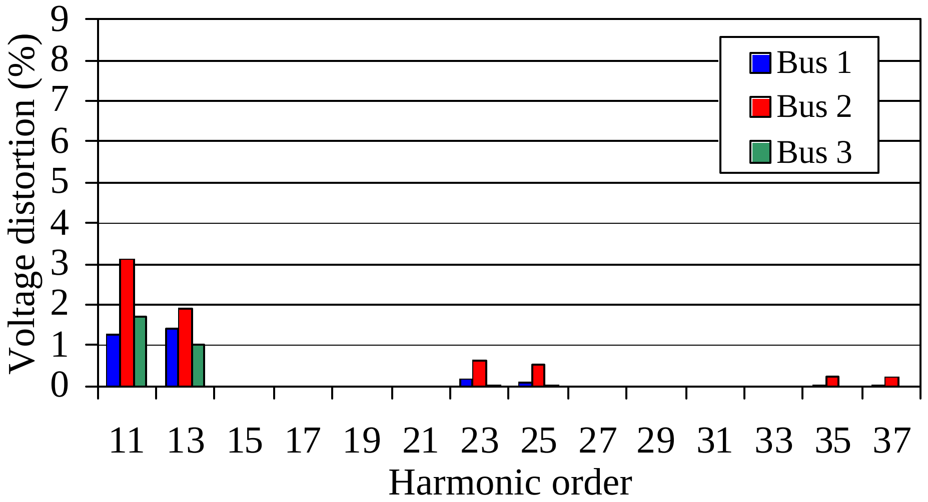
Harmonic Problem Solution (2/2)





Reduction of 10 μF in C_1 and increase of 18 μF 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 seems to be particularly suitable for reducing harmonic distortions in larger systems which have several and spread nonlinear loads.