Extracting Dominant Oscillation Modes and their Shapes from Concentrated WAMS Measurements of Ringdown Tests in Power Systems

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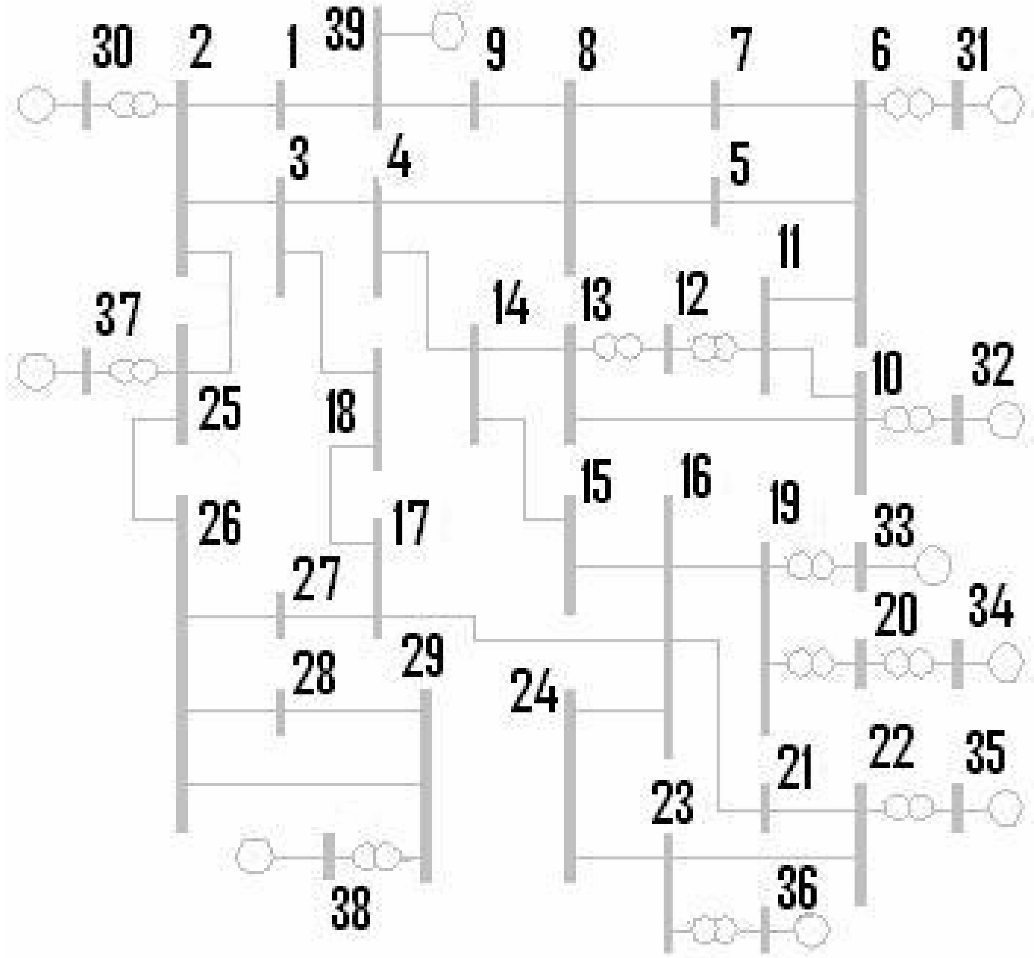
Outline

- Motivation
- Mode-shape identification process
- Identification of a SISO TF
- Identification of a SIMO TF
- Transformation from z to s-domain
- Tests and results
- Conclusions.

Motivation

- Interest in advanced identification techniques applied to Wide Area Monitoring System (WAMS)
- Time and frequency domain techniques → field measurements → dynamic system models
- Rational approximations of Transfer Function (TF) → fitting → time or frequency data
- Simultaneous identification of SIMO TFs
- Computation of system signatures to aid dynamic performance analysis

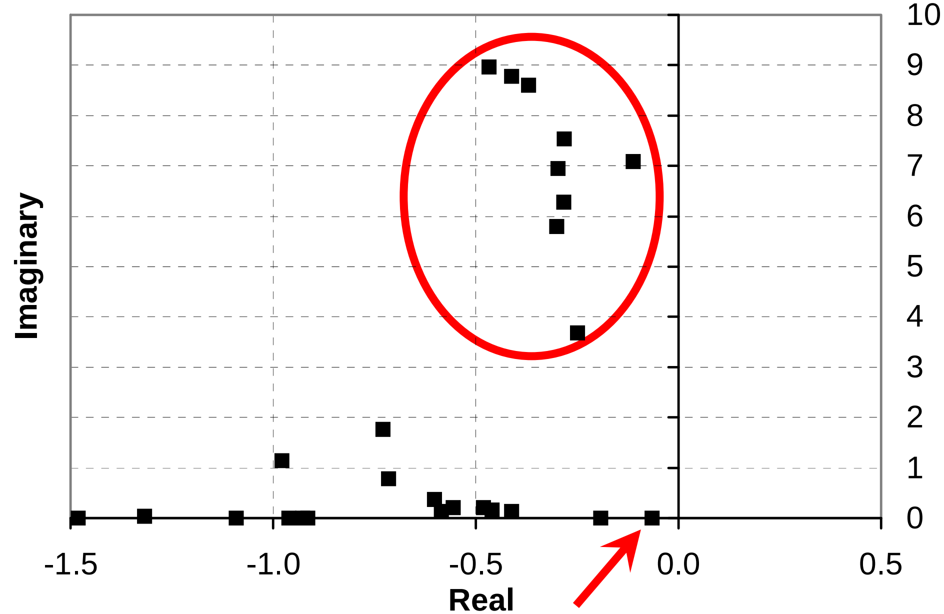
New England System: Mode Shapes, Time and Frequency Response Results



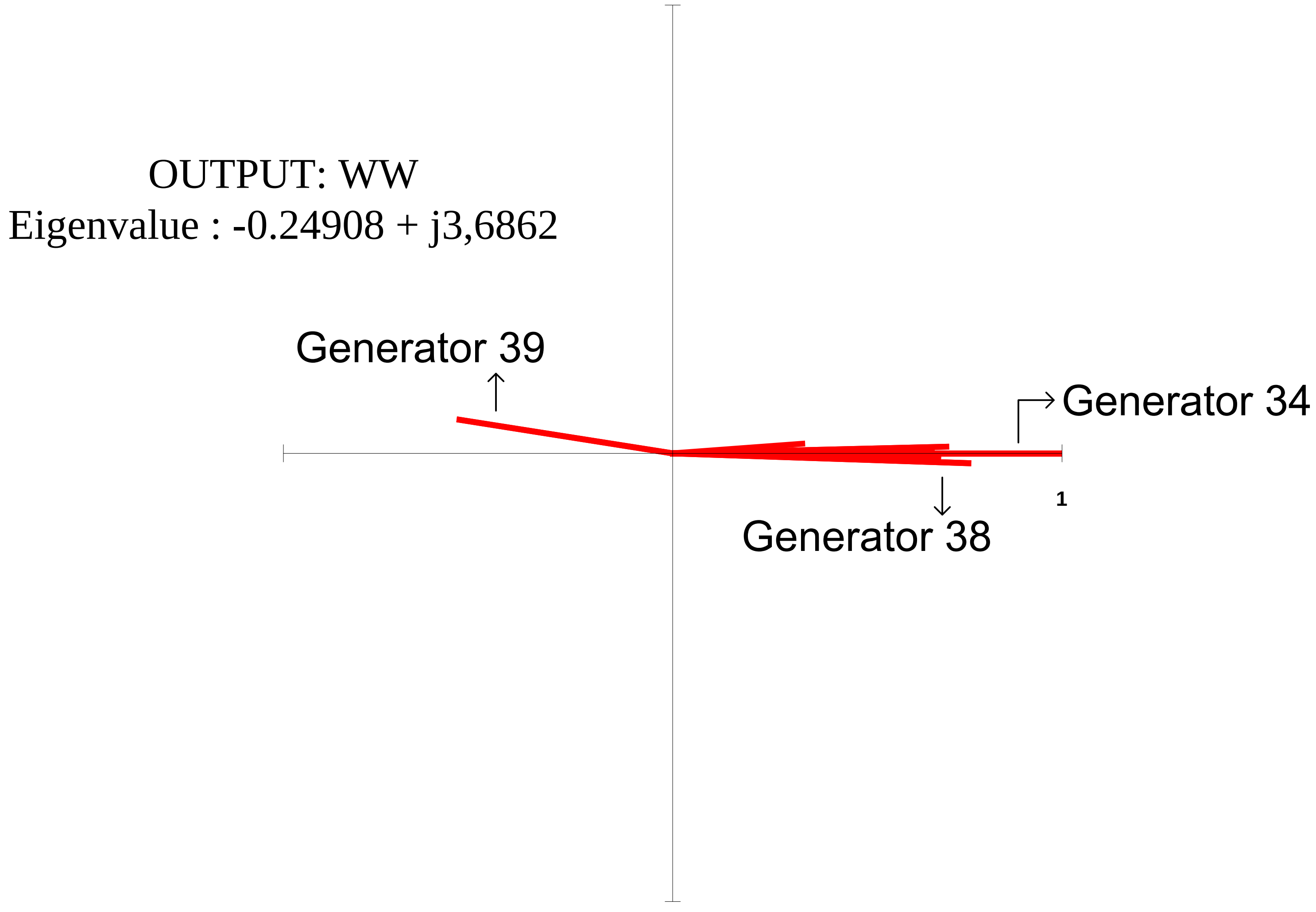
39 bus, 10-generator system has nine electromechanical modes and one mode of coherent return to “equilibrium” speed

New England System Eigenvalues

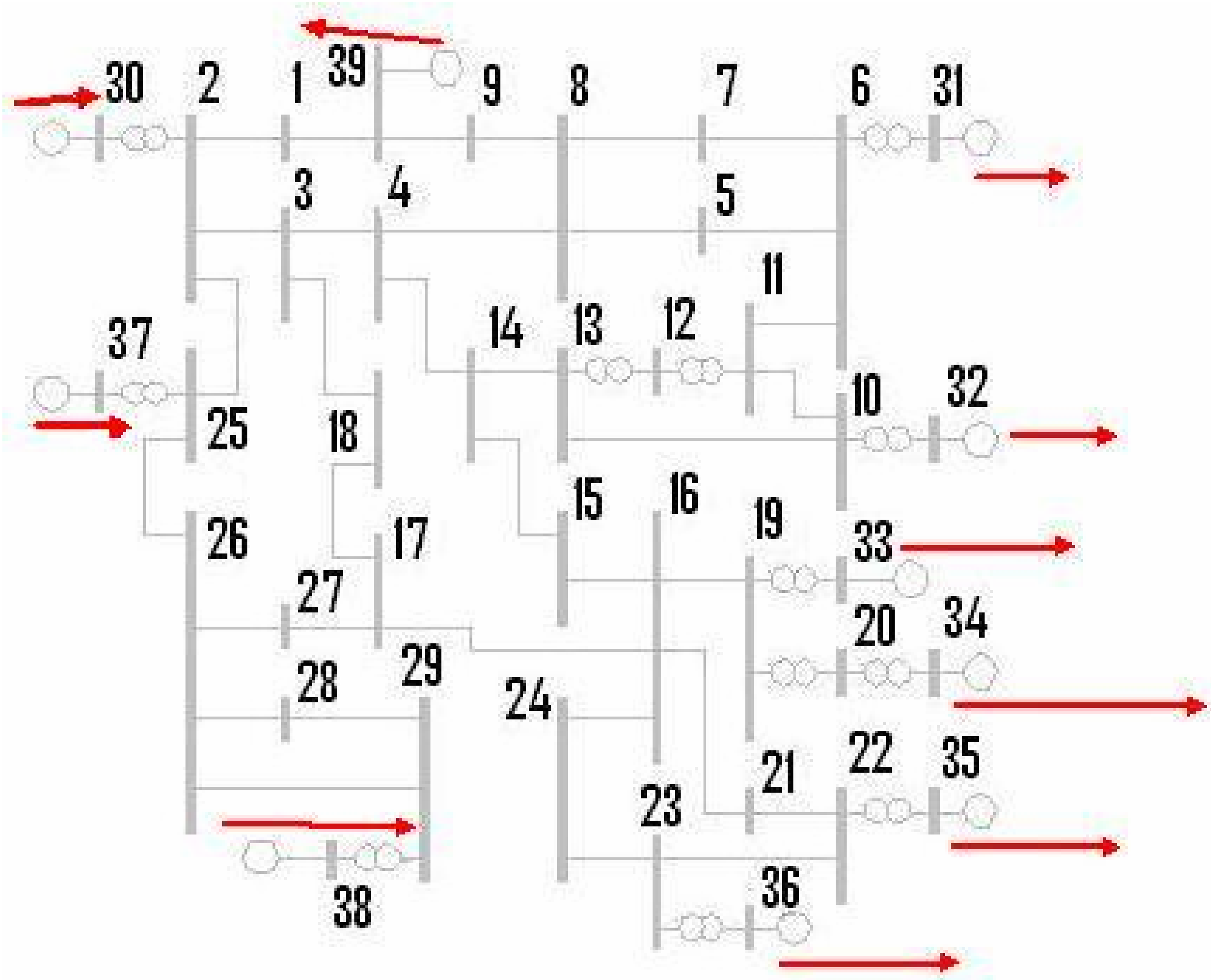
	Eigenvalue	Generators with Highest Participation
1	$-0.467 \pm j8.965$	36, 35
2	$-0.412 \pm j\,8.779$	37
3	$-0.370 \pm j\,8.611$	33
4	$-0.282 \pm j\,7.537$	32, 31
5	$-0.112 \pm j\,7.095$	30
6	$-0.297 \pm j\,6.956$	35, 36, 31
7	$-0.283 \pm j\,6.282$	31, 32, 34, 38
8	$-0.301 \pm j\,5.792$	38, 34
9	$-0.249 \pm j\,3.686$	39, 38, 34



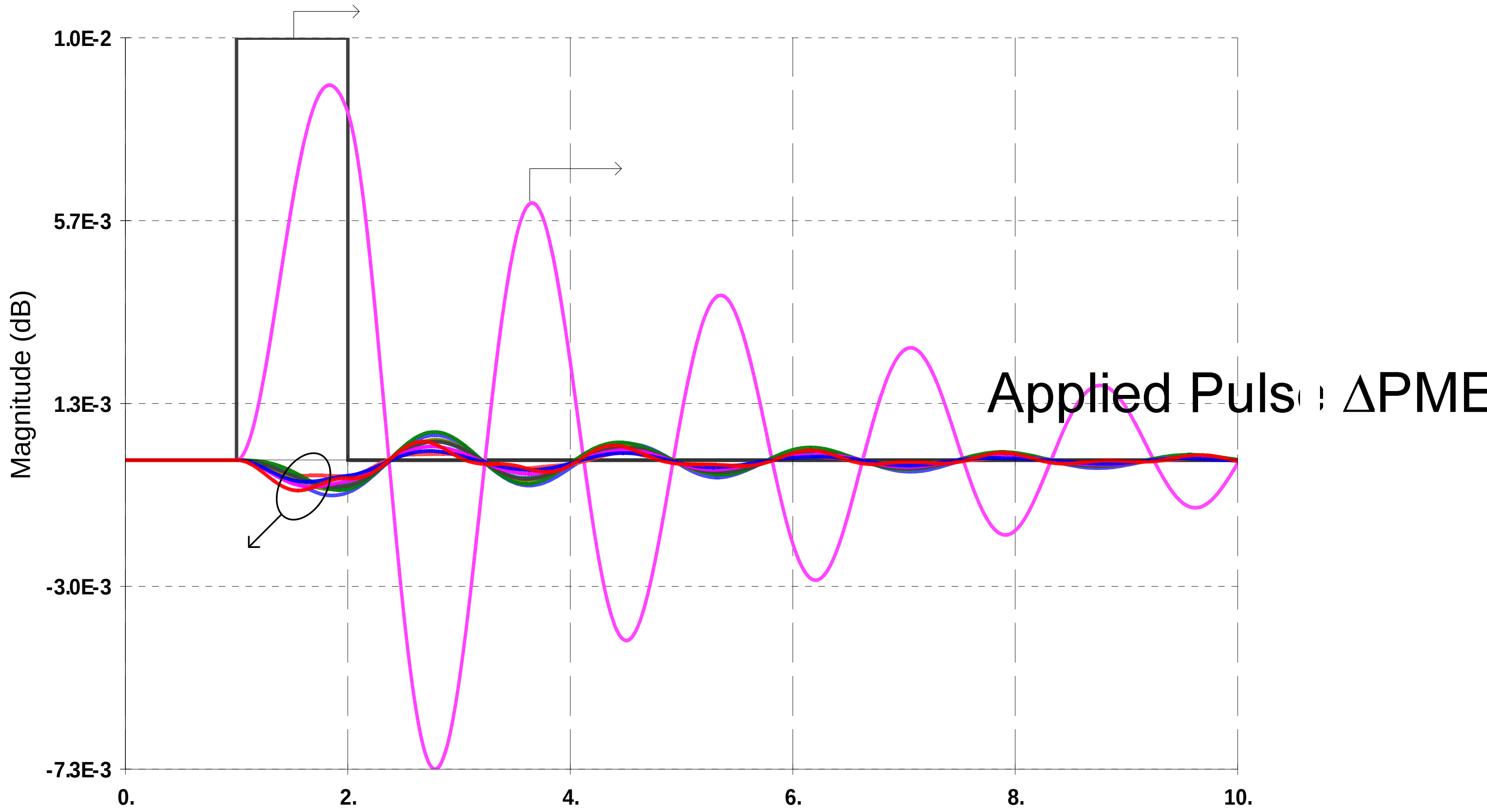
New England System – Rotor Speed Mode Shape (-.249+j3.68)



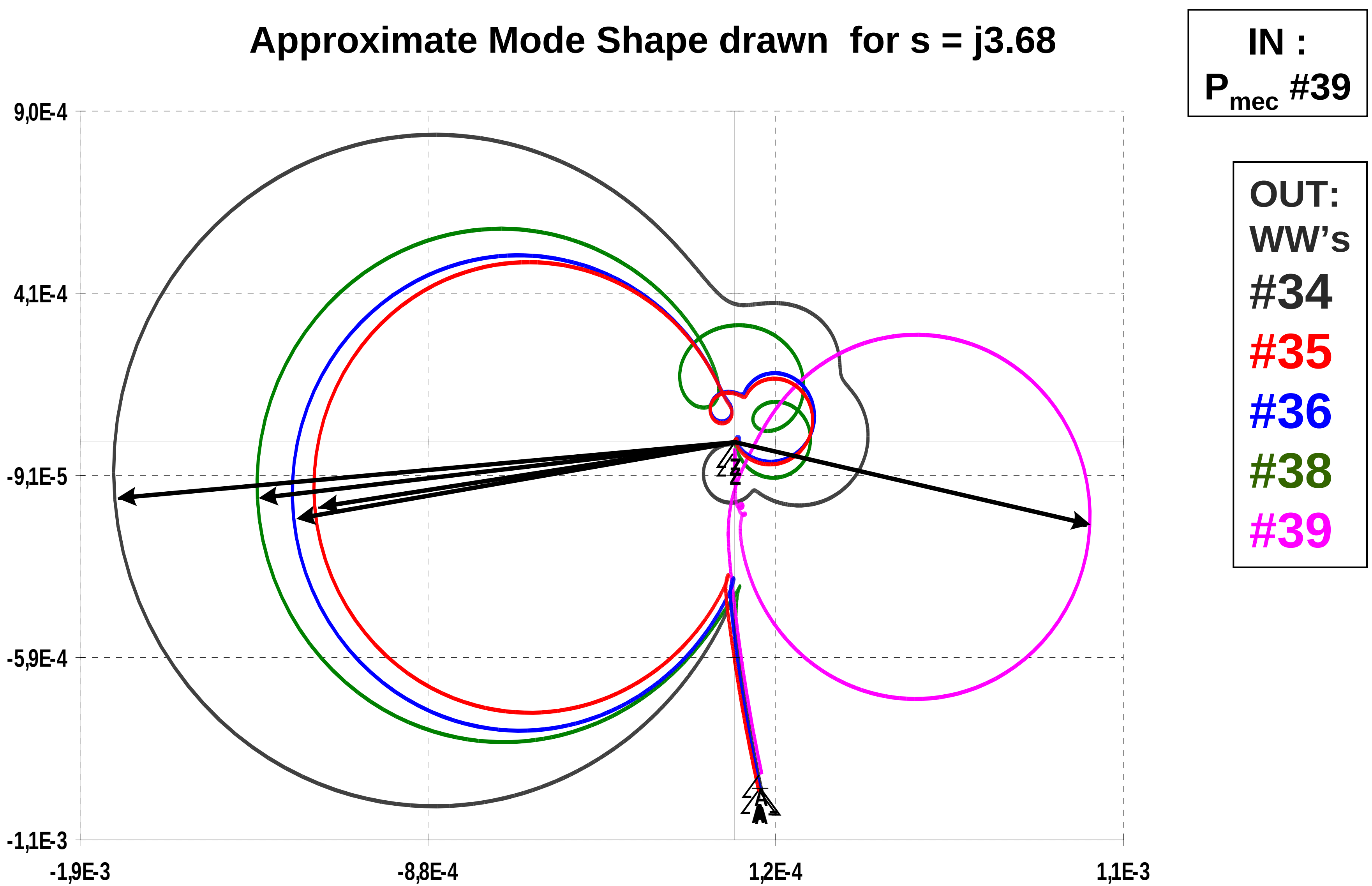
New England System Diagram with Rotor Speed Mode Shape (-.249+j6.28)



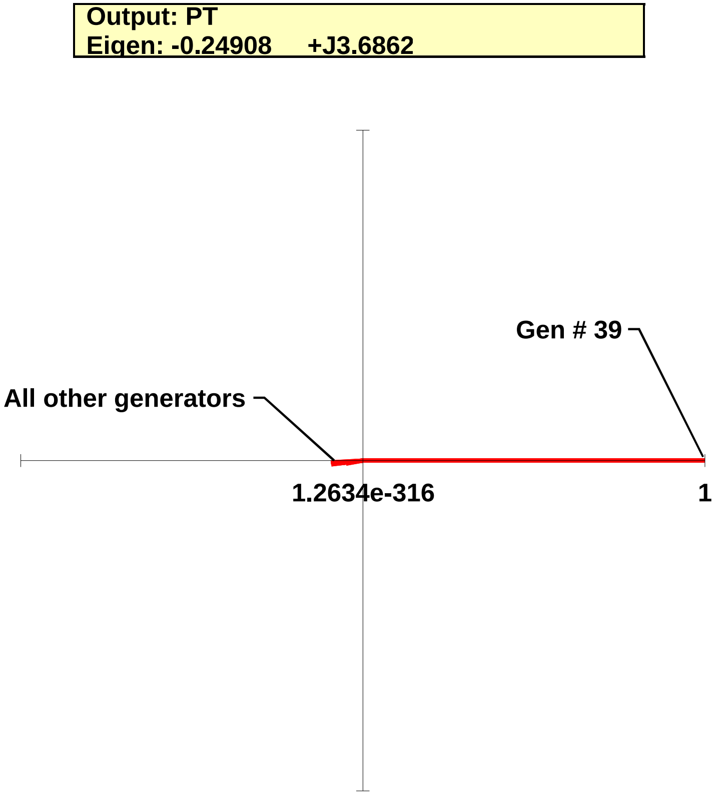
New Eng. Syst. – Generator Powers Ringdown following 1s Pulse in Pmec of Gen # 39



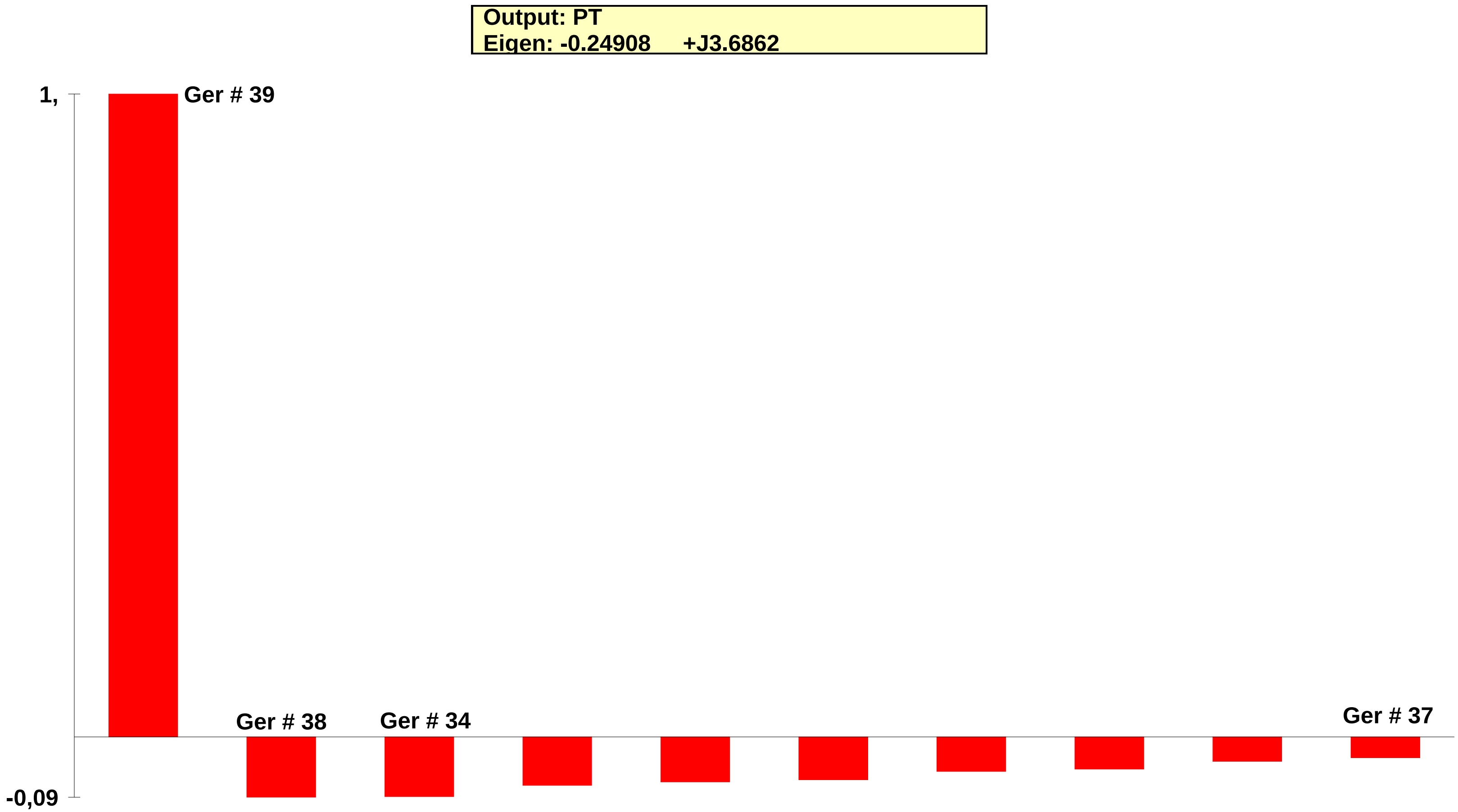
New England System – Polar Plots of Rotor Speeds for a Pmec # 39 Common Input



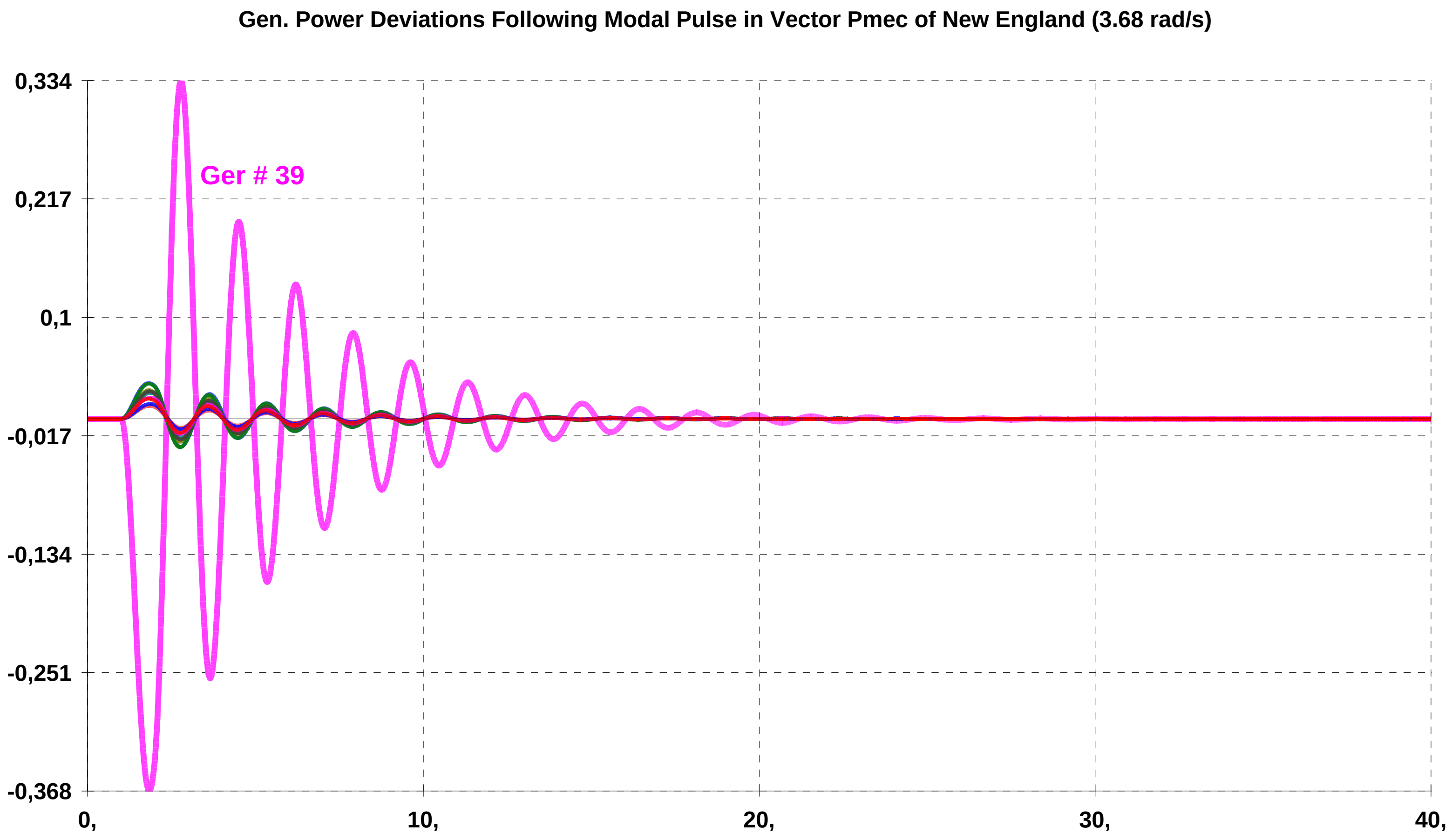
Generator Powers Mode-Shape for New England (-.249+j3.68)



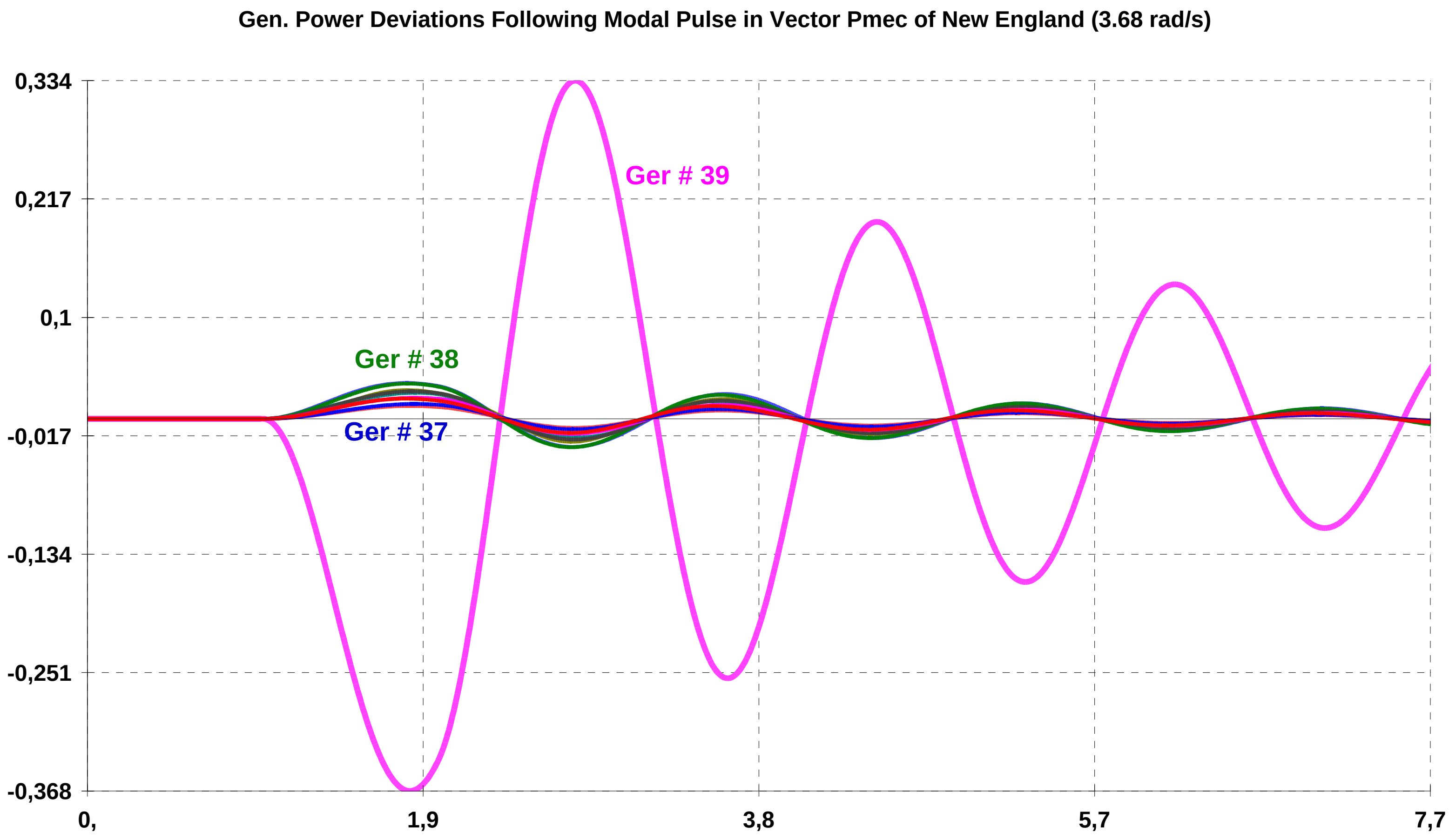
Mode-Shape of Generator Powers for New England (-.249+j3.68)



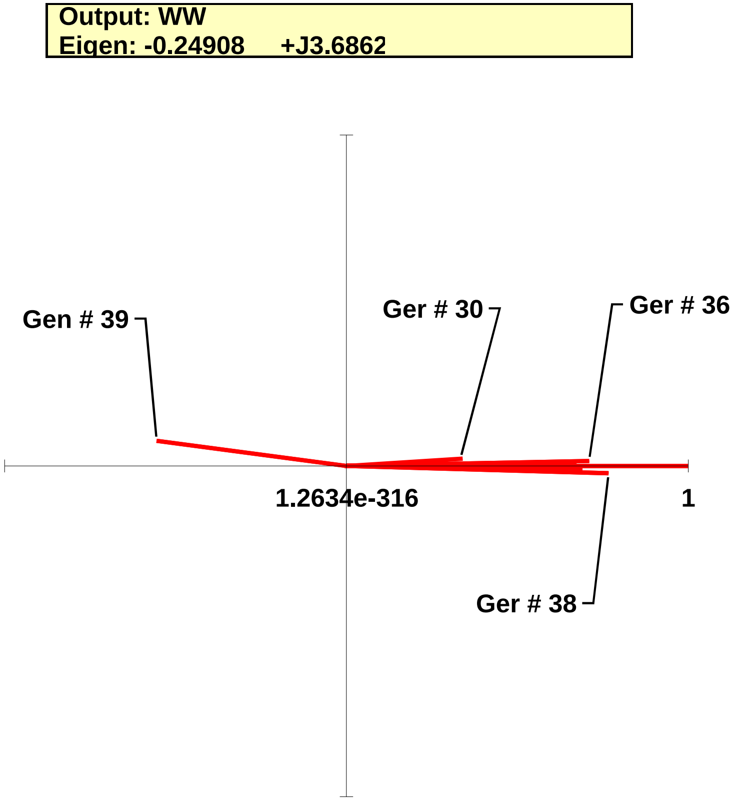
Gen. Powers Ringdown following a 1s Modal Pulse in vector Pmec (-.249+j3.68)



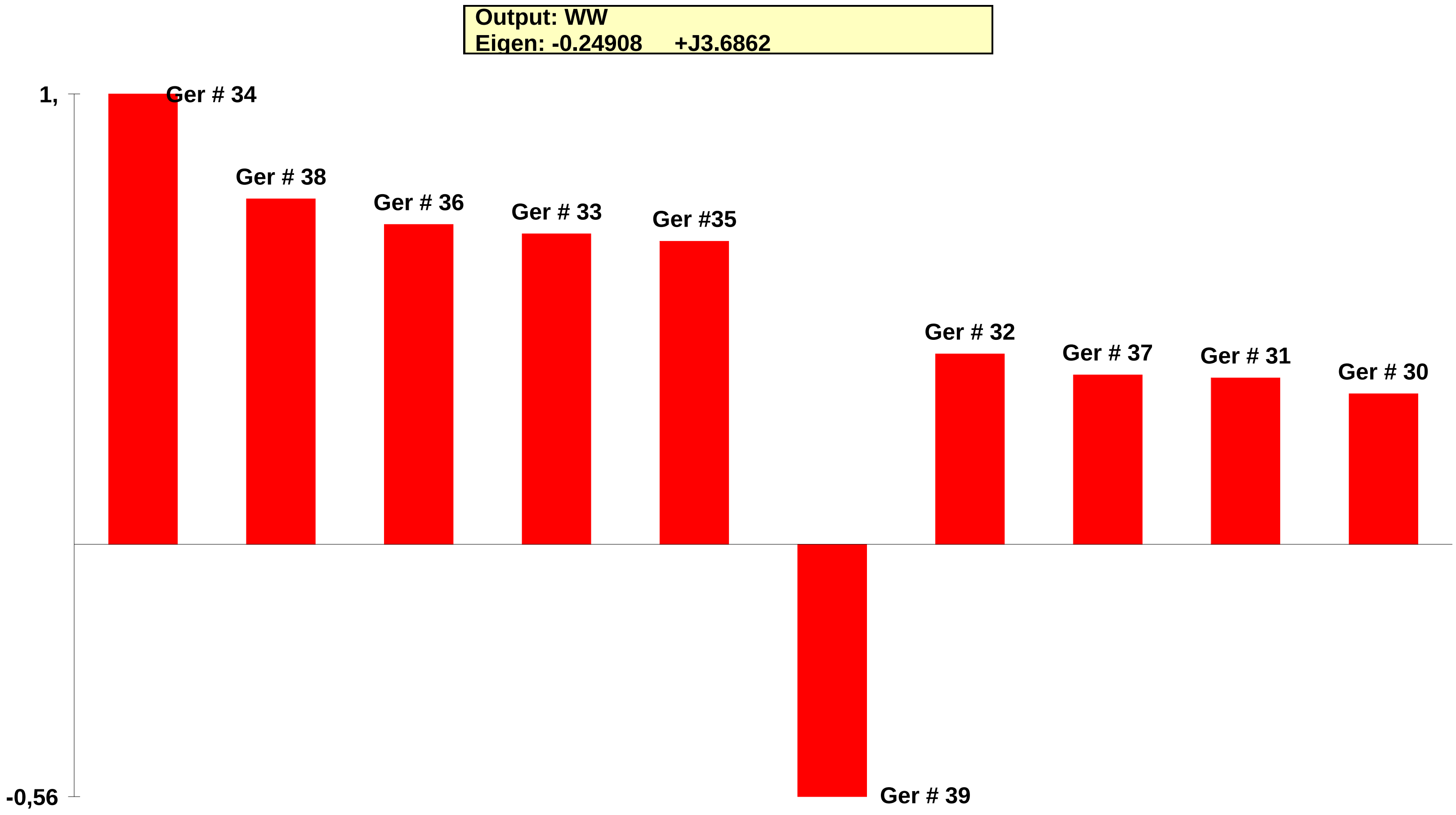
Gen. Powers Ringdown following a 1s Modal Pulse in vector Pmec (-.249+j3.68)



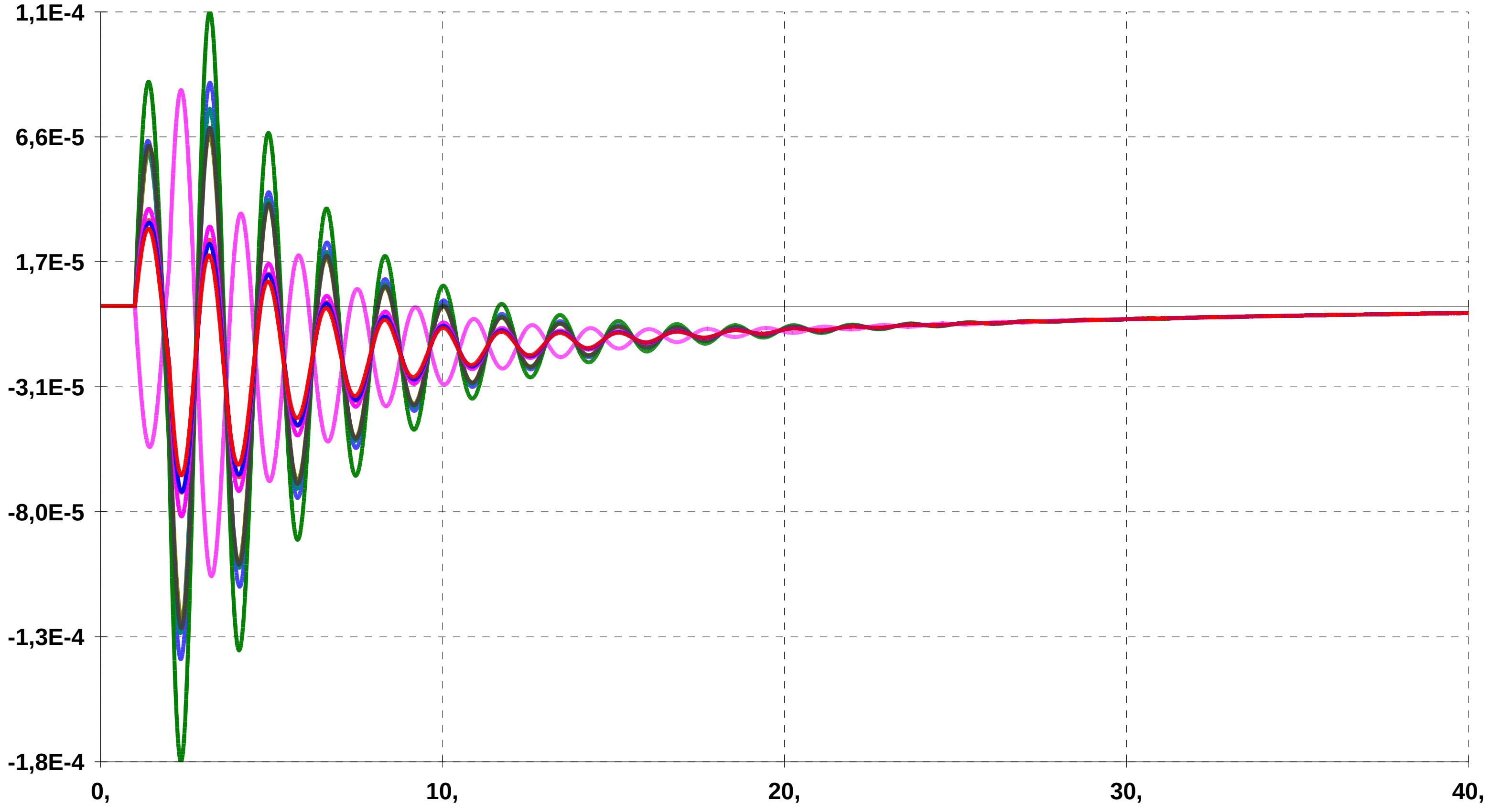
Rotor Speed Mode-Shape for New England (-.249+j3.68)



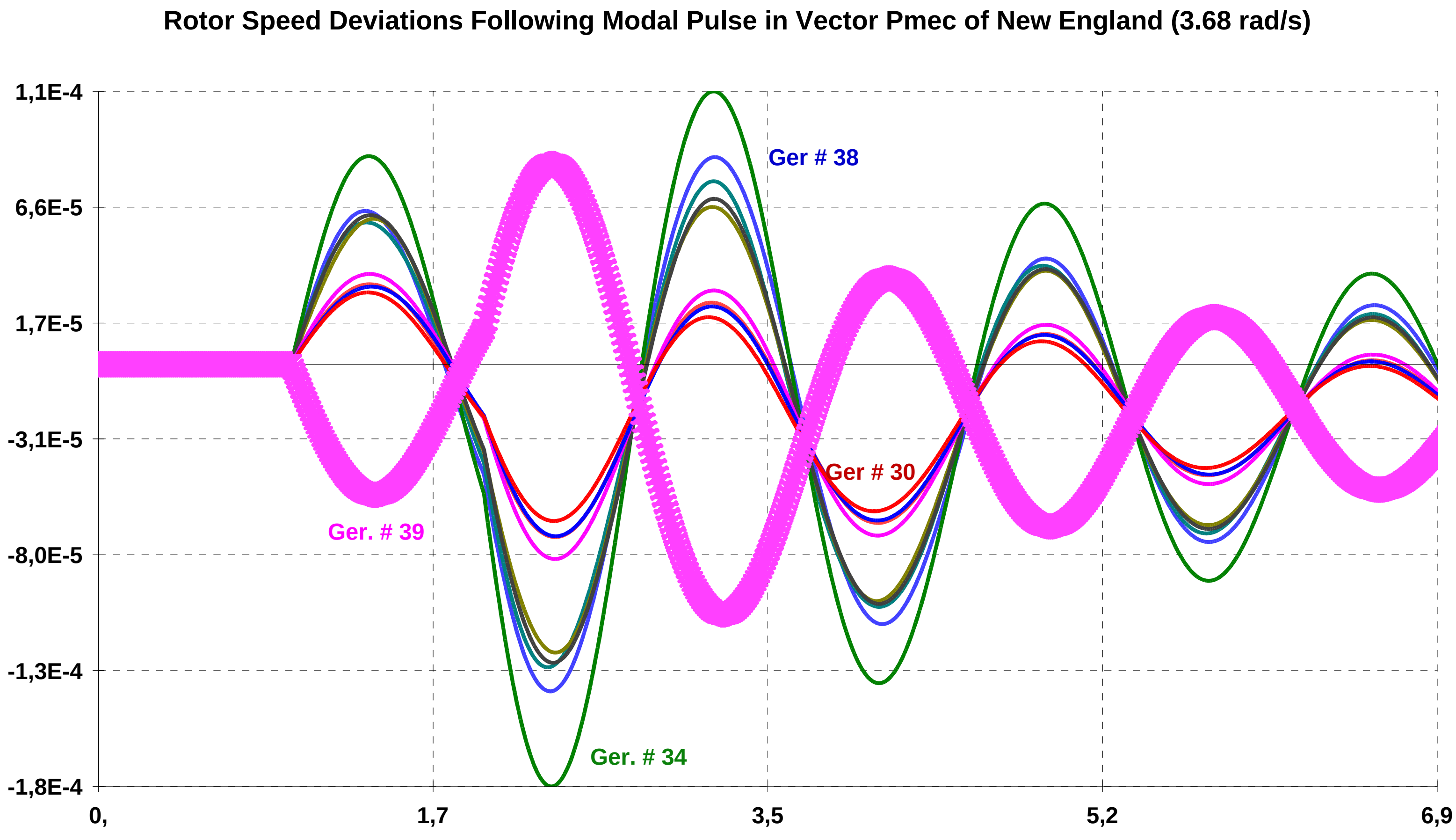
Rotor Speed Mode-Shape for New England (-.249+j3.68)



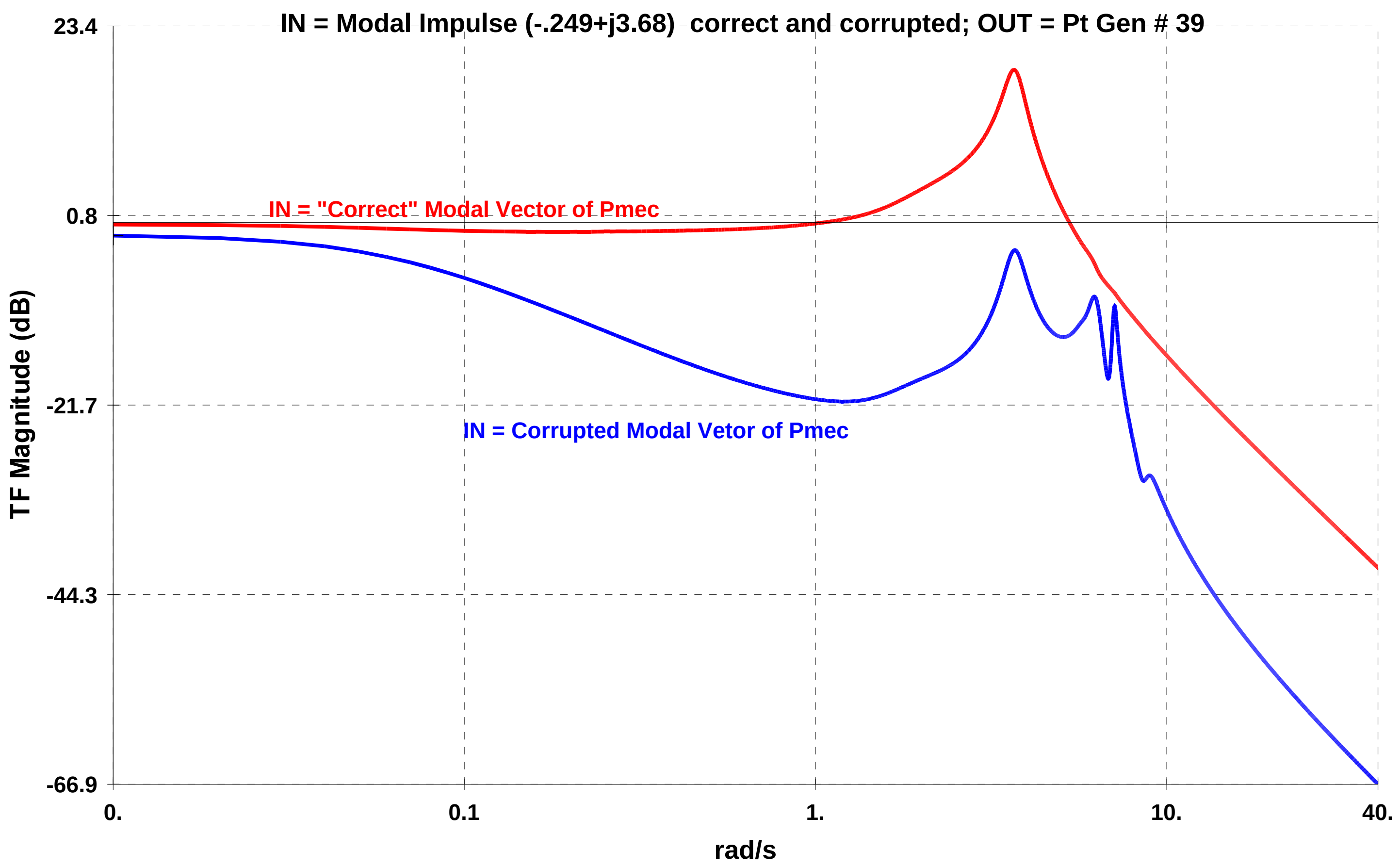
Rotor-Speeds Ringdown following a 1s Modal Pulse in vector Pmec (-.249+j3.68)



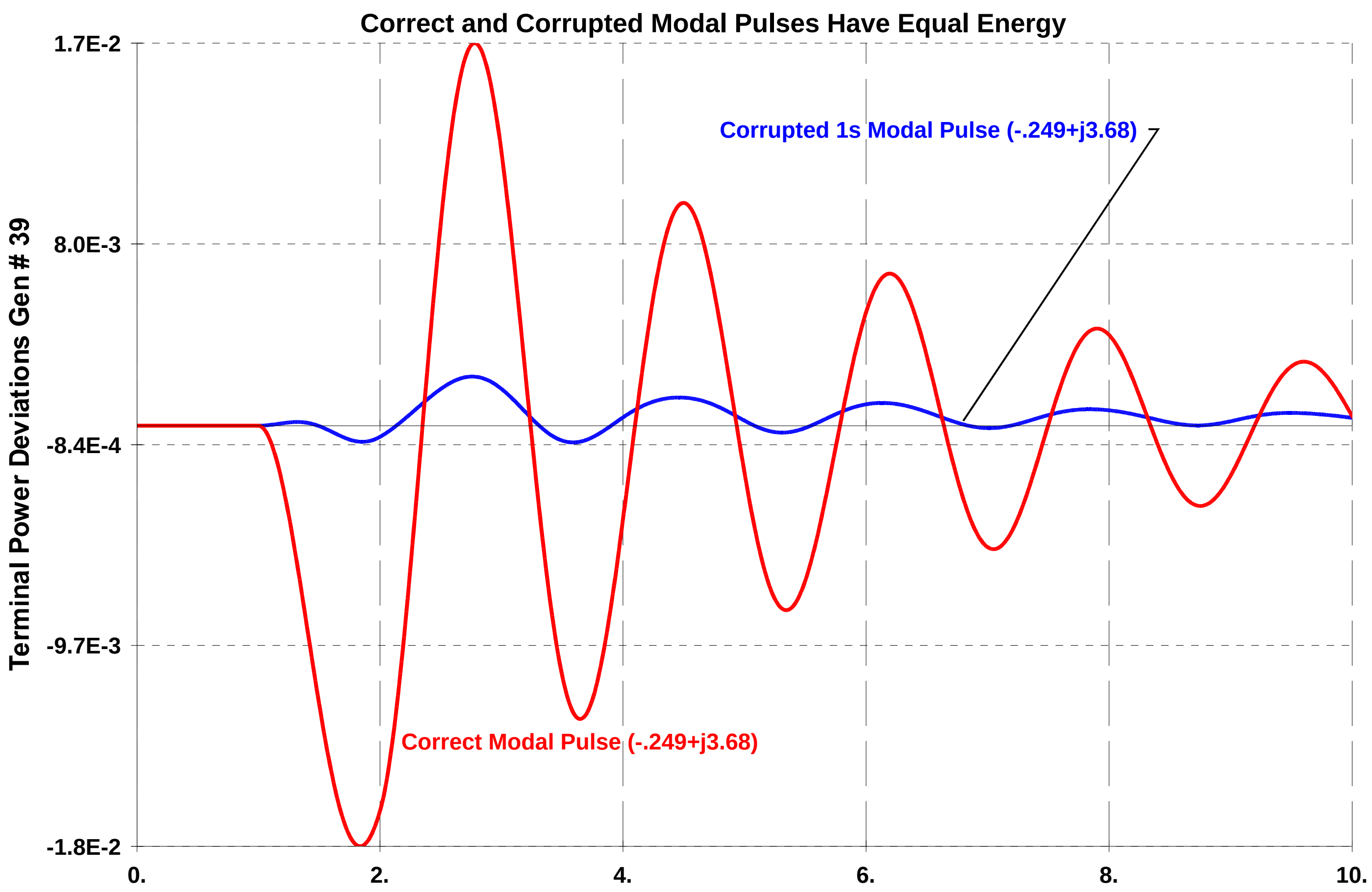
Rotor-Speeds Ringdown following a 1s Modal Pulse in vector Pmec (-.249+j3.68)



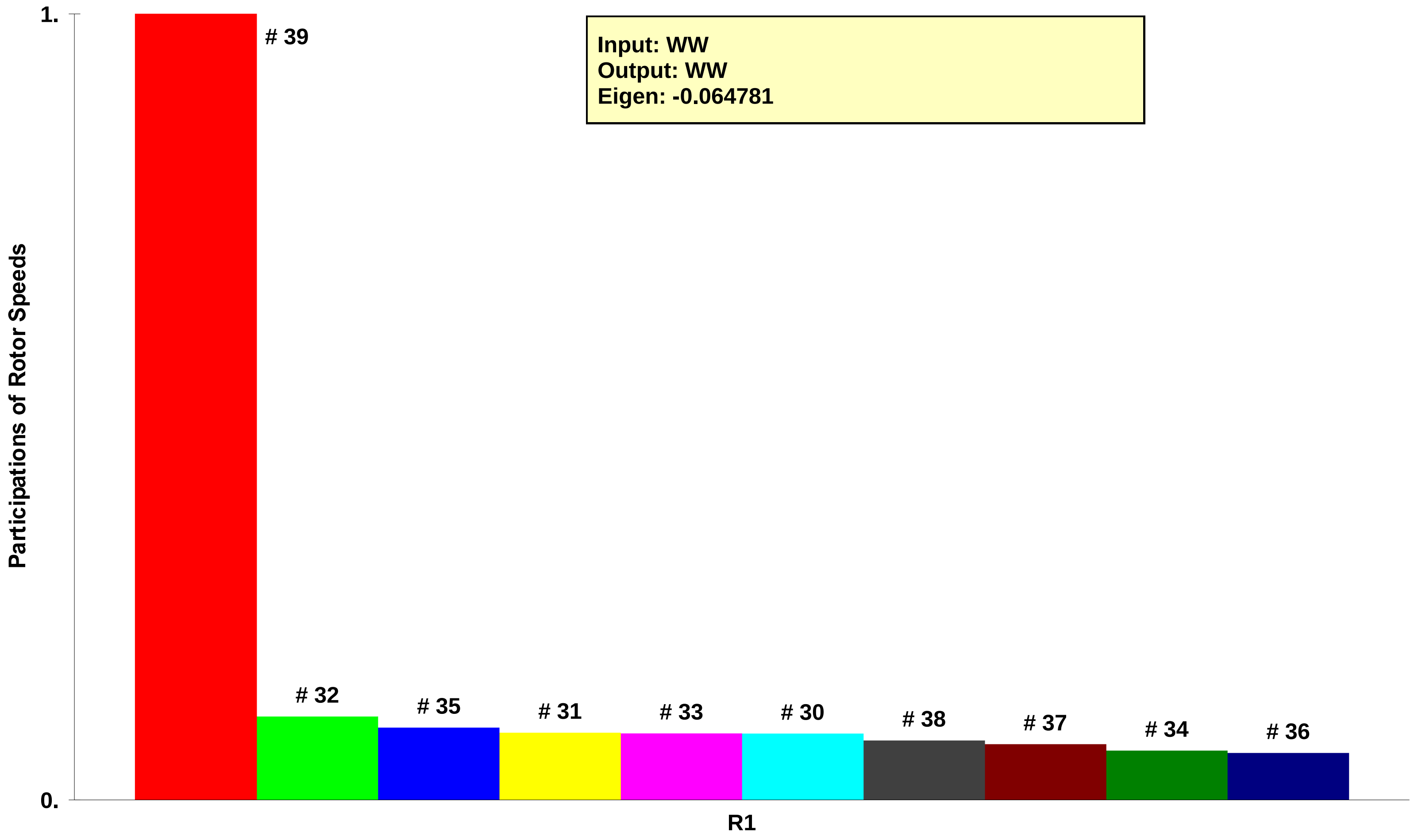
Bode Plots for Correct and Corrupted Modal Vector Inputs, considering OUT = Pt Gen # 39



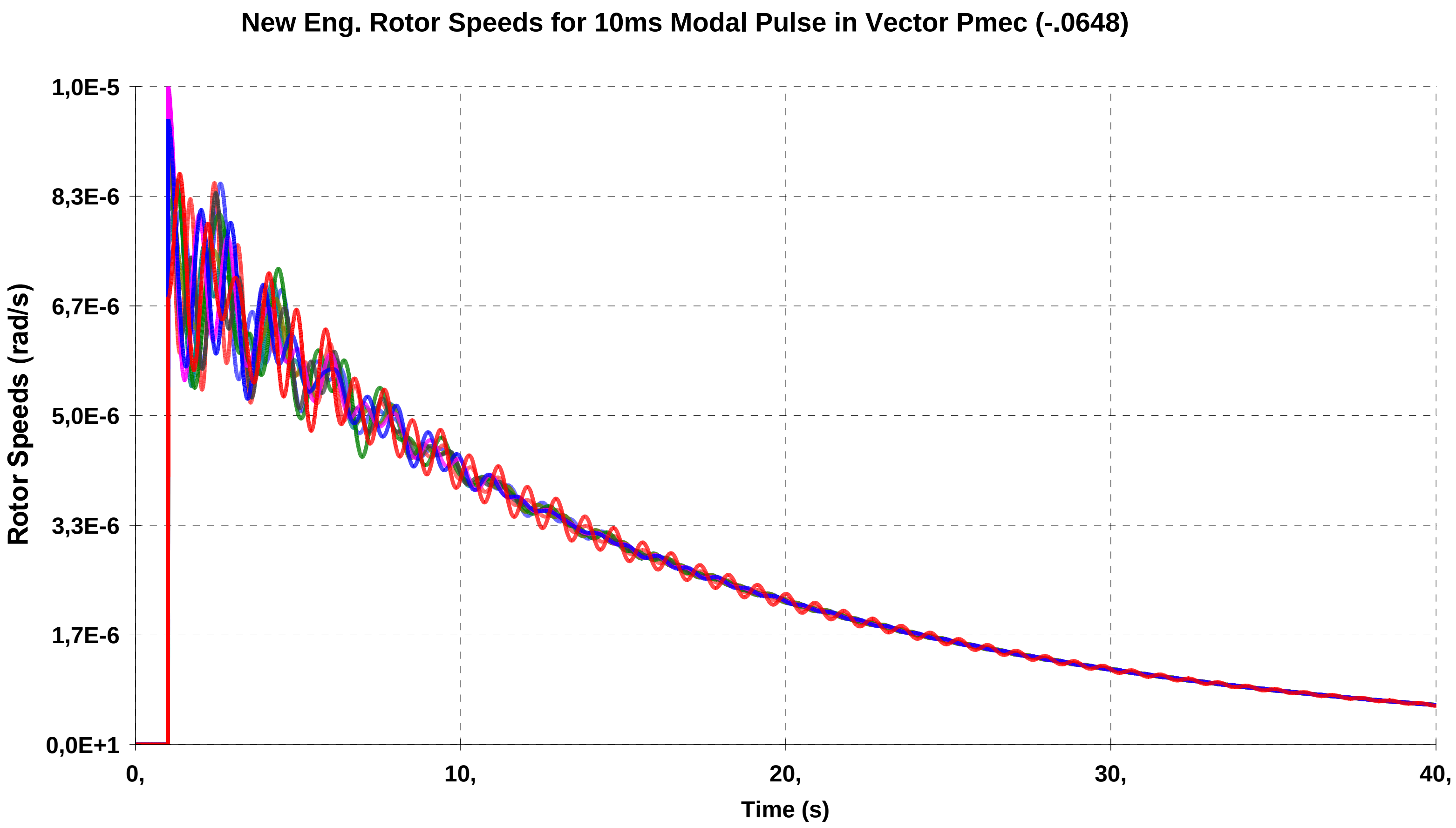
Gen. # 39 Power Deviations for 1s Modal Pulses (Correct and Corrupted)



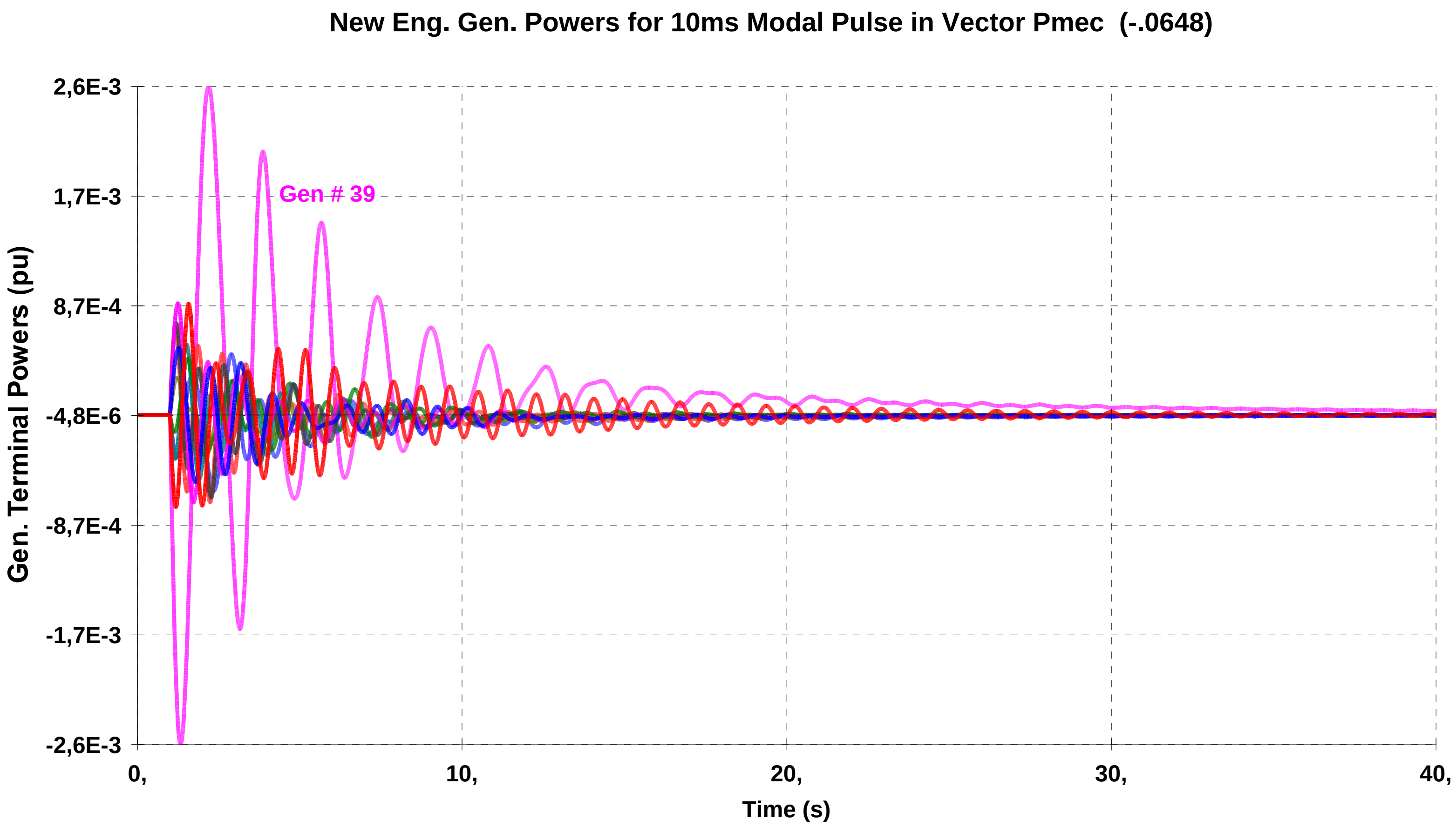
Participations of Rotor Speeds (-0.0647)



Rotor Speeds Ringdown following a 10ms Modal Pulse in Pmec (-.0648)



Gen. Powers Ringdown following a 10ms Modal Pulse in Pmec (-.0648)

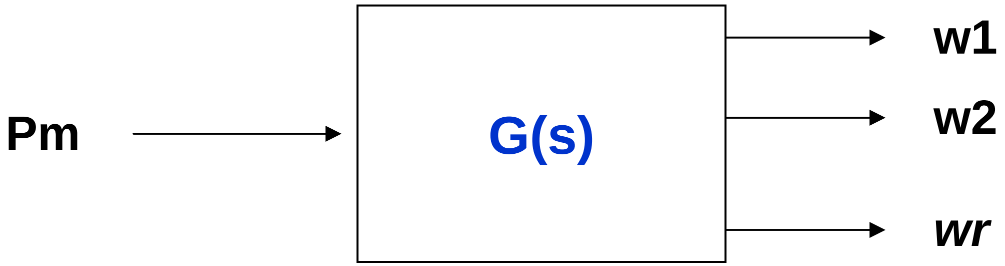


Mode-shape identification process

- WAMS comprises many functions to obtain, manage and process data (from various monitored variables) into valuable system information
- Data concentration → Phasor Data Concentrator (PDC) → advanced signal analysis computational procedures for time-tagged measurements
- TF residues → verification of modal dominance****
- Generator rotor speeds → PDC → main poles and mode-shapes may be computed****

Mode-shape identification process

- Single-input Multiple-output (SIMO) system



- Perturbation in the mechanical power *Pm* of a generator ➔ measurements of rotor speeds *w1, w2, …, wr*
- *G(s)* formed from the LTI system, where *u=Pm, y=[w1 w2 … wr]^T*

$$\dot{x}(t) = Ax(t) + Bu(t)$$
$$y(t) = Cx(t) + Du(t)$$

➔ $G(s) = C(sI - A)^{-1}B + D$

Identification of a SISO TF

- Let *H(z)* be the truncated *z*-transform of a discrete sequence h(k), k=0,1,…,M (samples)

$$H(z) = \frac{Y(z)}{U(z)} = \sum_{k=0}^{M} h_k z^{-k}$$

- Approximations → by rational function *N*<<*M*

$$\widehat{H}(z) = \frac{a_0 + a_1 z^{-1} + \cdots + a_{N-1} z^{-(N-1)}}{1 + b_1 z^{-1} + b_2 z^{-2} + \cdots + b_N z^{-N}}$$

$$\widehat{H}(z) = z \left\{ \frac{a_0 z^{(N-1)} + a_1 z^{(N-2)} + \cdots + a_{(N-1)}}{z^N + b_1 z^{(N-1)} + \cdots + b_N} \right\}$$

Identification of a SISO TF

- Structure of TF in terms of poles and residues

$$H(z) = z\left\{\sum_{i=1}^{Nc}\left[\frac{\gamma_1^i z + \gamma_0^i}{z^2 + \alpha_1^i z + \alpha_0^i}\right] + \sum_{i=1}^{Nr}\left[\frac{\rho_i}{z - p_i}\right]\right\}$$

- Nc=number of complex poles
- Nr=mumber of real poles

$\gamma_1^i,\ \gamma_0^i,\ \alpha_1^i,\ \alpha_0^i,\ \rho_i$ and p_i are parameters to be determined

- After determining a_i and b_i , compute

$$\gamma_1^i,\ \gamma_0^i,\ \alpha_1^i,\ \alpha_0^i,\ \rho_i \text{ and } p_i$$

Identification of a SISO TF

- Equivalent form of *H(z)* in the time domain

$$y(k) = -\sum_{j=1}^{N} b_j y(k-j) + \sum_{i=1}^{N-1} a_i u(k-i) + \xi(k), \quad k = 0, 1, \ldots, M$$

- The quantity $\xi(k)$ can be interpreted as a deviation between the effective measurement and the approximated value, at each sample *k*
- Problem:

  Minimize the function $\xi^T \xi$ for $k=0,1,\ldots,M$

Identification of a SISO TF

- Problem statement:

Minimize the function $\xi^T \xi$ for *k=0,1,…,M*

- Solution: $$\widehat{\theta} = (\mathbf{A}_y^T \mathbf{A}_y)^{-1} \mathbf{A}_y^T \mathbf{b}_y$$

- where $$\widehat{\theta} = [b_1\ b_2 \dots b_N\ a_0\ a_1\ \dots\ a_{N-1}]^T$$

$$\mathbf{b}_y = [y_k\ y_{k+1}\ y_{k+2}\ \dots\ y_M]^T$$

$$\mathbf{A}_y = \begin{bmatrix} -y_{k-1} & -y_{k-2}\cdots & u_k & u_{k-1}\cdots \\ -y_k & -y_{k-1}\cdots & u_{k+1} & u_k\cdots \\ \vdots & \vdots & \vdots & \vdots \\ -y_{M-1} & -y_{M-2}\cdots & u_M & u_{M-1}\cdots \end{bmatrix}$$

Identification of a SIMO TF

- We assume that each pair input-output produces a TF $H_i(z)$, $I=1,2,\ldots,r$
- SIMO TF

$$\widehat{H}(z) = [\widehat{H}_1(z)\ \widehat{H}_2(z)\ \ldots\ \widehat{H}_r(z)]^T$$

- The *ith* output can be put as

$$\widehat{Y}_i(z) = \widehat{H}_i(z)U(z) = z\frac{P_i(z)}{Q(z)}U(z), \quad i = 1, 2, \ldots, r$$

- In the discrete time domain

$$y_i(k) = -\sum_{j=1}^{N} b_j y_i(k-j) + \sum_{q=1}^{N-1} a_{qi} u(k-q) + \xi_i(k)$$

Identification of a SIMO TF

- Now, the *i*th output contributes with $\xi_i(k)$ for *k=0,1,…,M* and *i=1,2,…,r*

- We must minimize all contributions of the type $\xi_i^T \xi_i$

Problem statement:

$$Minf(\widehat{\theta}) = \sum_{j=1}^{r} \sum_{k=1}^{M} \xi_i(k)^2$$

where

$$\widehat{\theta} = [b_1\, b_2 \ldots b_N\, a_{01}\, a_{11}\, \ldots\, a_{(N-1)1} \ldots a_{0r}\, a_{1r}\, \ldots a_{(N-1)r}]^T$$

Transformation from z to s-domain

- Mapping function $z_i = e^{s_i T}$ where *T* is the sampling time, s_i is a pole in the *s*-domain

- For the *i*th output

$$H_i(s) = \sum_{j=1}^{\overline{N}c} \left[\frac{\overline{\gamma}_1^{ij} s + \overline{\gamma}_0^{ij}}{s^2 + \overline{\alpha}_1^j s + \overline{\alpha}_0^j} \right] + \sum_{k=1}^{\overline{N}r} \left[\frac{\overline{\rho}_{ik}}{s - \lambda_k} \right]$$

where

$$\overline{\gamma}_1^{ij}, \overline{\gamma}_0^{ij}, \overline{\alpha}_1^j, \overline{\alpha}_0^j, \overline{\rho}_{ik} \text{ and } \lambda_k$$

are calculated from the poles and residues of $H_i(z)$

- For $s=jw$ it is possible to compute a value for $H_i(jw)$ and values for specific frequencies w_k ➔ value of $H_i(jw_k)$ ➔ idea of approximated mode-shape

Tests and results

- 39-bus 10-generator New England system
- Input: pulse at the mechanical power of a generator
- Output: speed deviation at each generator

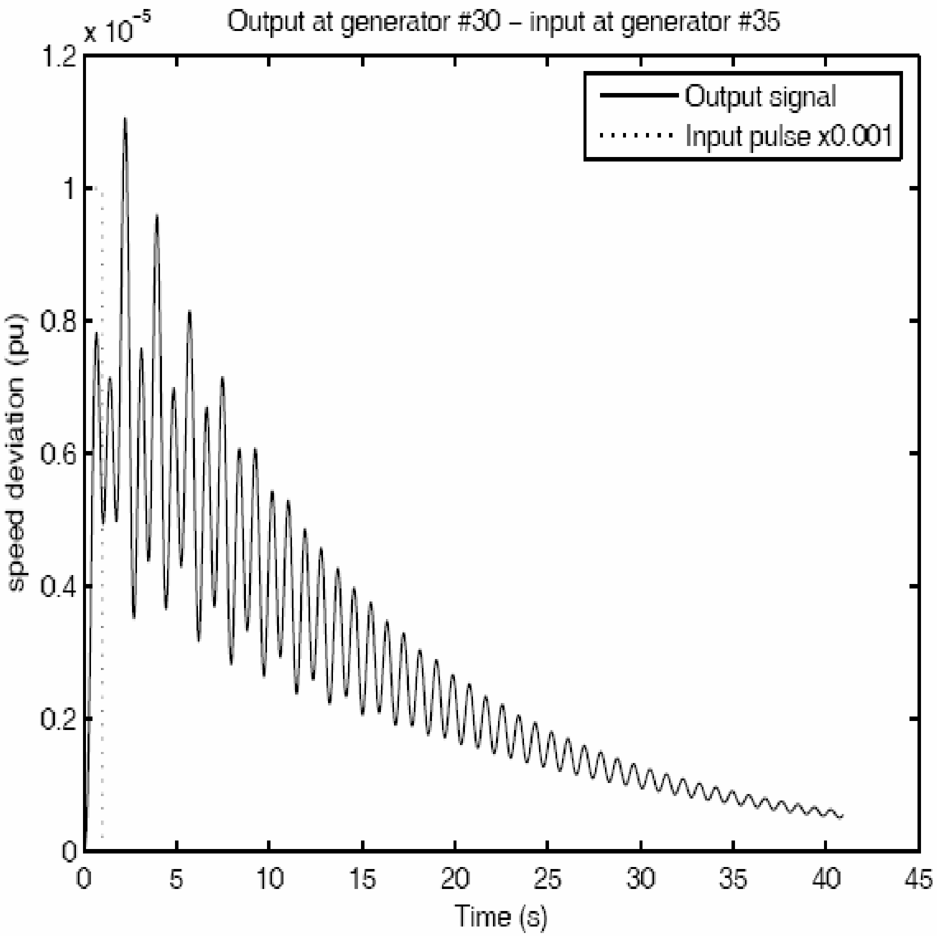
- The pulse has amplitude equal to 0.01 pu and duration of 1 s.
- perturbations are used at the generators #35, #36, or #39 and always 10 output speed deviation signals are identified.
- Each impulse response $H_i(s)$ (due to input applied and the i^{th} output observed) is identified

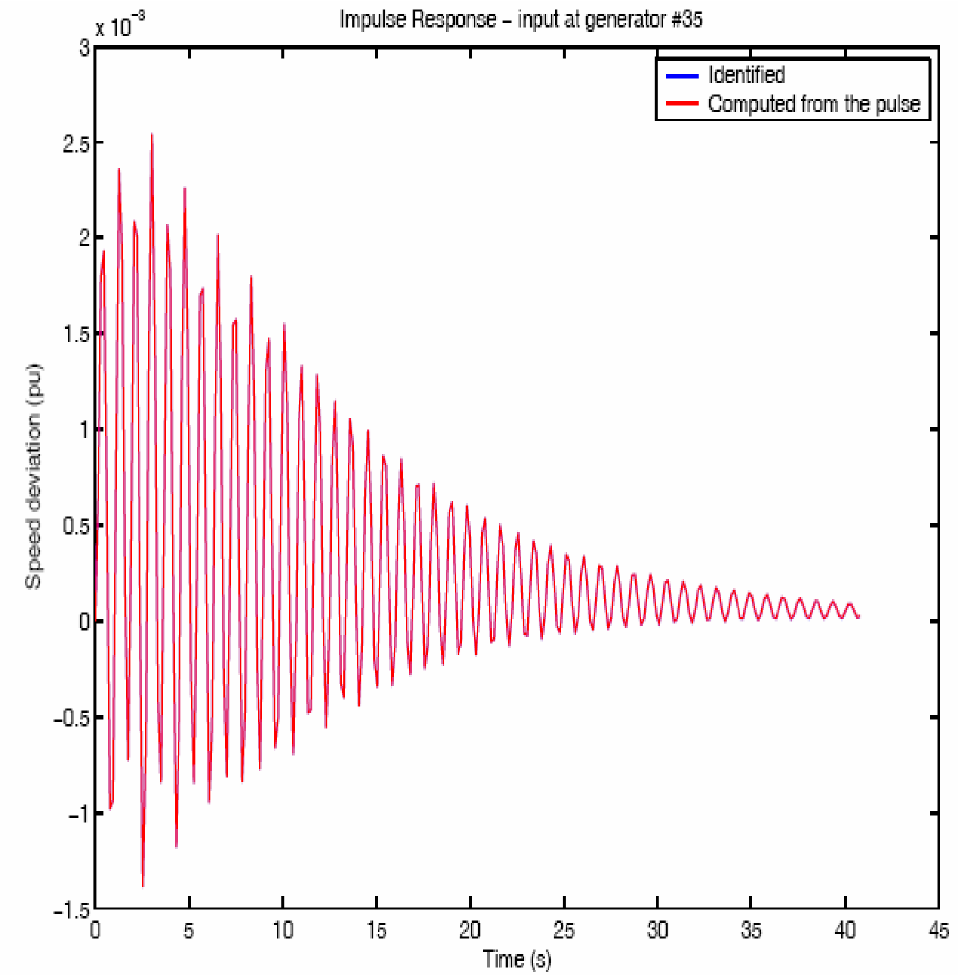
Tests and results

- There is a mode of frequency equal to 3.68 rad/s, which is dominant for all impulse responses.
- The full model (exact) has 65 states. It was used to generate time responses and for comparing results obtained by using the approximate model
- A 27- state model has been identified

Tests and results

- **Perturbation at the generator #35 and output at the generator #30 : output (black) and impulse response computed (identified (blue) and exact (red))**





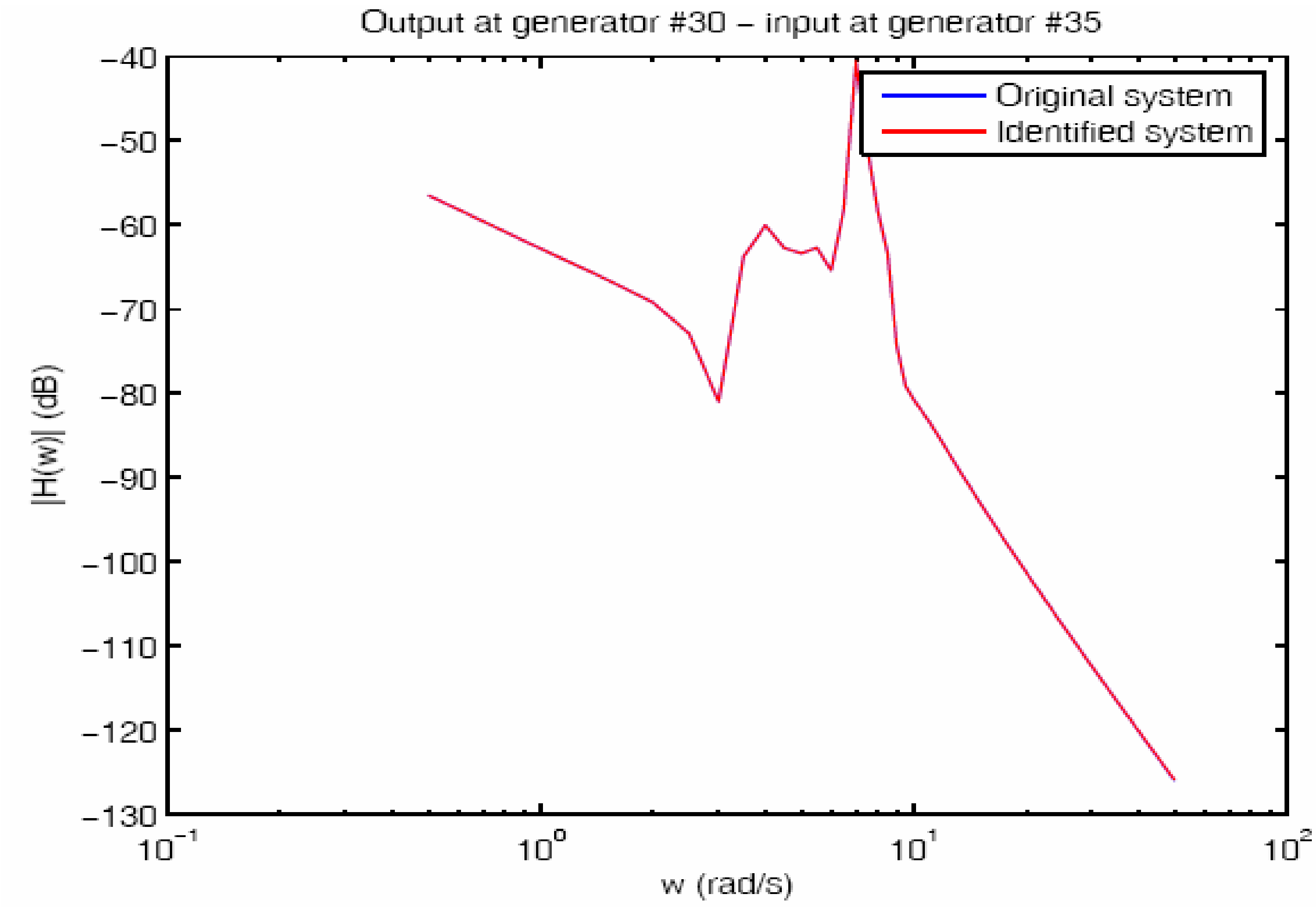
Tests and results

- **Dominant eigenvalues for two tests: perturbation at the generator #35 and at the #36 – all output signals are used to compute an 1-input 10-output 27-state SIMO reduced system model**

mode	input #35	input #36	Exact
1	-0.249 ± 3.686	-0.249 ± 3.686	-0.249 ± 3.686
2	-0.112 ± 7.092	-0.112 ± 7.092	-0.119 ± 7.095
3	-0.281 ± 7.533	-0.281 ± 7.533	-0.282 ± 7.537
4	-0.301 ± 5.791	-0.300 ± 5.791	-0.301 ± 5.792
5	-0.283 ± 6.279	-0.281 ± 6.279	-0.283 ± 6.282
6	-0.296 ± 6.954	-0.295 ± 6.955	-0.297 ± 6.956
7	-0.370 ± 8.606	-0.370 ± 8.606	-0.370 ± 8.611
8	-0.413 ± 8.771	-0.411 ± 8.773	-0.412 ± 8.779
9	-0.466 ± 8.959	-0.466 ± 8.959	-0.467 ± 8.964
10	-0.786 ± 1.874	-0.750 ± 1.832	-0.729 ± 1.771
11	-0.067	-0.067	-0.067

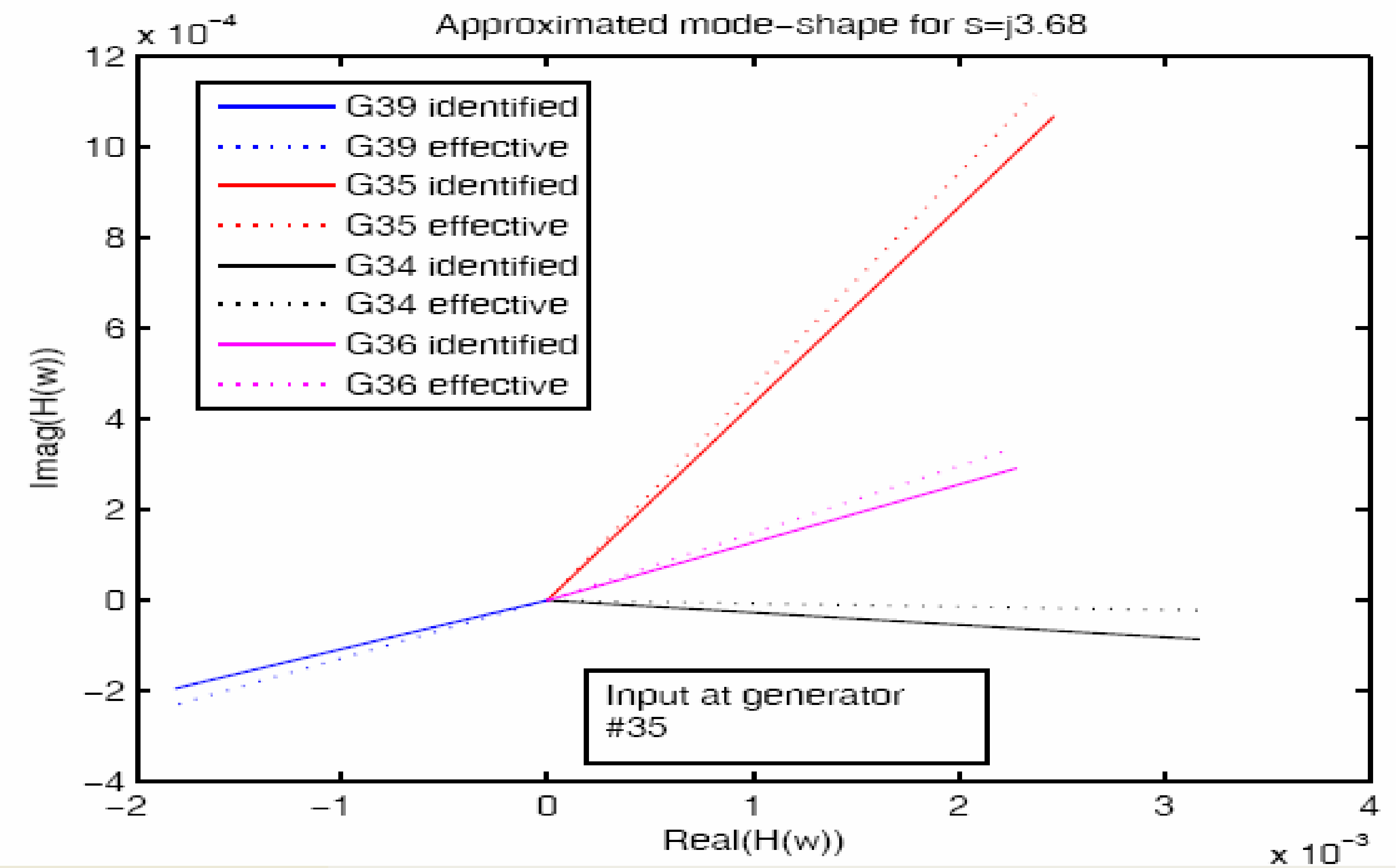
Tests and results

- **Test: perturbation at the generator #35 - magnitude of TF**



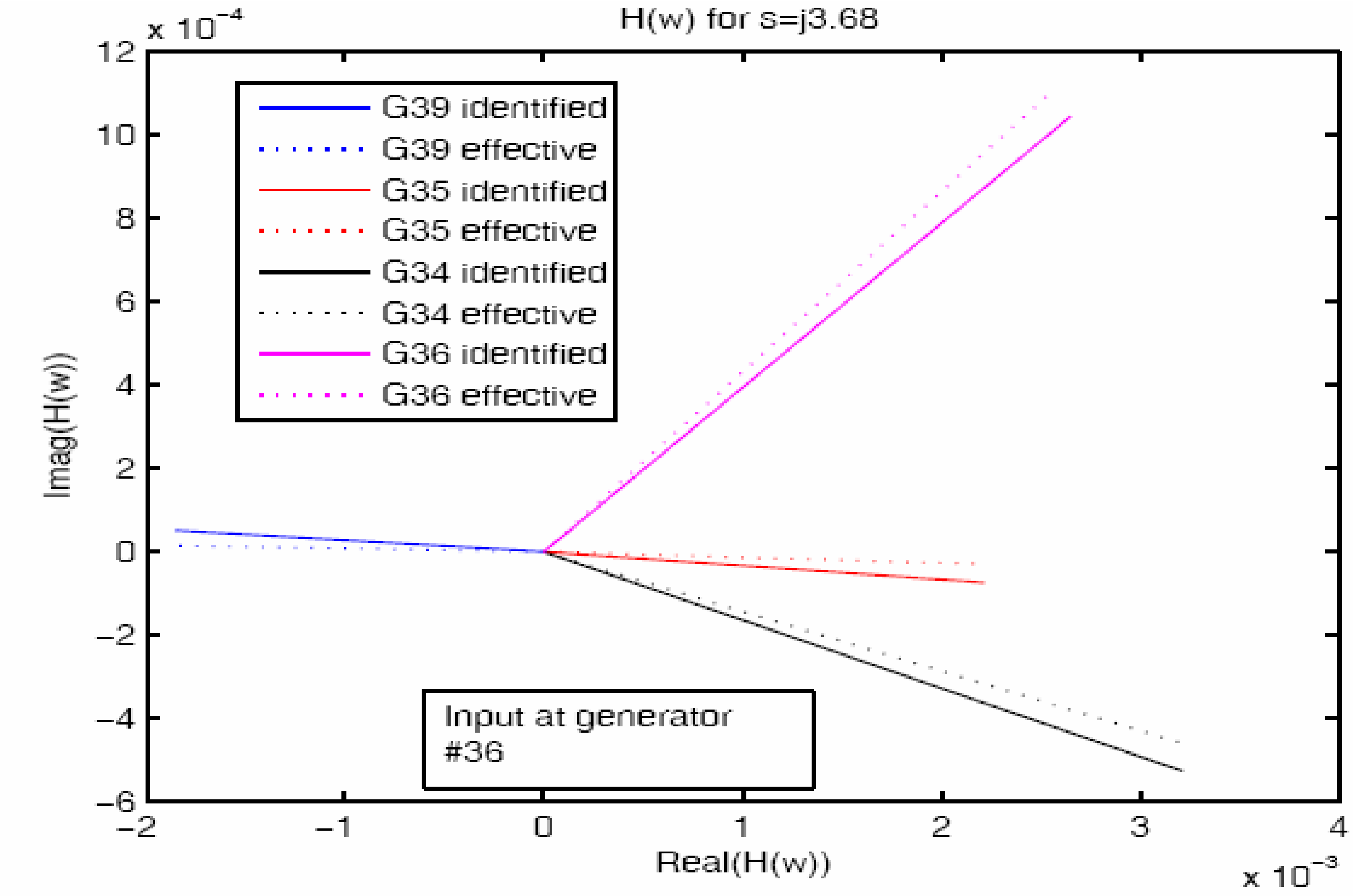
Tests and results

- **Test: perturbation at the generator #35 - values of *real(H_i(j3.68))* and *imag(H_i(j3.68))* – effective and identified =>** **approximated mode-shapes**



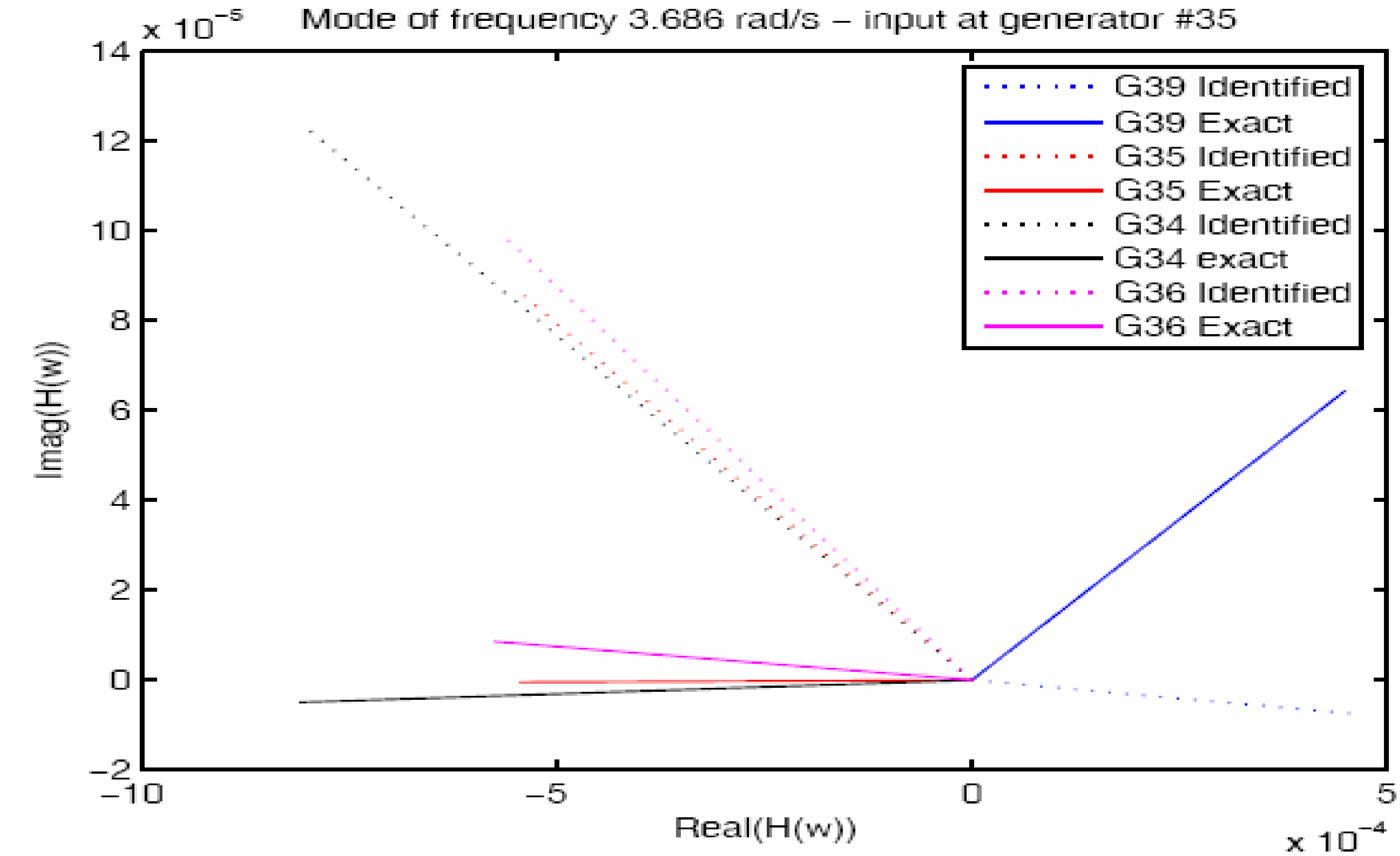
Tests and results

- **Test: perturbation at the generator #36 - values of *real(H_i(j3.68))* and *imag(H_i(j3.68))* – effective and identified =>** **approximated mode-shapes**



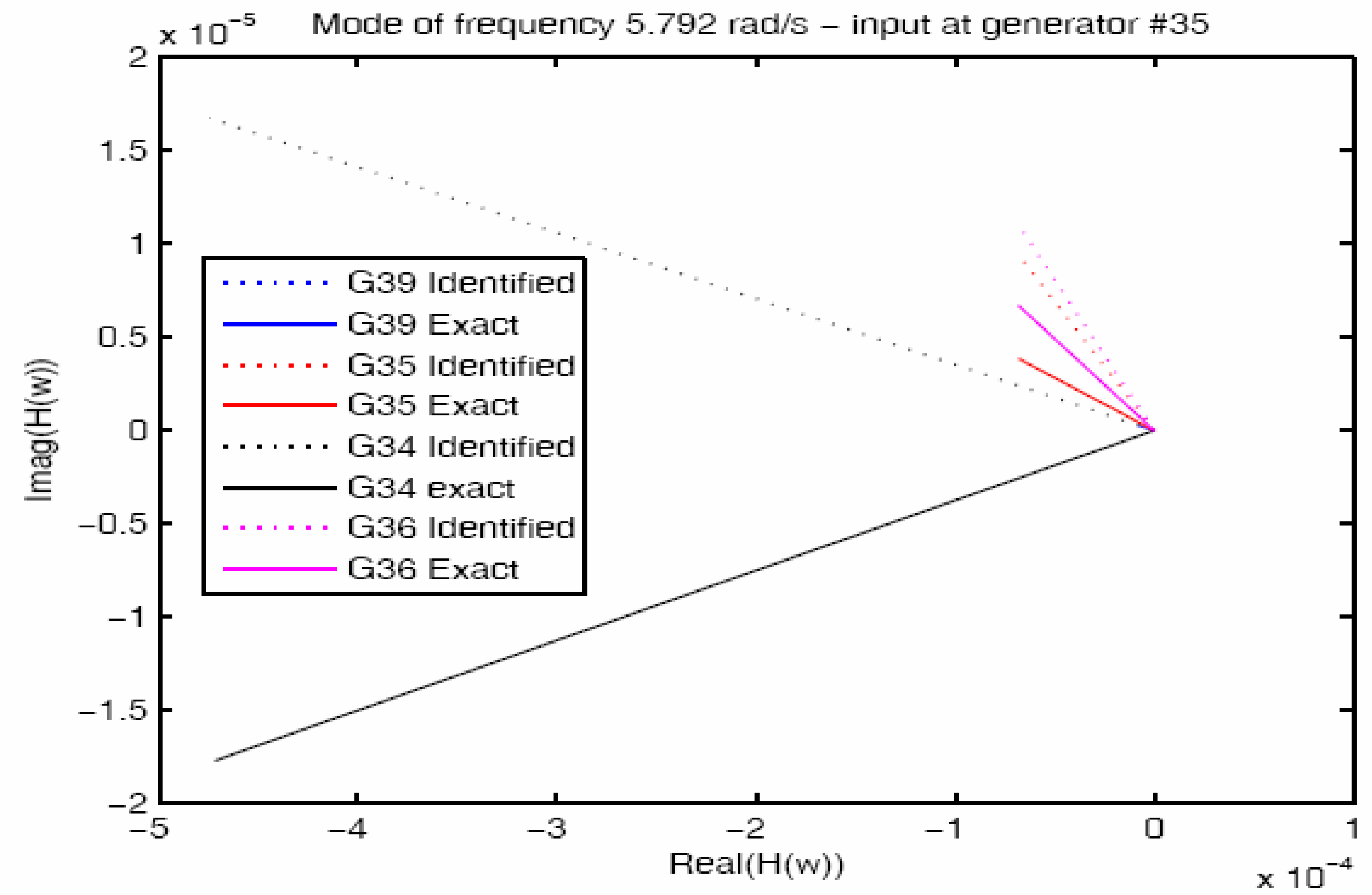
Tests and results

- **Test: perturbation at the generator #35 - values of *real(res(H_i(j3.68)))* and *imag(res(H_i(j3.68)))* – effective and identified residues => real part are nears, small imaginary contribution => rotation: exact and identified**



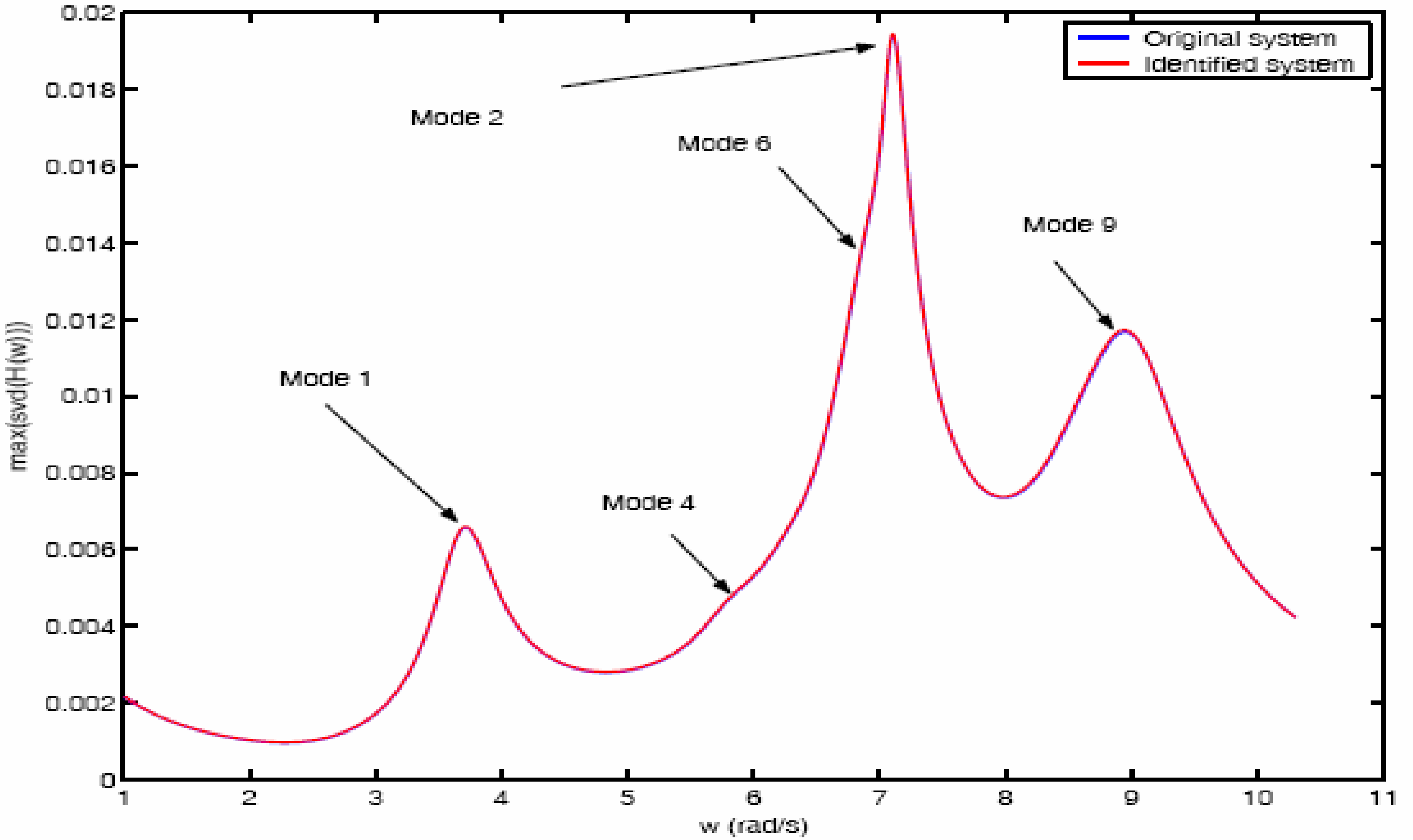
Tests and results

- **Test: perturbation at the generator #35 - values of *real(res(H_i(j5.792)))* and *imag(res(H_i(j5.792)))* – effective and identified residues => real part are nears, small imaginary contribution => rotation: exact and identified**



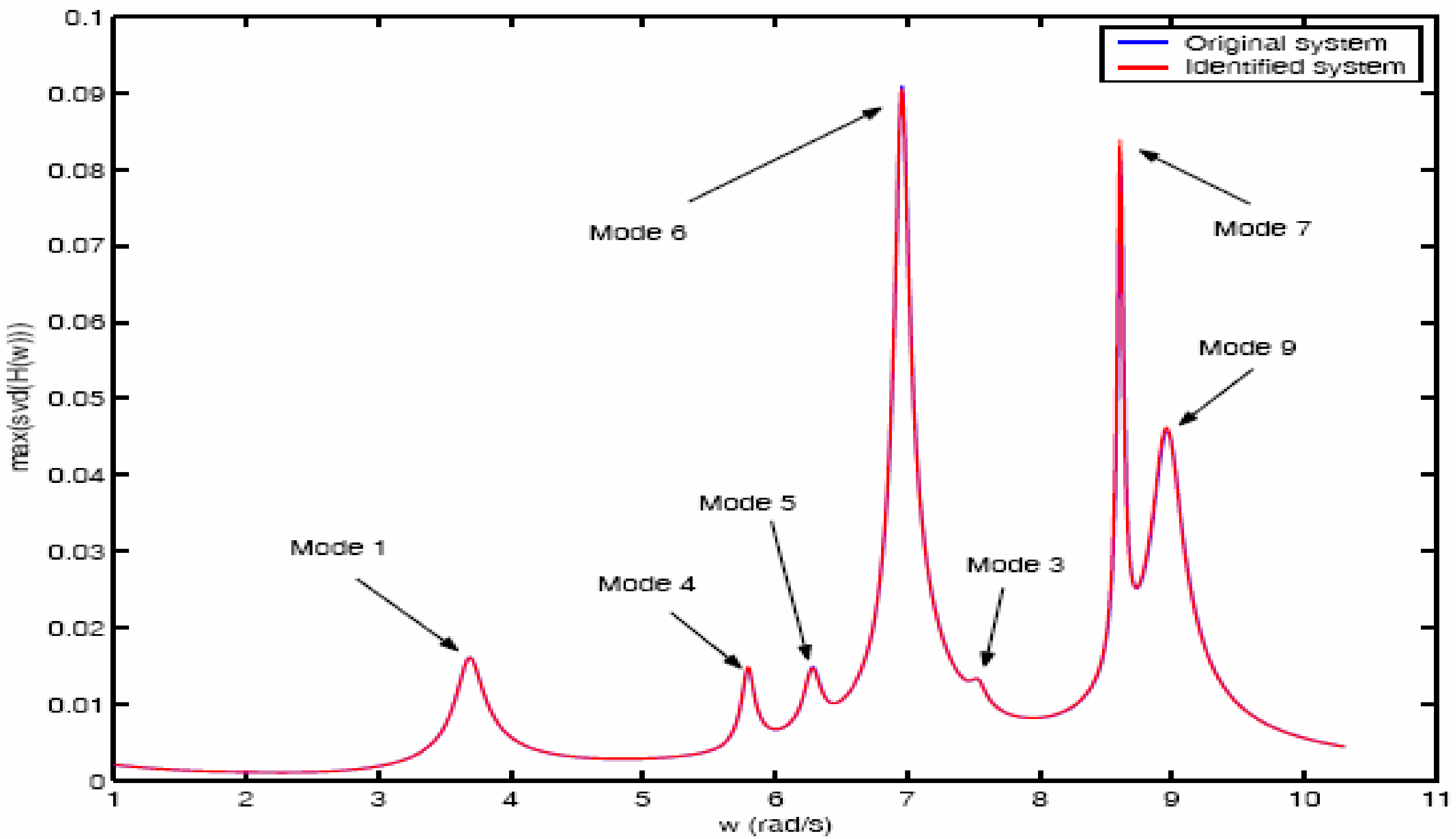
Tests and results

- **Test: perturbation at the generator #35 - SVD plot – modes are indicated at Tab. I – for this input the most dominant is the mode 2 of frequency equal to 7.09 rad/s. But other modes are identified**



Tests and results

- **Test: perturbation at the generator #35 - SVD plot for *H(–0.35+jw)* - modes 2 and 6 are closer – all dominant modes are identified and is observed good matching between exact and identified model**



Concluding Remarks (1/2)

- The described technique identifies, from ringdown tests and availability of multiple PMU's, a SIMO model and its dominant poles with associated mode-shapes.
- Identifies major rotor speed deviations from transients induced by a small pulse in the power output of a generating station or load/HVDC link.
- Tests made on 39-bus, 10-gen New Eng system model.
- Results are exploratory but indicated the algorithms perform well for ringdown tests, in the absence of noise.
- Work is now being extended to a large BIPS model => 150 power plants and more than 3000 states.
- Other probing signals and measurement noise will be considered next. Focus will then turn to oscillation damping assessment from multiple PMU's using only ambient noise information.

Concluding Remarks (2/2)

Topics discussed in this presentation

- Modal Analysis
- System Identification (Ringdown tests, numerical aspects of algorithms, etc)
- Selection of probing signals and monitored variables
- Online and off-line monitoring of oscillation damping and mode-shapes
- Model Reduction for SISO and SIMO systems

Many other topics related to WAMS, WAPS, WACS were not discussed in this presentation