Data-led Defence Lines Against Oscillation Induced by Power Electronic Devices

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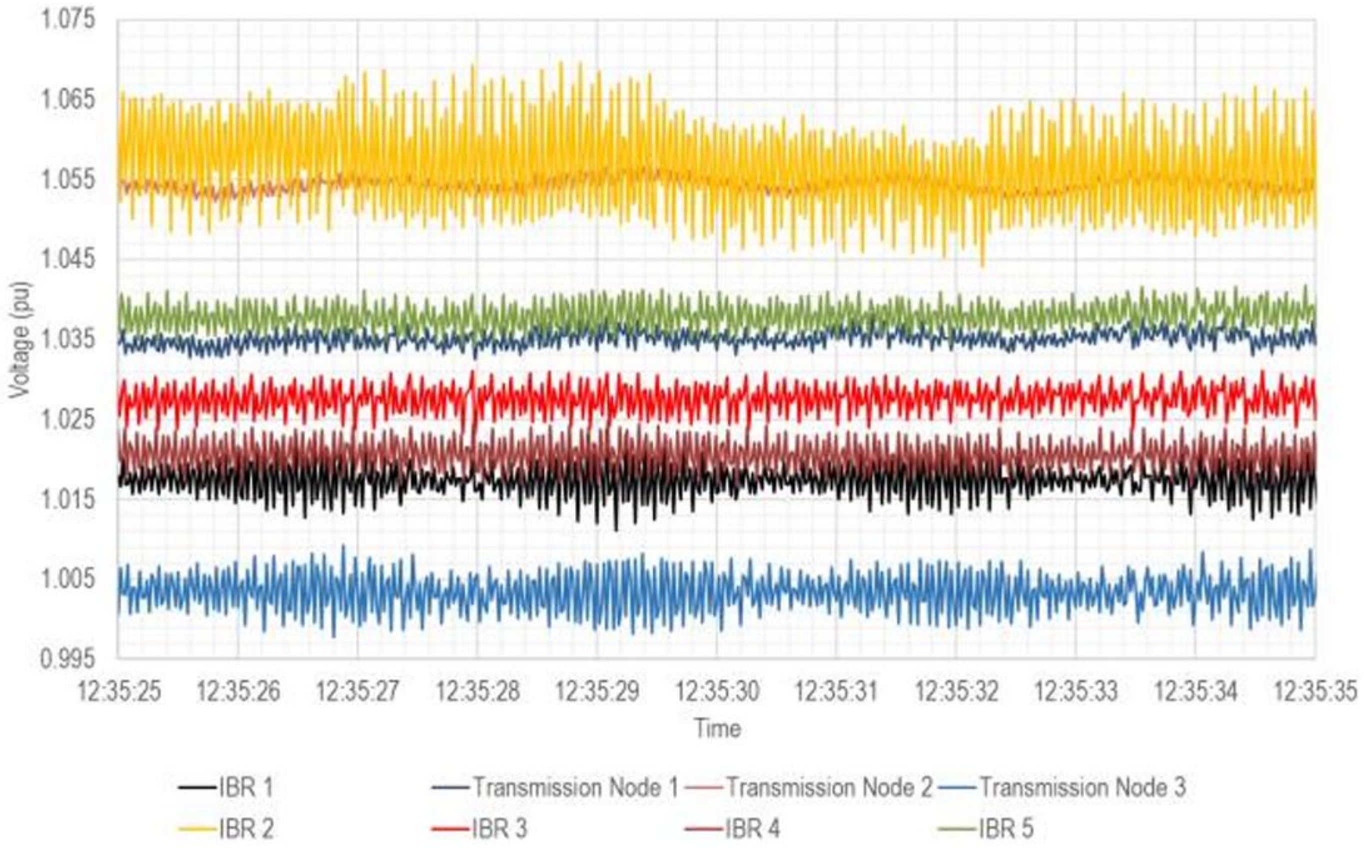
AEMO Oscillations



Sub-synchronous Oscillations in West Murray Zone (WMZ), Australia, since 2019. Source: [High level summary of WMZ – Subsynchronous Oscillations].

- The sub-synchronous oscillations seem to be intermittent and occurring both with and **without any apparent disturbance** in the WMZ or surrounding region.
- The frequency of oscillations is mostly around 17-19 Hz (RMS).
- The oscillations have been identified as contained in the north-west of Victoria and specifically around the Red Cliffs and Wemen area, likely **involving the following solar plants**: Wemen, Bannerton, Karadoc, Yatpool & Kiamal.
- Based on instances when the response of these solar plants was analysed, the **Q and V response from the solar plants were sometimes in-phase and sometimes out-of-phase**.
- The system operator replicated the oscillation in their EMT simulation models, after two years.

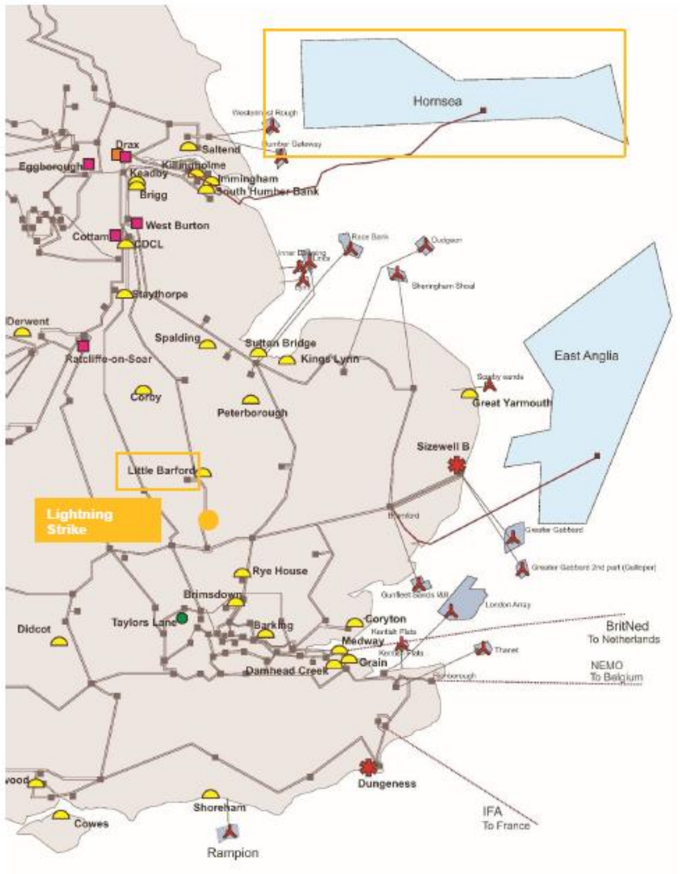
Scotland Oscillations

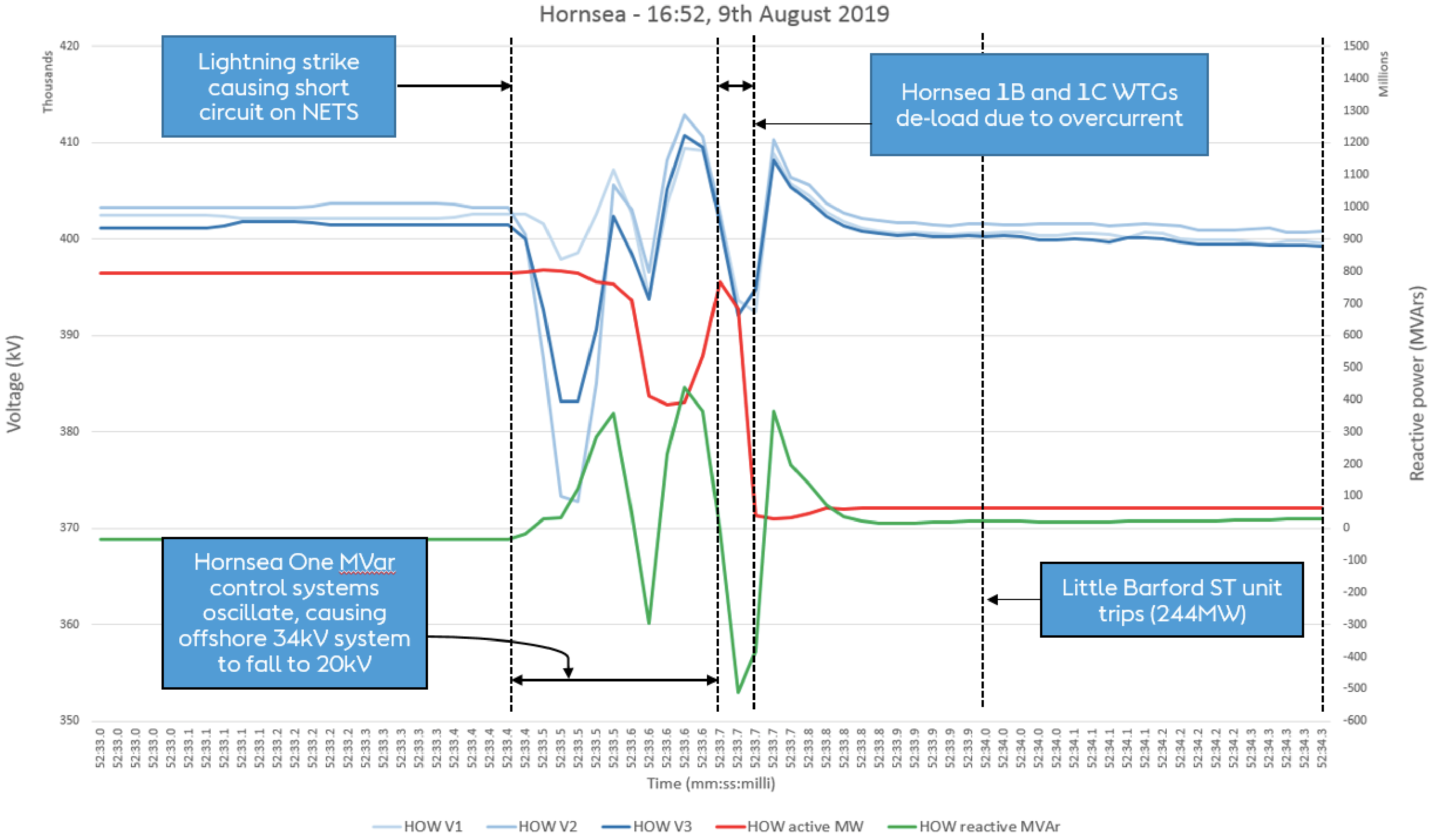
Voltage Oscillation in Scotland in 2021

- On 24/08/2021 severe voltage disturbances were observed on the SSEN-T and SPEN transmission systems.
- Major disturbance lasted 20-25 seconds on two occasions, approx. 30 minutes apart
- Investigation of available data suggests:
  - The oscillations with the largest magnitude were in the north of Scotland
  - The oscillations had a frequency of ≈8 Hz
- Some Users tripped off during the disturbances

nationalgridESO

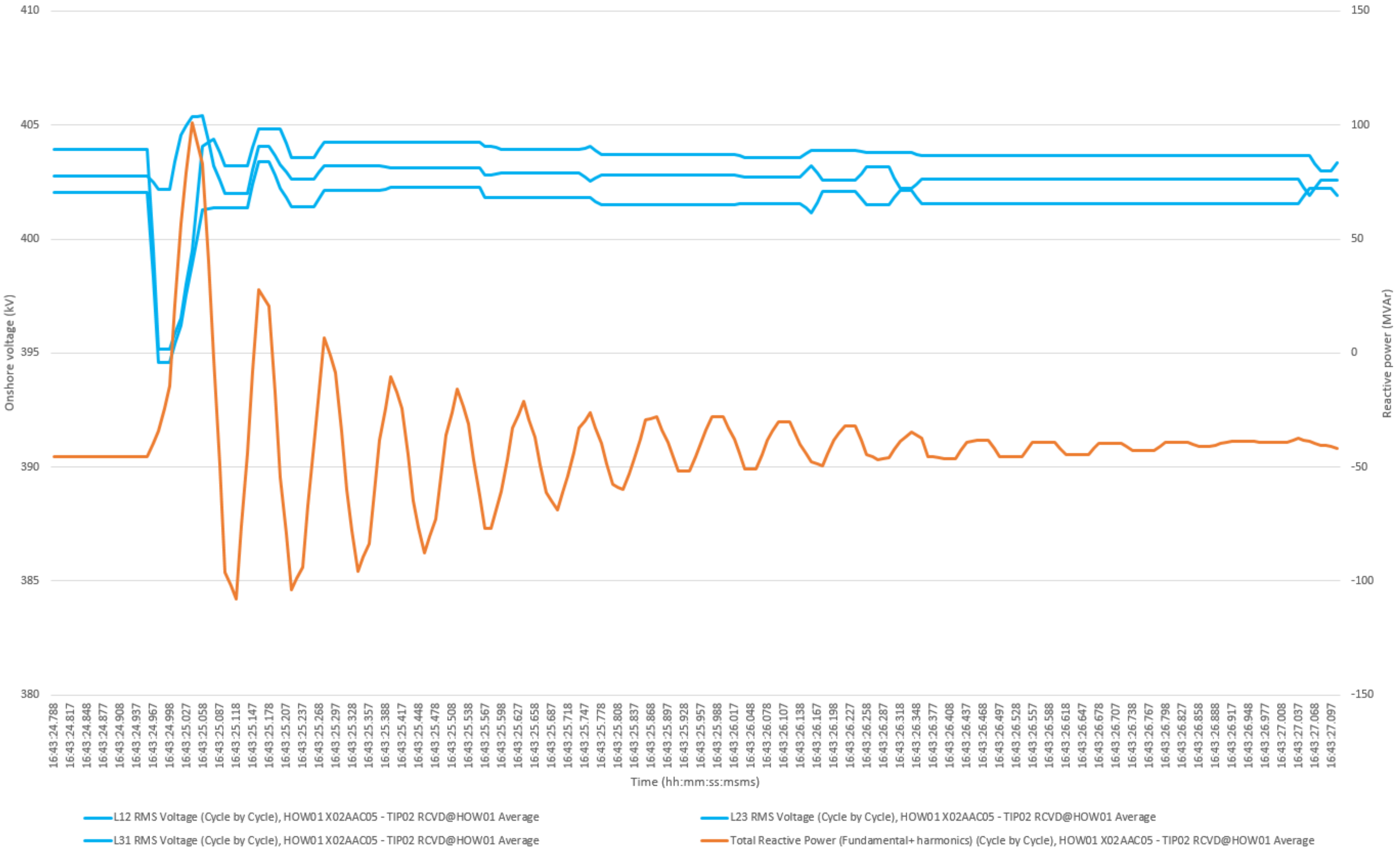
Hornsea Oscillations





Hornsea Oscillations

Before the Hornsea wind farm de-loading, there was an under-damped voltage oscillation



Defence Lines for Oscillations

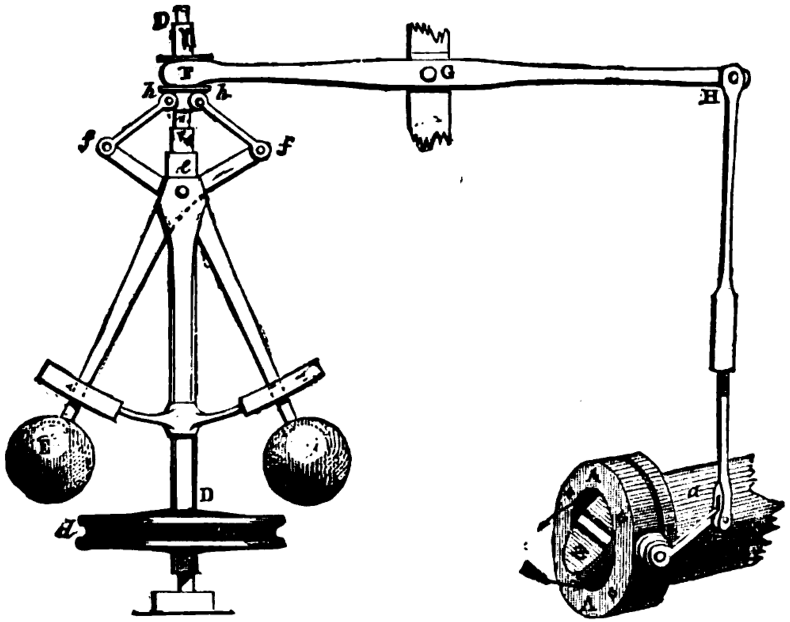
Planning: identify the strength and weakness of the network and perform connection planning accordingly

Pre-Event: provide predictions and early warnings of oscillations before they actually occur

Post-Event: identify the origins of oscillations and deploy mitigation actions to prevent them from happening again

This work is supported by National Grid ESO via Network Innovation Allowance projects "**D**ata-Driven **O**nline **M**onitoring and **E**arly Warning For GB System Stability" (**DOME**) and "Strength to Connect"

The Eigenvalue Approach



The stability of linear system $\dot{x} = Ax$

is determined by $\mathrm{eig}(A)$

I. "On Governors." By J. Clerk Maxwell, M.A., F.R.SS.L. & E.
Received Feb. 20, 1868.

A Governor is a part of a machine by means of which the velocity of the machine is kept nearly uniform, notwithstanding variations in the driving-power or the resistance.

1868.] Mr. J. C. Maxwell *on Governors*. 271

Most governors depend on the centrifugal force of a piece connected with a shaft of the machine. When the velocity increases, this force increases, and either increases the pressure of the piece against a surface or moves the piece, and so acts on a break or a valve.

In one class of regulators of machinery, which we may call *moderators* *, the resistance is increased by a quantity depending on the velocity. Thus in some pieces of clockwork the moderator consists of a conical pendulum revolving within a circular case. When the velocity increases, the ball of the pendulum presses against the inside of the case, and the friction checks the increase of velocity.

In Watt's governor for steam-engines the arms open outwards, and so contract the aperture of the steam-valve.

In a water-break invented by Professor J. Thomson, when the velocity is increased, water is centrifugally pumped up, and overflows with a great velocity, and the work is spent in lifting and communicating this velocity to the water.

In all these contrivances an increase of driving-power produces an increase of velocity, though a much smaller increase than would be produced without the moderator.

State Sensitivity: Participation Factor

$$\dot{\begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_3 \end{pmatrix}} = \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_3 \end{pmatrix}$$

$$\boldsymbol{x} = \boldsymbol{\Phi z}$$
$$\boldsymbol{z} = \boldsymbol{\Psi x}$$

$$\dot{\begin{pmatrix} z_1 \\ z_2 \\ \vdots \\ z_3 \end{pmatrix}} = \begin{pmatrix} \lambda_1 & & & \\ & \lambda_2 & & \\ & & \ddots & \\ & & & \lambda_n \end{pmatrix} \begin{pmatrix} z_1 \\ z_2 \\ \vdots \\ z_3 \end{pmatrix}$$

$$\Delta\lambda_k = \phi_{ik}\psi_{ki} \; \Delta a_{ii}$$

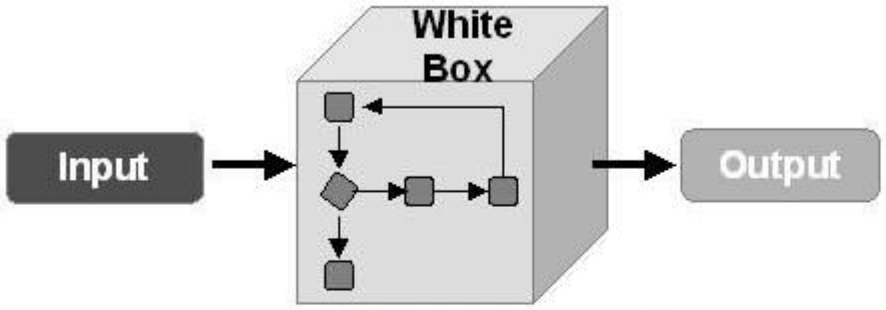
$$p_{ik} \triangleq \phi_{ik}\psi_{ki}$$

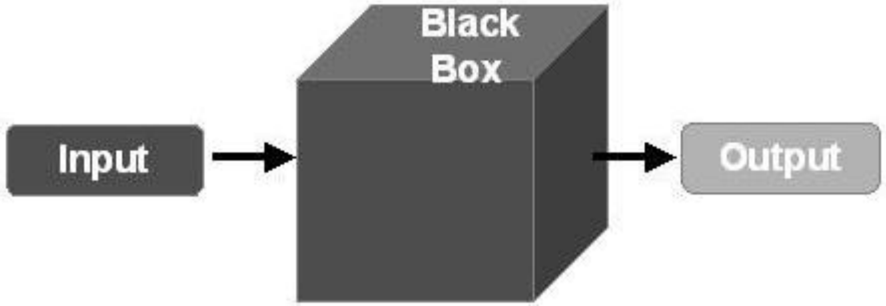
Participation factor: sensitivity of an oscillation mode to a state

Pagola, F.L.; Perez-Arriaga, I.J.; Verghese, George C. (1989). "On sensitivities, residues and participations: Applications to oscillatory stability analysis and control". *IEEE Transactions on Power Systems*.

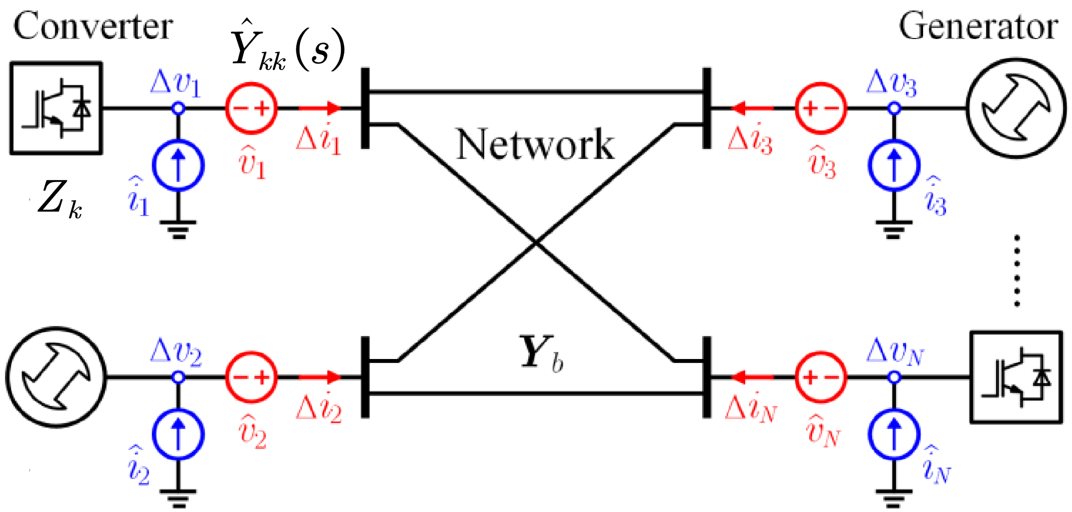
Model? We don't have a good one

- Sensitivity (participation factor) analysis is a powerful tool to understand oscillations, **only if we have a good (white-box) model.**
- The first generation of inverter-based resources (IBRs) do not provide models at all.
- Newer IBRs are obliged to provide model, but in a black-box form (compiled executables).





Port-Based Sensitivity: Impedance Participation Factor



Z_k : impedance of device connected at bus k

$\hat{Y}_{kk}(s)$: admittance of whole-system seen at bus k

$$\hat{Y}_{kk}(s) = \frac{R_1}{s-\lambda_1} + \frac{R_2}{s-\lambda_2} + \cdots \frac{R_N}{s-\lambda_N}$$

← *Residue*

← *Pole/Eigenvalue*

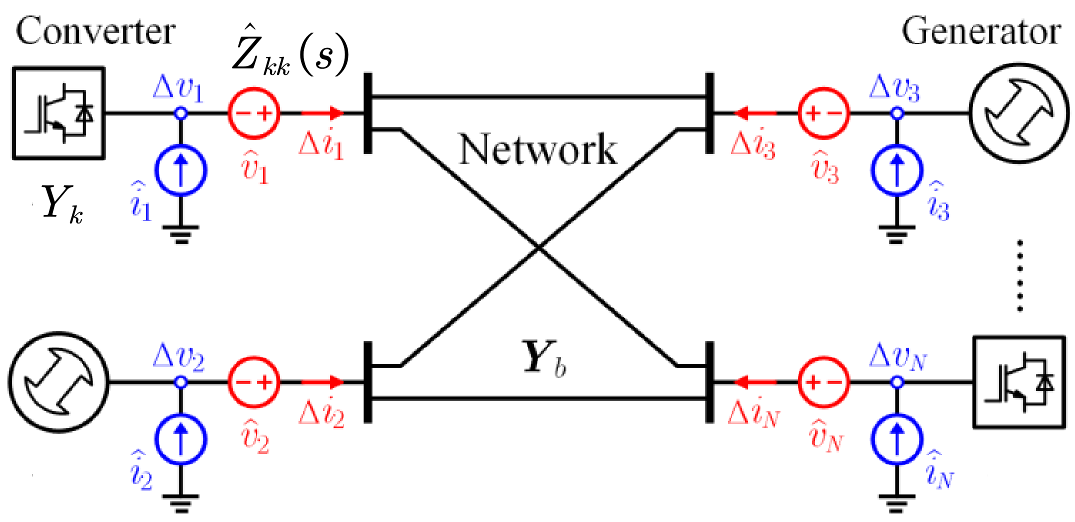
The residue Lamma*: residue of admittance $\hat{Y}_{kk}$ at node k equals the sensitivity of each pole to the device impedance at that node.*

$$\Delta\lambda = \langle -\mathrm{Res}_\lambda^* \hat{Y}_{kk} \ , \ \Delta Z_k(\lambda) \rangle_F$$

*From the residue Lamma, we define an "****impedance participation factor****"*

$$p_{\lambda,Z_k} \triangleq -\mathrm{Res}_\lambda^* \hat{Y}_{kk}$$

Admittance Participation Factor



Y_k : admittance of device connected at bus *k*

$\hat{Z}_{kk}(s)$: impedance of whole-system seen at bus *k*

$$\hat{Z}_{kk}(s) = \frac{R_1}{s-\lambda_1} + \frac{R_2}{s-\lambda_2} + \cdots \frac{R_N}{s-\lambda_N}$$

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*From the residue Lamma, we define an "**admittance participation factor**"*

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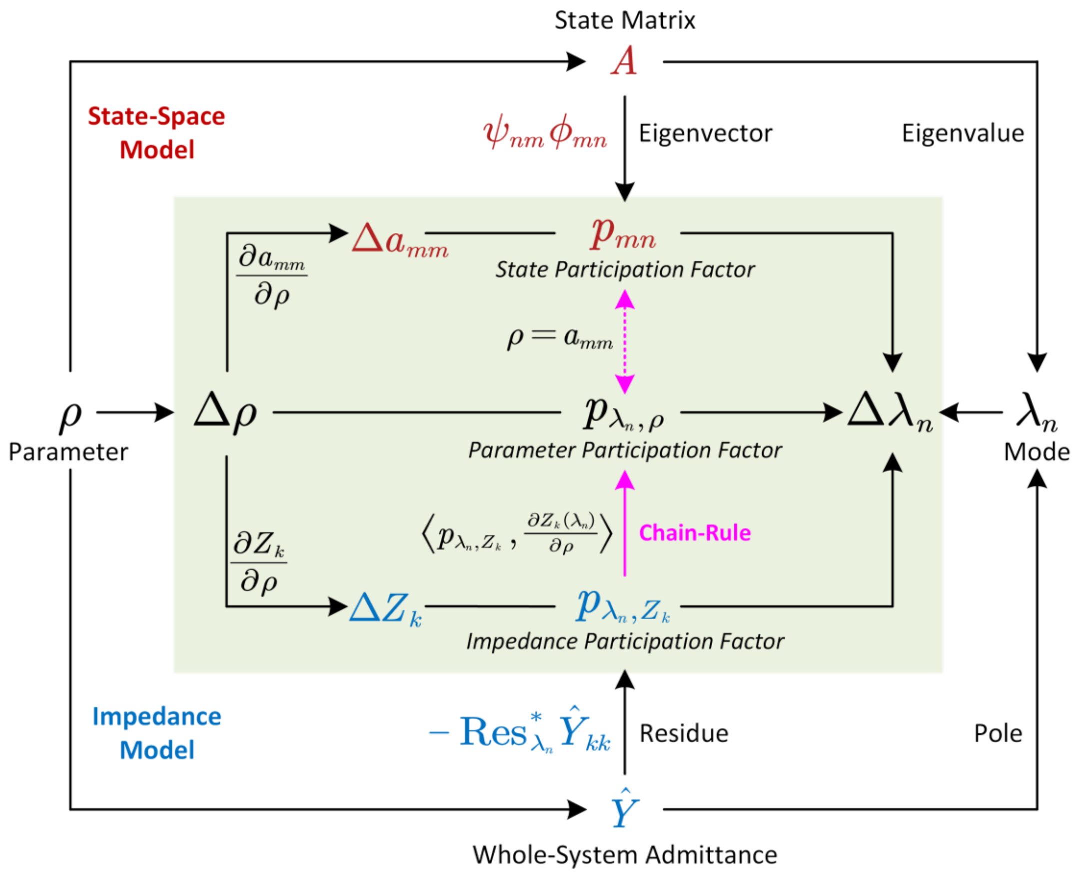
Unified Sensitivity Relationships



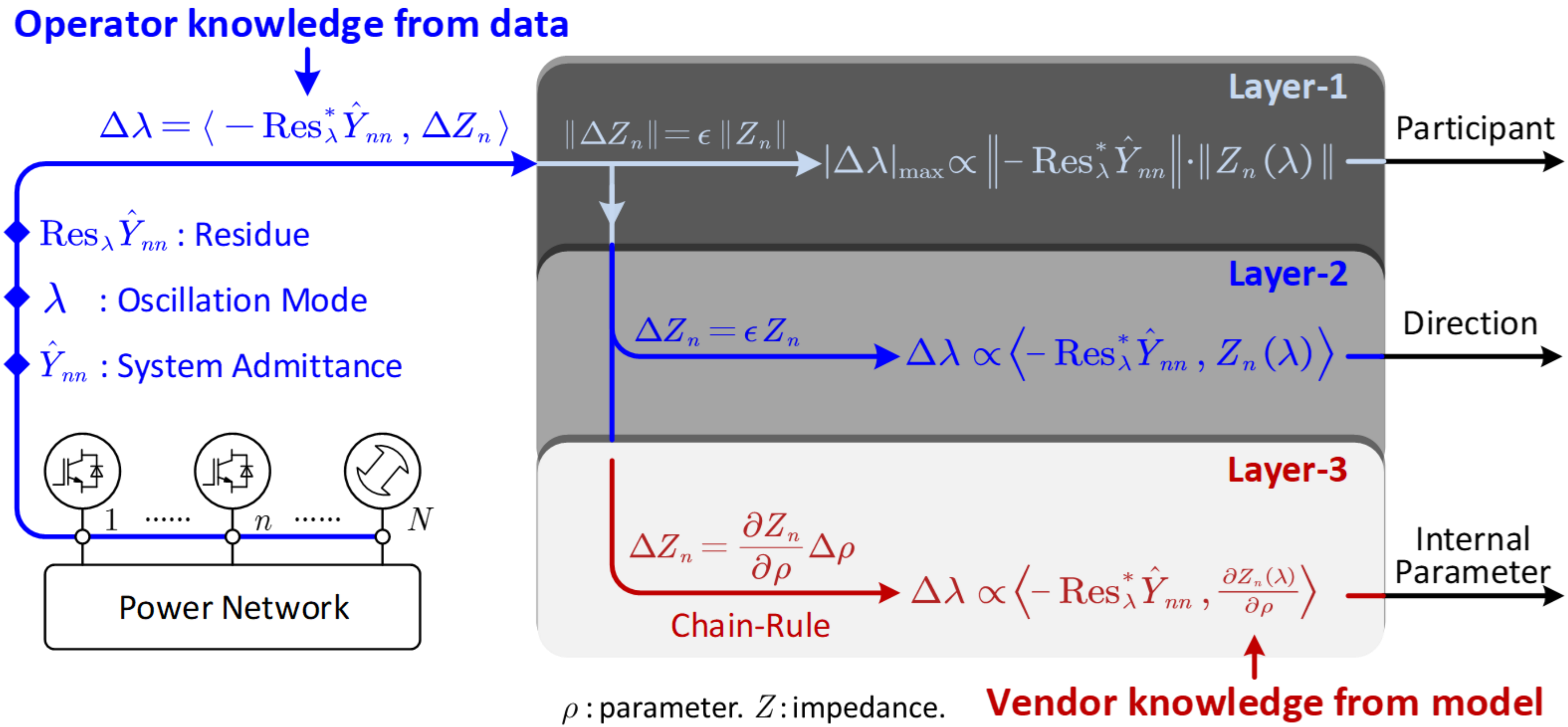
If you know the parameters, ρ, you can:

- *Build the state-space matrix A*
- *Find the eigenvalues λ and identify poorly damped modes*
- *Find the participation factors p_{mn} and determine which states n participate in a given mode m*
- *Find the sensitivity of the mode to a parameter $\partial\lambda/\partial\rho$ (parameter participation) and re-tune*

If you only know the equipment and network impedances, you can:

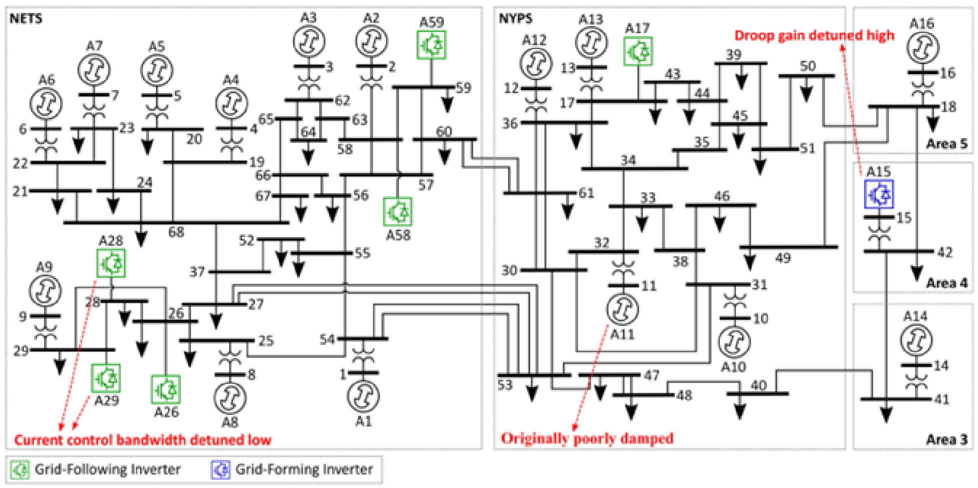
- *Find modes λ by observation of impedance spectrum $\hat{Y}_{kk}$*
- *Find the residues of $-\mathrm{Res}^* \hat{Y}_{kk}$ as impedance participation factors $p_{\lambda,Z}$*
- *Use a chain-rule to identify sensitivity to a mode to a parameter, $\partial\lambda/\partial\rho$*

The Grey-Box Approach

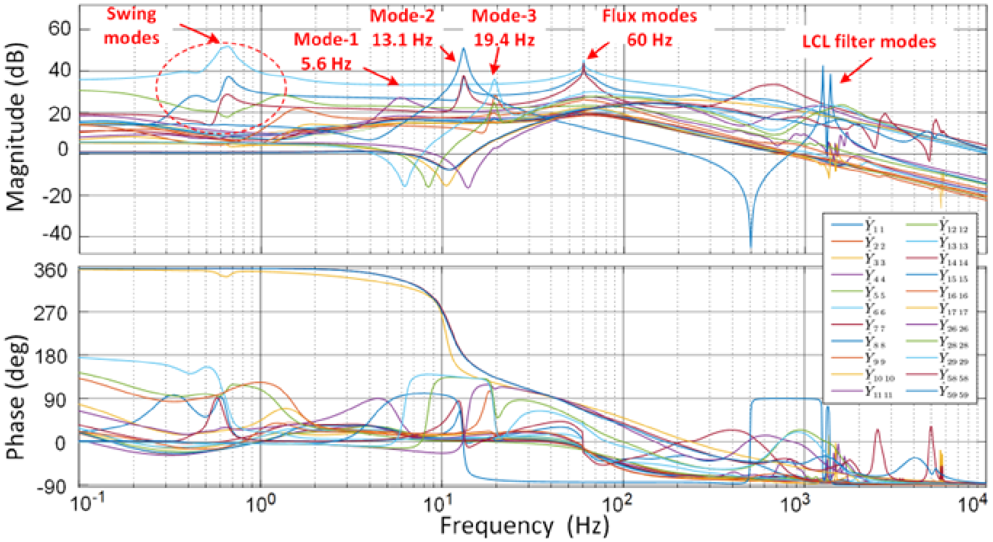


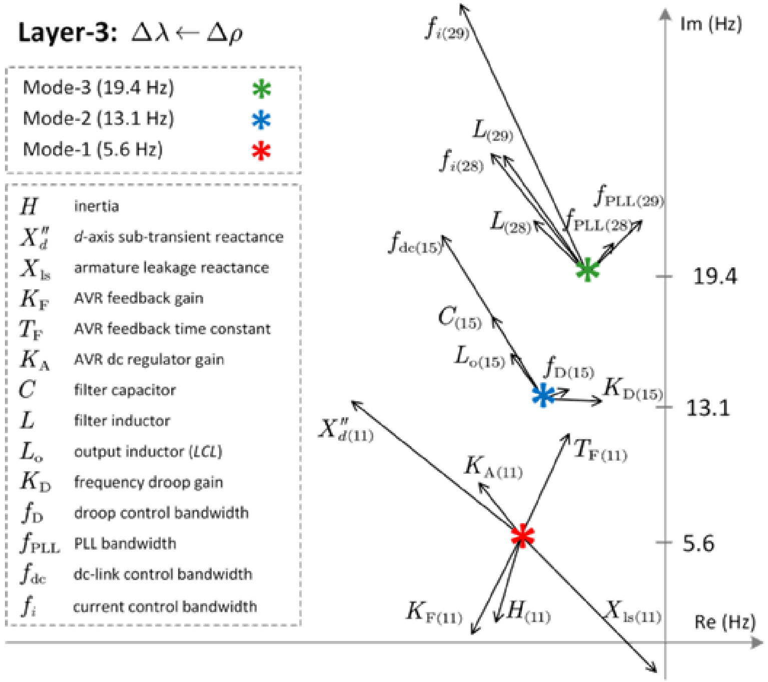
ρ : parameter. Z : impedance.

Case Study: Modified IEEE 68 Bus System



PMU Data → Whole-System Admittance $\hat{Y}_{ik}(s)$





$\Delta\lambda$ mode

$$\frac{\partial\lambda}{\partial Z_k} = R_k(\lambda)$$

ΔZ_k impedance

$$\frac{\partial Z}{\partial\rho}$$

$\Delta\rho$ parameter

Grey-box sensitivity analysis

$$\hat{Y}_{ik}(s) = \frac{R_1}{s-\lambda_1} + \frac{R_2}{s-\lambda_2} + \cdots \frac{R_N}{s-\lambda_N}$$

← Residue
← Pole (Mode)

Pole-Residue Factorisation

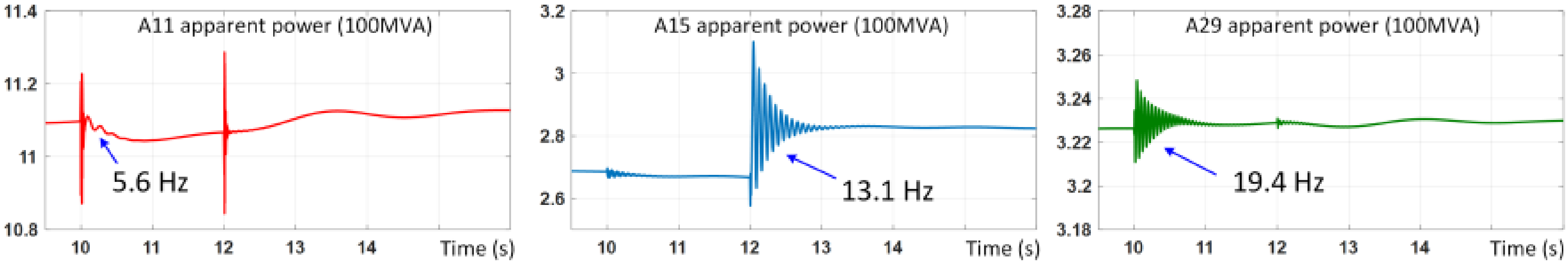
Y.Zhu, Y. Gu, Yi. Li, T.C Green, "Participation Analysis in Impedance Models: The Grey-Box Approach for Power System Stability", IEEE Trans PWRS, 2021.

Models and Toolbox at https://github.com/Future-Power-Networks/Publications

Case Study: Modified IEEE 68 Bus System

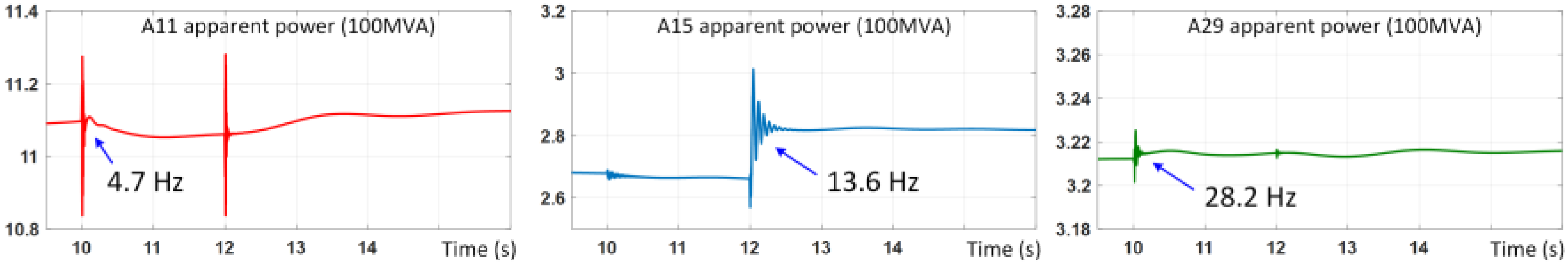
(a) De-tuned system.

Mode-1 (5.6 Hz) stands out in A11 at $t = 10$ s;
Mode-2 (13.1 Hz) stands out in A15 at $t = 12$ s;
Mode-3 (19.4 Hz) stands out in A29 at $t = 10$ s.



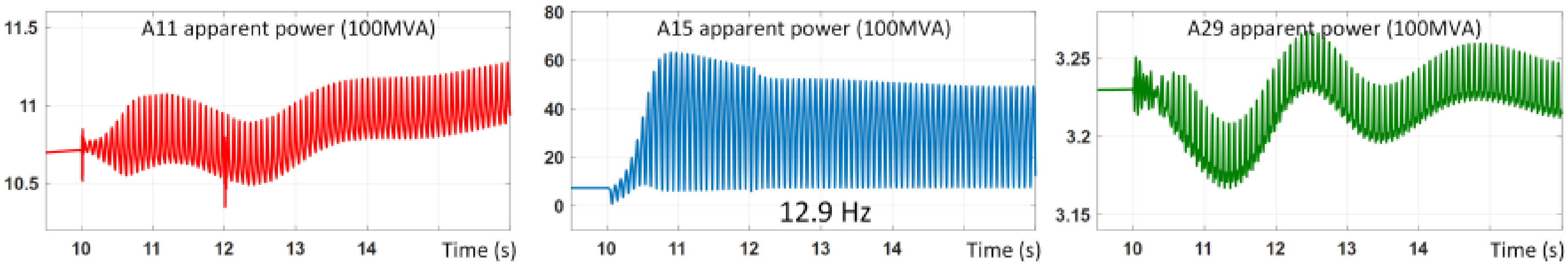
(b) Tuned following the grey-box results.

Mode-1, mode-2 and mode-3 all becomes better damped, and their natural frequencies move to 4.7 Hz, 13.6 Hz, and 28.2 Hz respectively

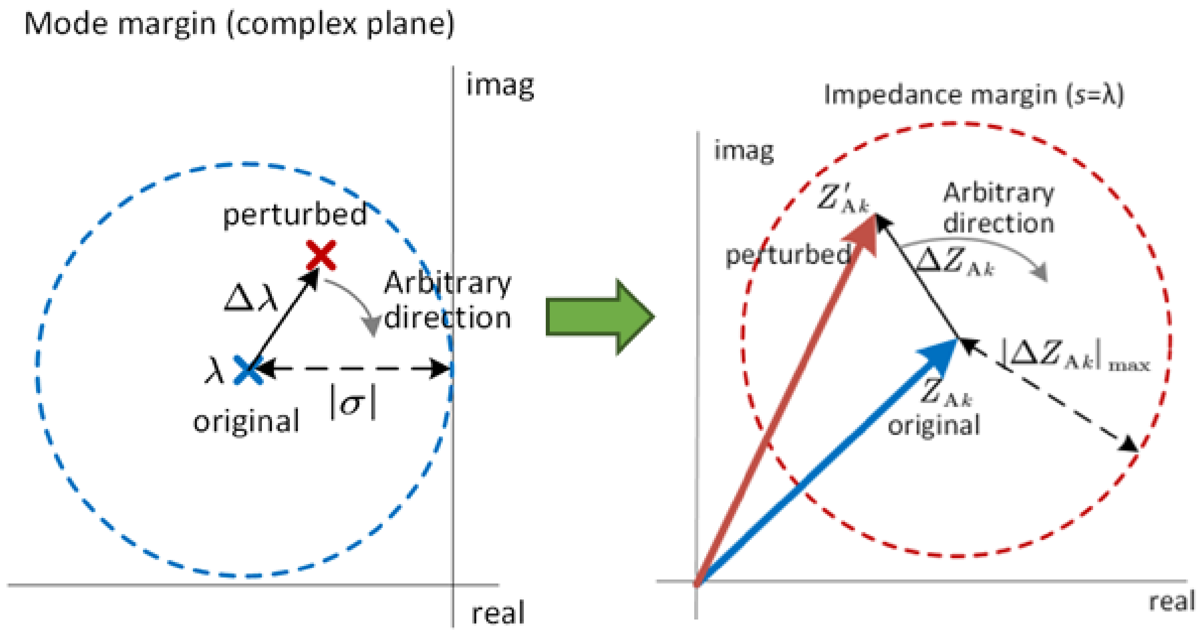


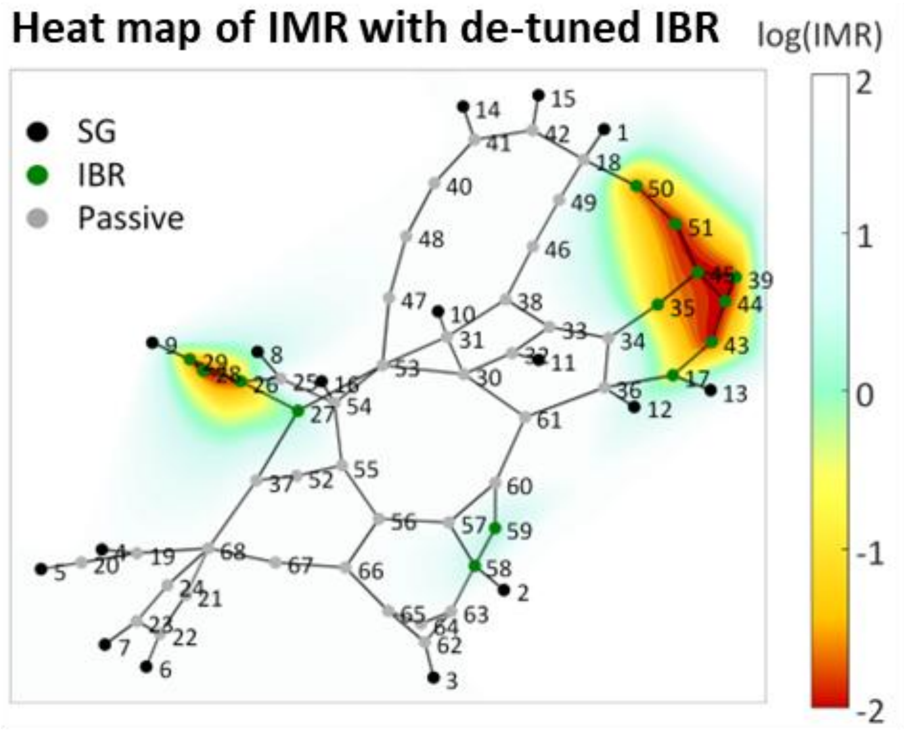
(c) Tuned against the grey-box results.

Mode-2 becomes unstable and its natural frequency moves to 12.9 Hz. The corresponding oscillation propagate throughout the system but is most notable in A15 who participates the most in this mode.



Impedance Margin Ratio: New Index of System Strength

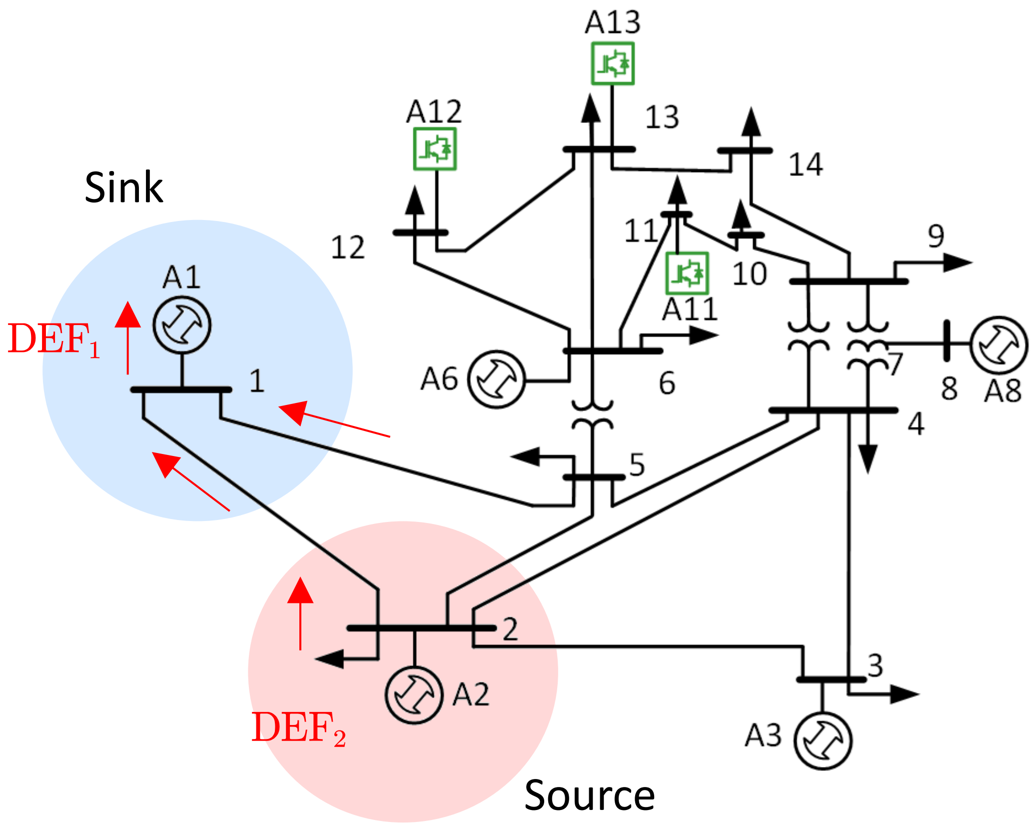




$$\mathbf{IMR} \triangleq \frac{\|\Delta Z_{Ak}(\lambda)\|_{max}}{\|Z_{Ak}(\lambda)\|} = \frac{|\sigma|}{\|\mathrm{Res}^*_{\lambda} Y^{sys}_{kk}\| \, \|Z_{Ak}(\lambda)\|}$$

Y.Zhu, Y. Gu, T.C Green, “Impedance Margin Ratio: a New Metric for Small-Signal System Strength ”, IEEE Trans PWRS, under review.

Dissipating Energy Flow (DEF)



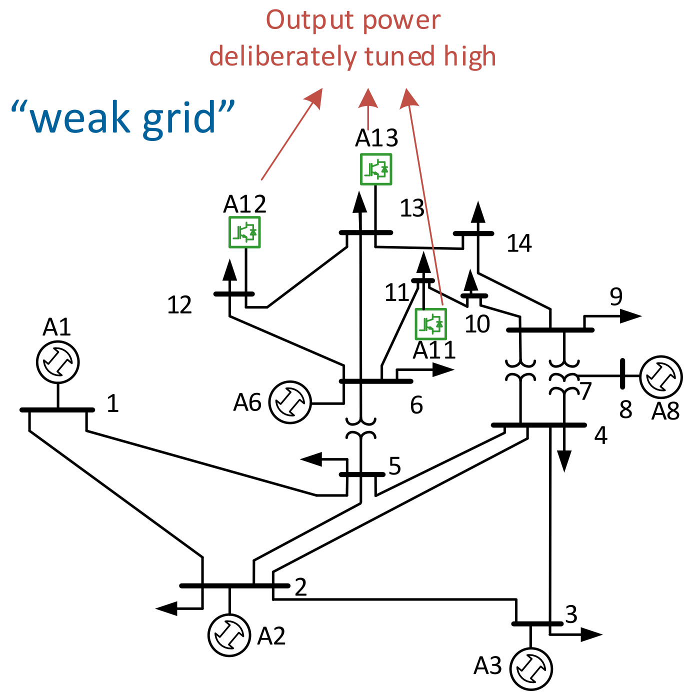
DEF: Dissipation Energy Flow

- DEF indicates the flow of “damping power” in the system.
- The sign of the dc component of DEF indicates contribution to damping.
- Positive DEF indicates sources of oscillation, and negative DEF indicates sinks of damping.
- DEF was proposed in [1] and applied to the New England system in [2], with 100% accuracy.
- DEF can be fully calculated from PMU data: model free.

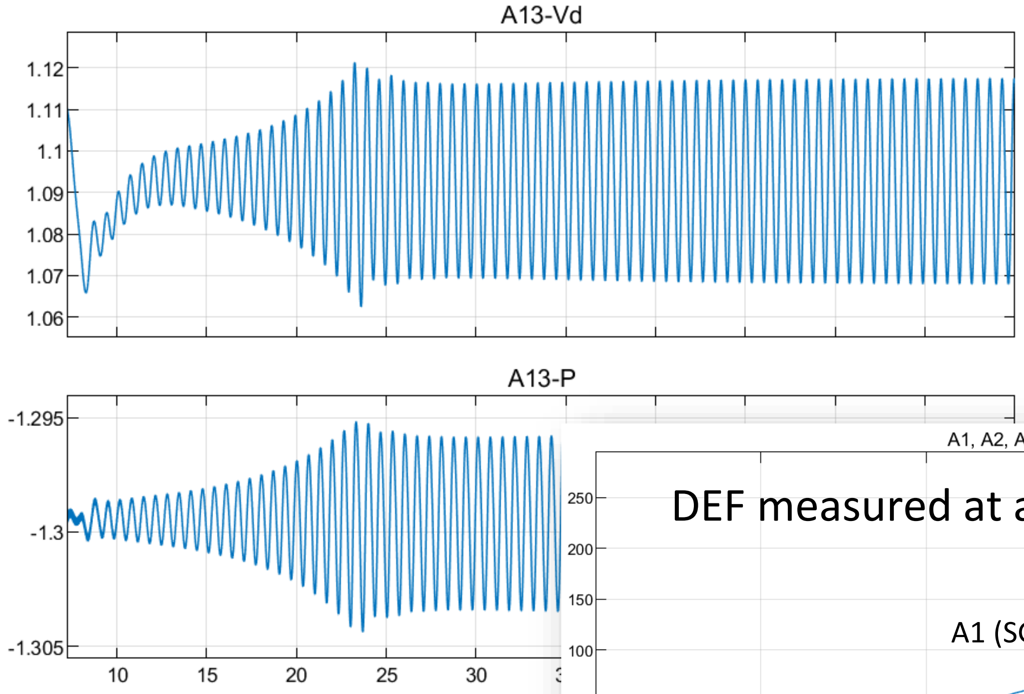
$$\mathrm{DEF} = \mathrm{Im}\left(\Delta \boldsymbol{I}^{*} \Delta \dot{\boldsymbol{V}}\right) = \Delta P \, \Delta\omega + \Delta Q \, \Delta\dot{V}/V$$

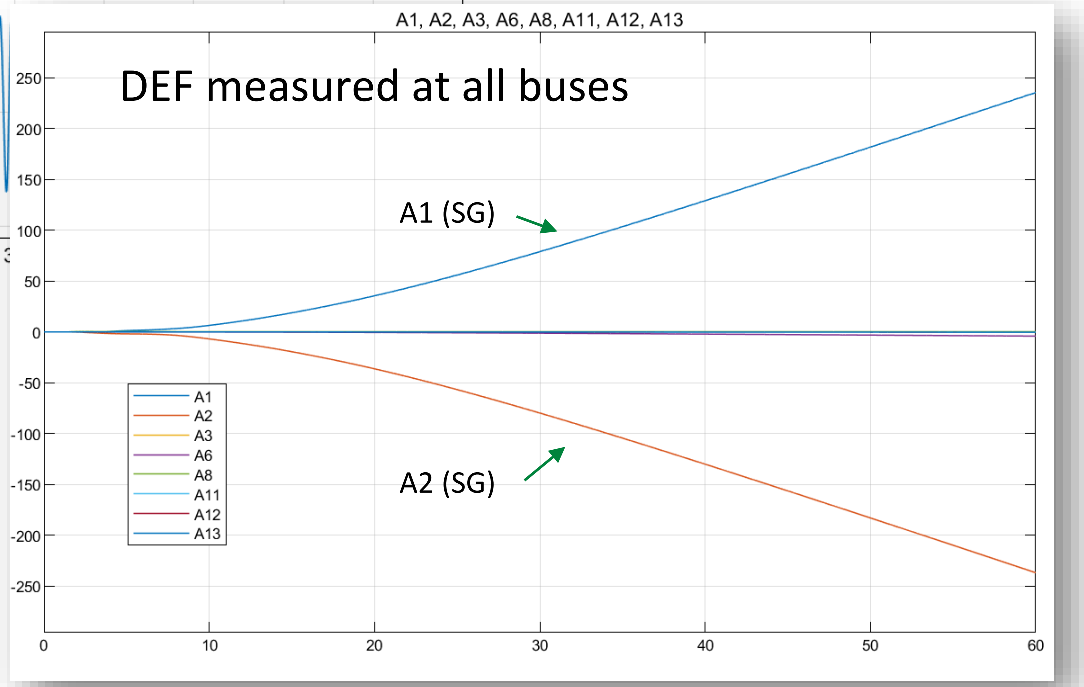
[1] Chen, L., Min, Y. and Hu, W., 2012. An energy-based method for location of power system oscillation source. IEEE Transactions on Power Systems, 28(2), pp.828-836.
[2] Maslennikov, S., Wang, B. and Litvinov, E., 2017. Dissipating energy flow method for locating the source of sustained oscillations. *International Journal of Electrical Power & Energy Systems*, *88*, pp.55-62.

DEF may fail for IBRs



1.5 Hz weak-grid oscillation

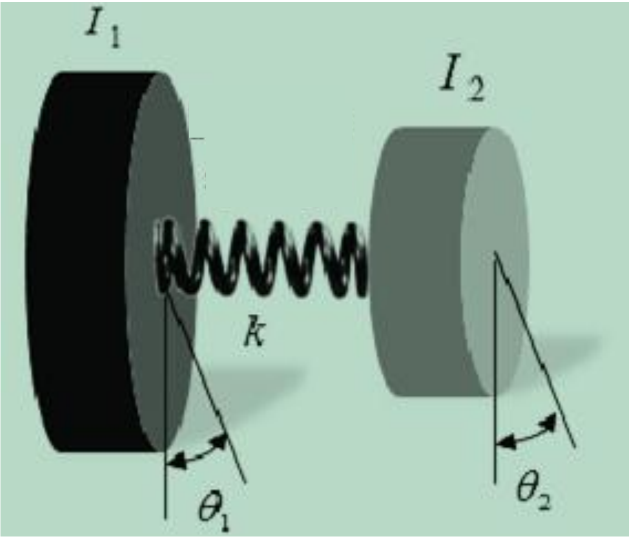




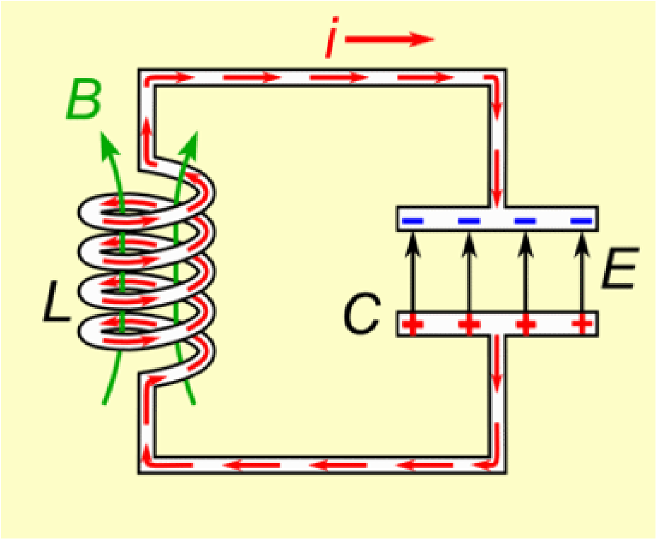
Oscillation is induced by IBRs, but DEF points towards synchronous generators (SGs)

Dissipation v.s. Damping

- Dissipation: the rate of energy loss (time derivative of the energy function)
- Damping: the rate of oscillation decay (real part of eigenvalue)
- Dissipation contributes to damping only if they are consistent
    - ➢ Mechanical dissipation contributes to the damping of angle swing and torsional resonance
    - ➢ Electrical dissipation contributes to the damping of electromagnetic resonance



Torsional resonance: damped by mechanical dissipation (positive torque coefficient)



Electromagnetic resonance: damped by electrical dissipation (positive resistance)

Can we adapt DEF to inverters?

Name	Abbreviation	Definition
Original DEF	DEF	$\mathrm{DEF} = \mathrm{Im}\left(\Delta \boldsymbol{I}^* \Delta \dot{\boldsymbol{V}}\right)$
Complex DEF [1]	cDEF	$\mathrm{cDEF} = \mathrm{Im}\left(e^{j\varphi} \Delta \boldsymbol{I}^* \Delta \dot{\boldsymbol{V}}\right)$
Dual DEF [2]	dDEF	$\mathrm{dDEF} = \mathrm{Im}\left(\Delta \dot{\boldsymbol{I}}^* \Delta \boldsymbol{V}\right)$
Sub/Super-Synchronous DEF [3]	sDEF	$\mathrm{sDEF} = \mathrm{Re}\left(\Delta \boldsymbol{I}^* \Delta \boldsymbol{V}\right)$

Multiple attempts have been made to modify DEF to make it work for IBRs. They all succeed in some cases but not in all cases.

[1] PG Estevez, Complex dissipating energy flow method for forced oscillation source location, IEEE Trans Power Systems.
[2] L Fan, Z Wang, Z Miao, S Maslennikov, Oscillation Source Detection for Inverter-Based Resources via Dissipative Energy Flow, TechRxiv
[3] X Xie, Y Zhan, J Shair, Z Ka, X Chang, Identifying the source of subsynchronous control interaction via wide-area monitoring of sub/super-synchronous power flows, IEEE Trans Power Delivery.

The unified DEF: uDEF

$$\text{uDEF} = [\Delta I_d, \Delta I_q] \underbrace{\begin{bmatrix} w_{11} & w_{12} & w_{13} & w_{14} \\ w_{21} & w_{22} & w_{23} & w_{24} \end{bmatrix}}_{\boldsymbol{W}} \begin{bmatrix} \Delta V_d \\ \Delta V_q \\ \Delta \dot{V}_d \\ \Delta \dot{V}_q \end{bmatrix}$$

$\boldsymbol{W}$ is to be specified to make uDEF consistent with damping

uDEF covers all existing DEFs

Existing DEF	Definition	Equivalent W
DEF	$\mathrm{DEF} = \mathrm{Im}\left(\Delta \boldsymbol{I}^* \Delta \dot{\boldsymbol{V}}\right)$	$\begin{pmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 \end{pmatrix}$
cDEF	$\mathrm{cDEF} = \mathrm{Im}\left(e^{j\varphi} \Delta \boldsymbol{I}^* \Delta \dot{\boldsymbol{V}}\right)$	$\begin{pmatrix} 0 & 0 & \sin\varphi & \cos\varphi \\ 0 & 0 & -\cos\varphi & \sin\varphi \end{pmatrix}$
dDEF	$\mathrm{dDEF} = \mathrm{Im}\left(\Delta \dot{\boldsymbol{I}}^* \Delta \boldsymbol{V}\right)$	$\begin{pmatrix} 0 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 \end{pmatrix}$
sDEF	$\mathrm{sDEF} = \mathrm{Re}\left(\Delta \boldsymbol{I}^* \Delta \boldsymbol{V}\right)$	$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix}$

uDEF covers all possible DEF

Derivative on currents? Not needed.

$$\int \Delta \dot{I}\,\Delta V\,dt = \Delta I\,\Delta V - \int \Delta I\,\Delta \dot{V}\,dt$$

Higher order derivatives? Not needed.

$$\Delta V = A\sin(\omega t+\phi)\ ,\ \Delta \ddot{V} = -A\omega^2\sin(\omega t+\phi) = -\omega^2\Delta V$$

Other signals (ΔP, ΔQ, $\Delta\theta$, $\Delta\omega$)? Equivalent.

$$\Delta\theta = \Delta V_q/V_d\ ,\ \Delta\omega = \Delta\dot{V}_q/V_d$$

$$\Delta P = \Delta V_d I_d + \Delta I_d V_d + \Delta V_q I_q + \Delta I_q V_q\ ,\ \Delta Q = \Delta V_q I_d + \Delta I_d V_q - \Delta V_d I_q - \Delta I_q V_d$$

uDEF v.s. Damping

$$\mathrm{Re}\Delta\lambda = \frac{\epsilon}{|V_\lambda|^2}\left\langle\left[-\mathrm{Re}(\xi \boldsymbol{K}_i^{\mathrm{H}}) \quad \omega^{-1}\mathrm{Im}(\xi \boldsymbol{K}_i^{\mathrm{H}})\right], \mathrm{dc}(\mathbf{uDEF})\right\rangle_{\mathrm{F}}$$

$$\boldsymbol{W} = \left[-\mathrm{Re}(\xi \boldsymbol{K}_i^{\mathrm{H}}) \quad \omega^{-1}\mathrm{Im}(\xi \boldsymbol{K}_i^{\mathrm{H}})\right]$$

The relationship between eigenvalue and admittance matrix

$$\xi = -\frac{\mathrm{tr}\left(\mathrm{adj}(\boldsymbol{Y}^{\mathrm{nodal}}(\lambda))\right)}{\det(\boldsymbol{Y}^{\mathrm{nodal}}(\lambda))'} = -\mathrm{tr}(\mathrm{Res}_\lambda \hat{\boldsymbol{Z}})$$

The relationship between left and right eigenvector

$$\left[\boldsymbol{L}_{\mathrm{d}i\lambda} \quad \boldsymbol{L}_{\mathrm{q}i\lambda}\right] = \left[\boldsymbol{R}_{\mathrm{d}i\lambda} \quad \boldsymbol{R}_{\mathrm{q}i\lambda}\right]\boldsymbol{K}_i$$

uDEF is precisely consistent with damping if $\boldsymbol{W}$ is obtained by the residue and the eigenvector of the mode

The estimation of *W* by oscillation data

$$\boldsymbol{K}_i = \frac{k}{\sin(\theta_{\mathrm{q}i} - \theta_{\mathrm{d}i})} \begin{bmatrix} \sin(\theta_{\mathrm{q}i} + \theta_{\mathrm{d}i}) & -r^{-1} \sin 2\theta_{\mathrm{q}i} \\ -r \sin 2\theta_{\mathrm{d}i} & \sin(\theta_{\mathrm{q}i} + \theta_{\mathrm{d}i}) \end{bmatrix}$$

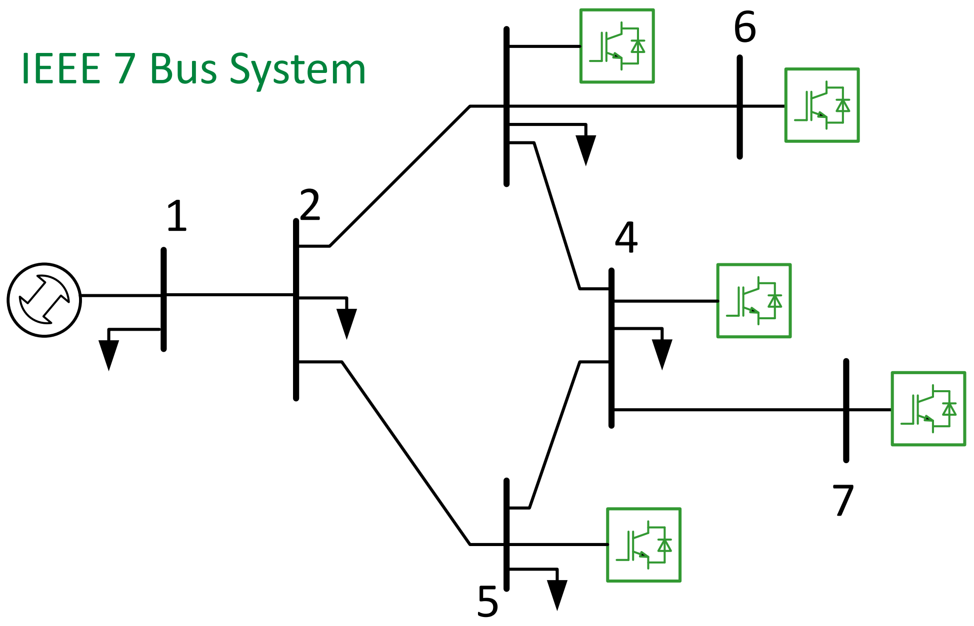
$$r = |\tilde{\boldsymbol{V}}_{\mathrm{d}i} / \tilde{\boldsymbol{V}}_{\mathrm{q}i}|$$

$$\xi = -\mathrm{tr}(\mathrm{Res}_{\lambda} \hat{\boldsymbol{Z}}) \approx \sigma \mathrm{tr}(\hat{\boldsymbol{Z}}(j\omega)) = \sigma \mathrm{tr}(\boldsymbol{Y}^{\mathrm{nodal}}(j\omega)^{-1}) \approx \sigma \gamma^{-1}$$

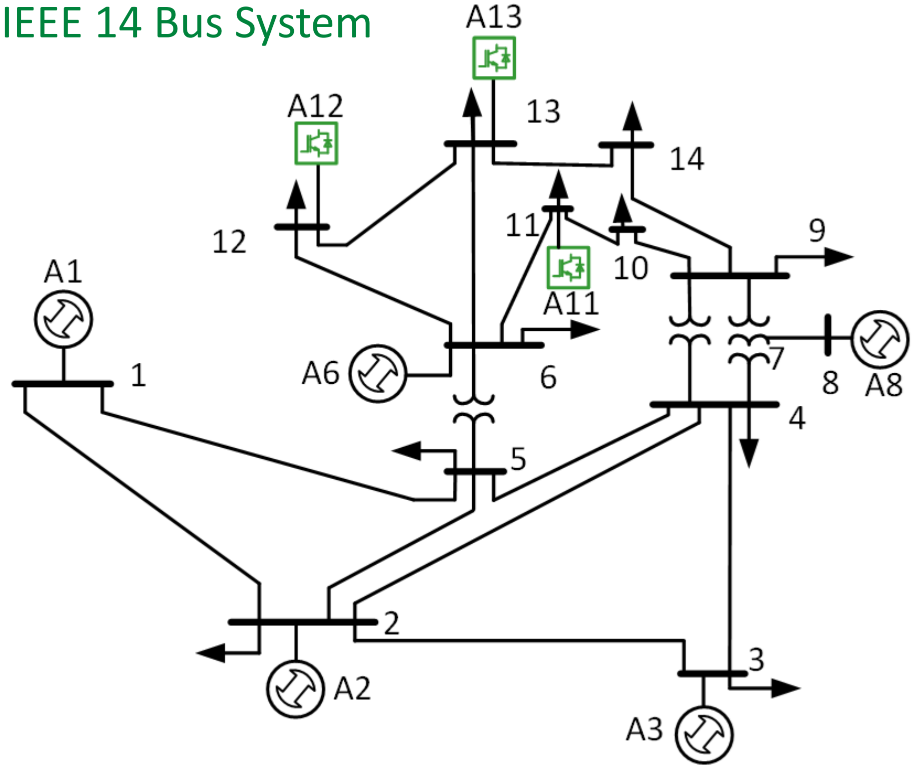
In practice, $\boldsymbol{K}_i$ can be obtained from the angle of oscillation voltage phasor, and ξ can set to -1.

Case Studies

IEEE 7 Bus System



IEEE 14 Bus System



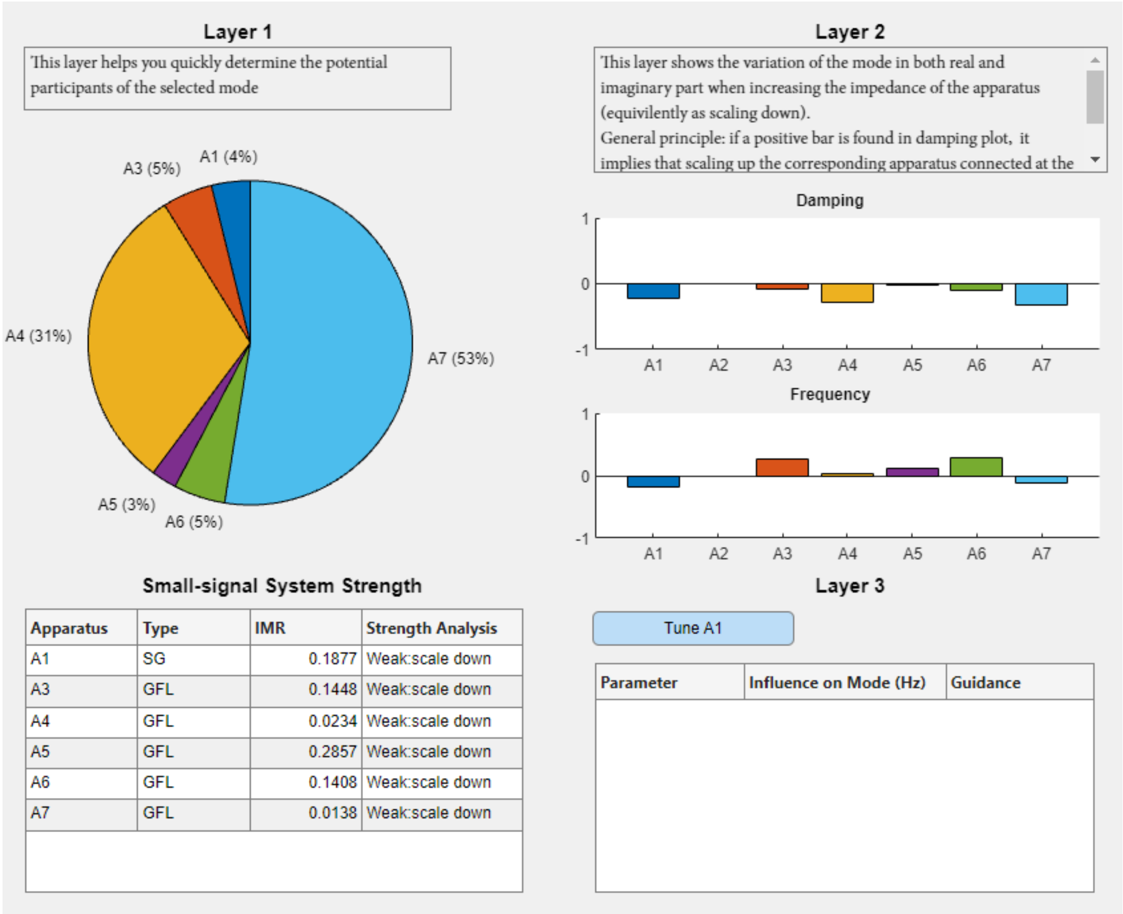
Case 1: Voltage Oscillation (18.8Hz)
Voltage control gain of IBRs at bus 4 & 7 tuned high.

Case 2: Weak Grid Oscillation (1.5Hz)
Power of IBRs at buses 11-13 tuned high

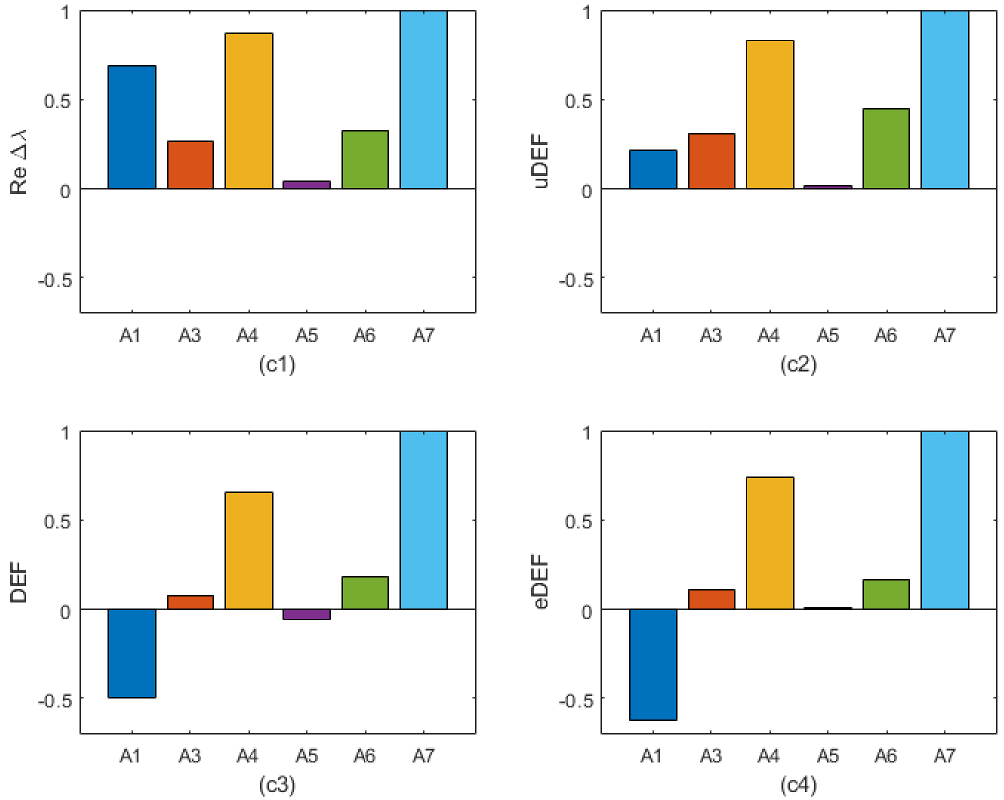
Case 3: Current-PLL Oscillation (8.8Hz)
Current loop of IBRs at buses 11-13 tuned low

Case 1: Current-PLL Oscillation

Ground truth from sensitivity analysis



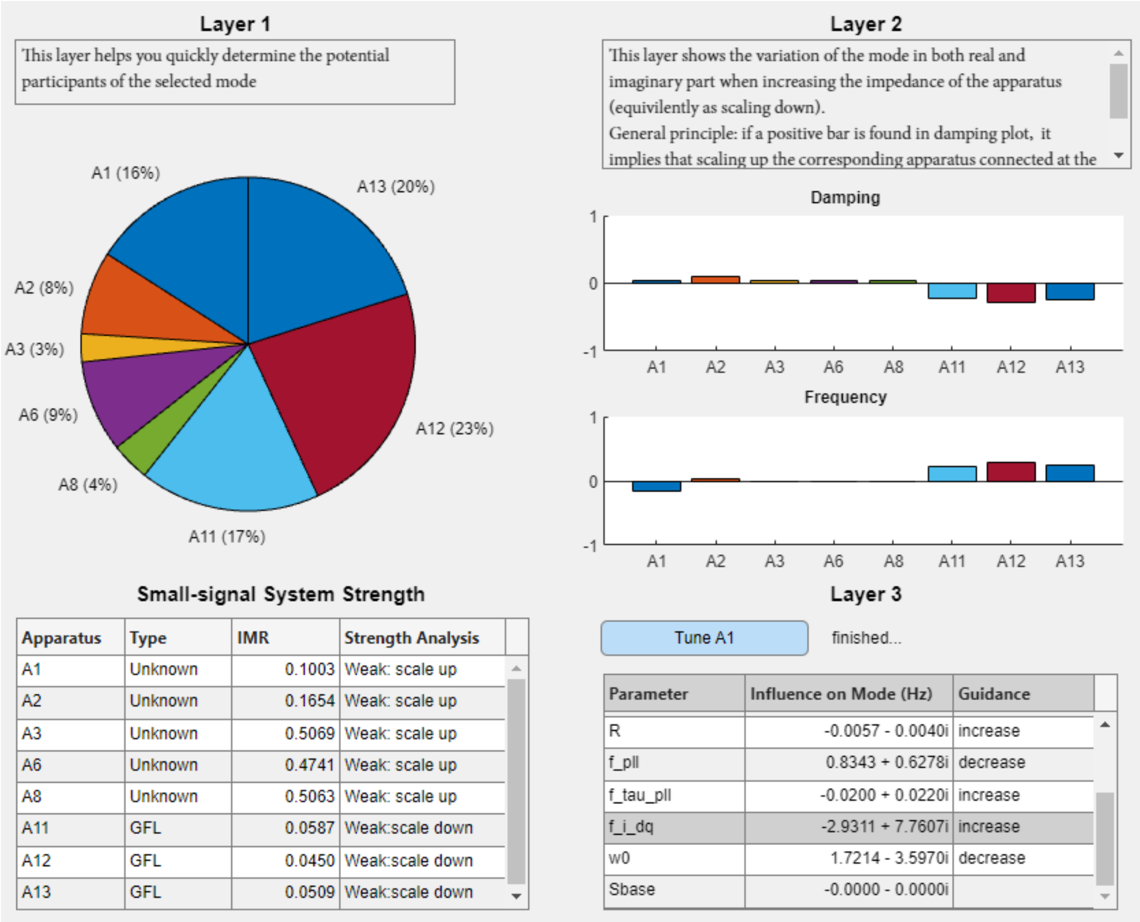
The performance of uDEF



uDEF can give correct indications approximately

Case 2: Weak Grid Oscillation

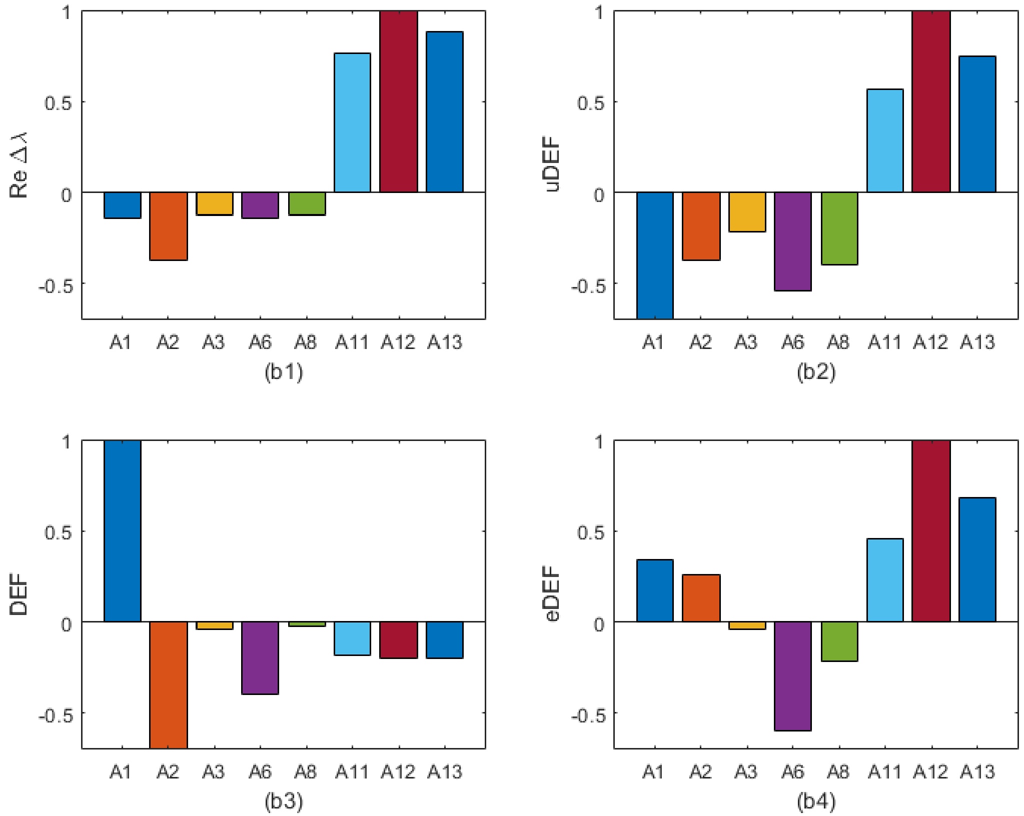
Ground truth from sensitivity analysis



Apparatus	Type	IMR	Strength Analysis
A1	Unknown	0.1003	Weak: scale up
A2	Unknown	0.1654	Weak: scale up
A3	Unknown	0.5069	Weak: scale up
A6	Unknown	0.4741	Weak: scale up
A8	Unknown	0.5063	Weak: scale up
A11	GFL	0.0587	Weak:scale down
A12	GFL	0.0450	Weak:scale down
A13	GFL	0.0509	Weak:scale down

Parameter	Influence on Mode (Hz)	Guidance
R	-0.0057 - 0.0040i	increase
f_pll	0.8343 + 0.6278i	decrease
f_tau_pll	-0.0200 + 0.0220i	increase
f_i_dq	-2.9311 + 7.7607i	increase
w0	1.7214 - 3.5970i	decrease
Sbase	-0.0000 - 0.0000i	

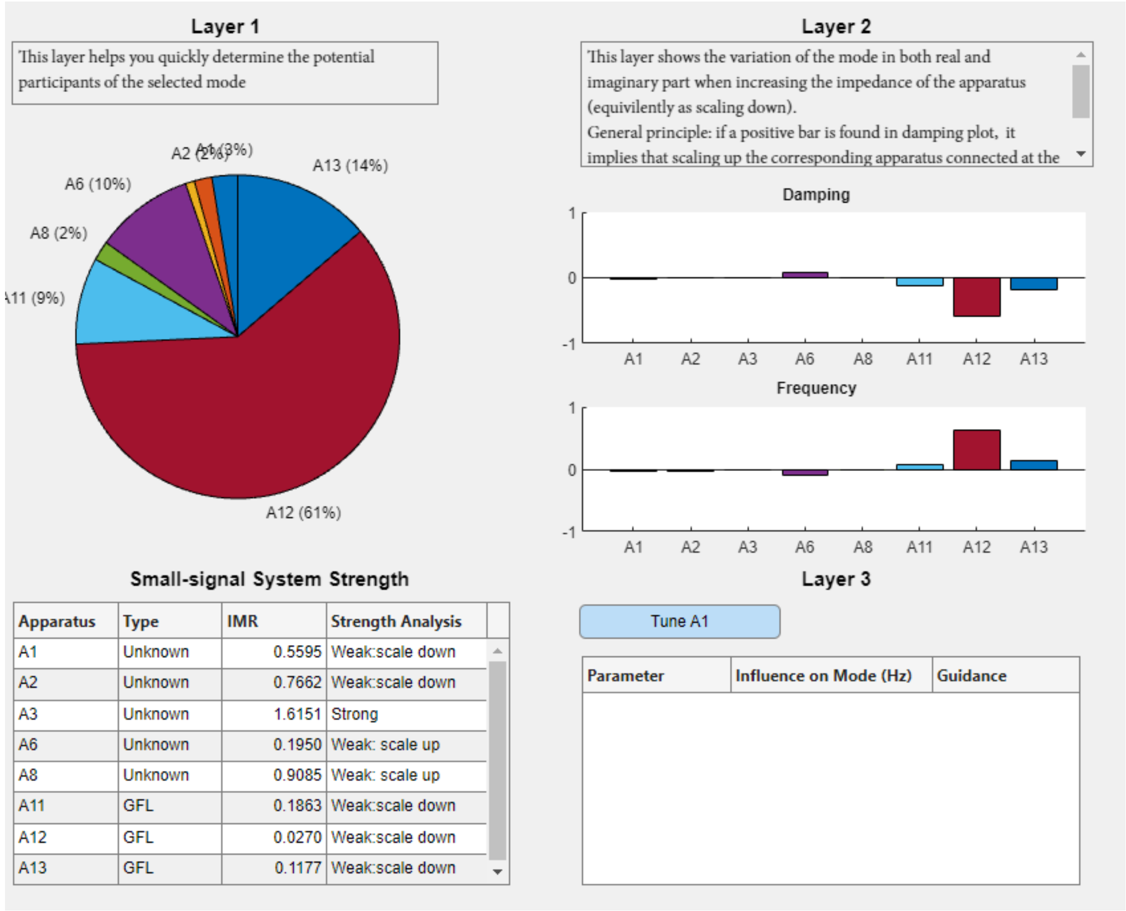
The performance of uDEF



uDEF can give correct indications approximately

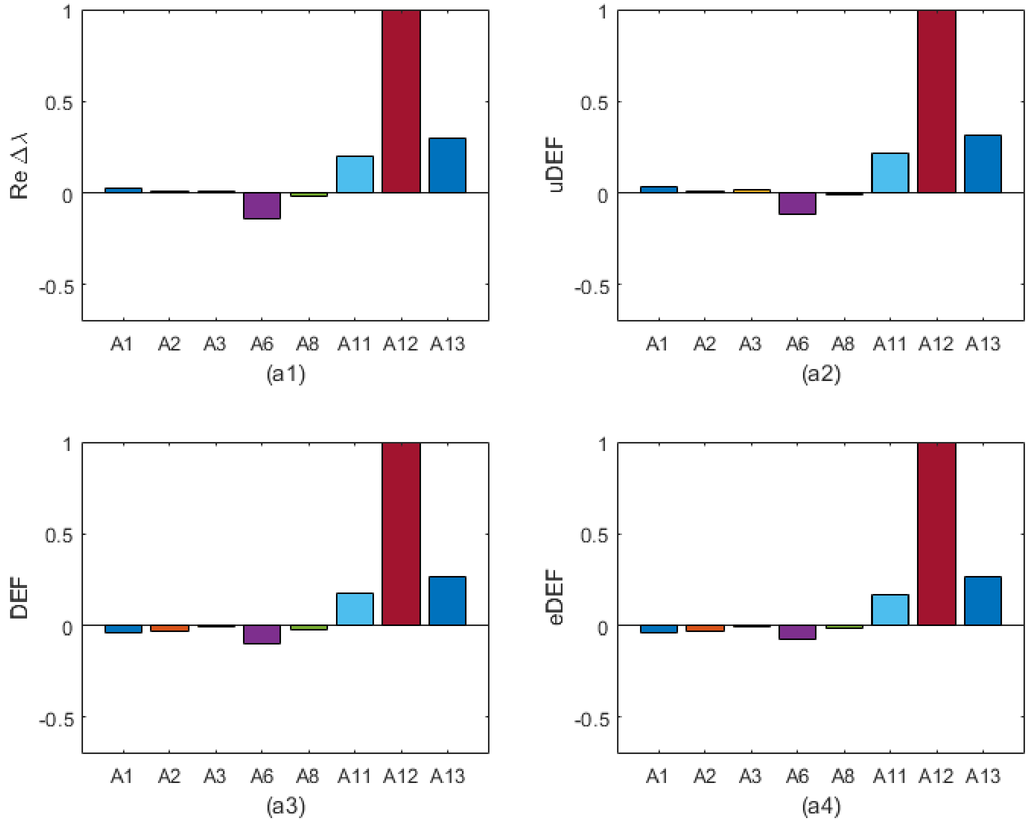
Case 3: Voltage Oscillation

Ground truth from sensitivity analysis



Apparatus	Type	IMR	Strength Analysis
A1	Unknown	0.5595	Weak:scale down
A2	Unknown	0.7662	Weak:scale down
A3	Unknown	1.6151	Strong
A6	Unknown	0.1950	Weak: scale up
A8	Unknown	0.9085	Weak: scale up
A11	GFL	0.1863	Weak:scale down
A12	GFL	0.0270	Weak:scale down
A13	GFL	0.1177	Weak:scale down

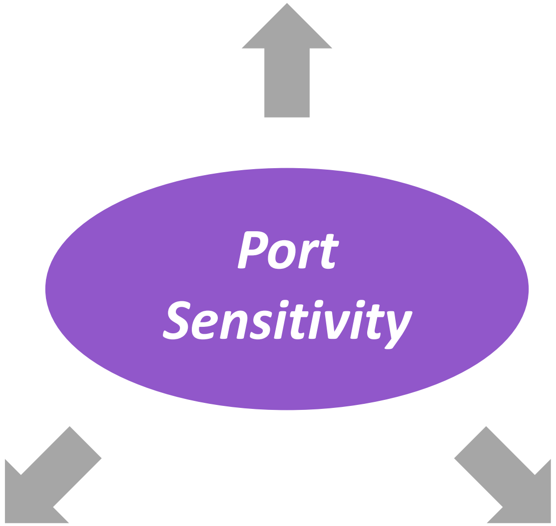
The performance of uDEF



uDEF can give correct indications

Conclusions

Impedance Participation Factor: Pre-event
Black-box models or real system



Impedance Margin Ratio: Planning
Black-box models or real system

Unified Dissipating Energy Flow: Post-event
Completely model free