

The Role of Inertia in Power System Dynamics during Cascading Failures

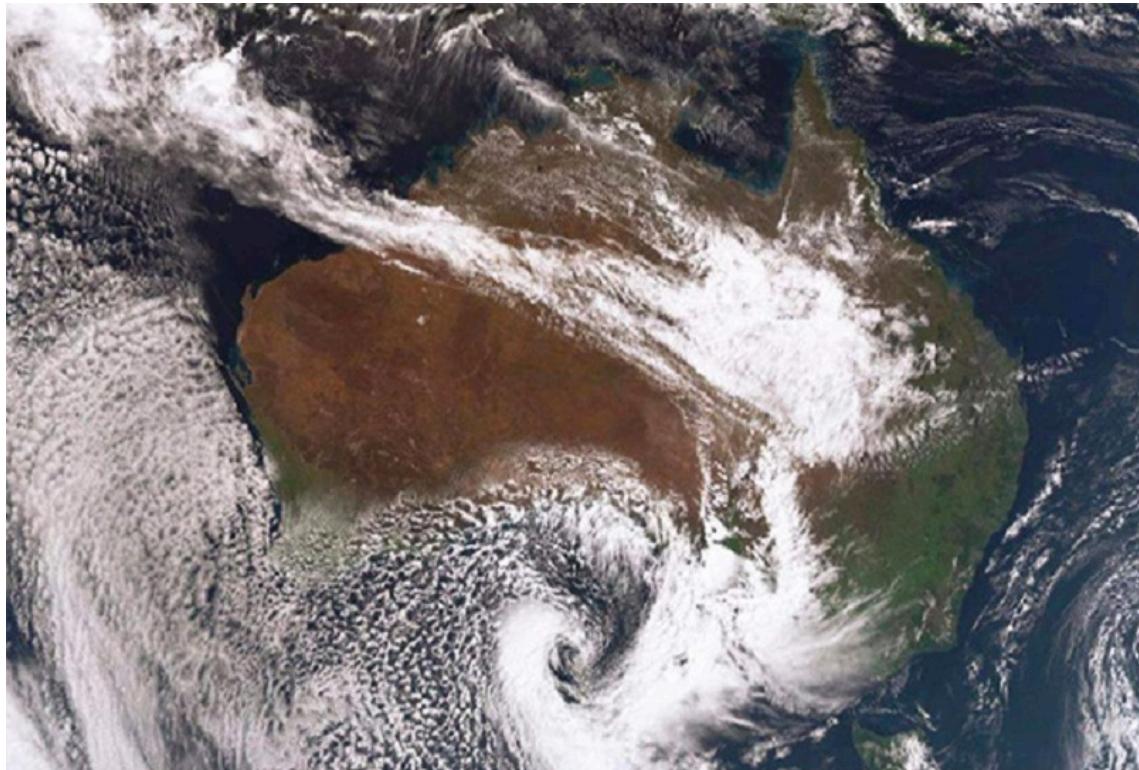
Sam Molnar

CU Boulder, Computer Science

Outline

1. Motivating example
2. Traditional vs. Renewable Generation
3. Previous Work
4. Contributions
5. Experimental Setup
6. Results
7. Conclusions and Future Work

South Australia Blackout – September 2016



Bureau of Meteorology, Australia



Bureau of Meteorology, Australia

South Australia Blackout – September 2016



ABC News: Leah MacLennan. [Accessed](#) 3-6-19



@NinaNewsAdelaide [Nine News Adelaide](#) Accessed 3-9-19

South Australia Blackout – September 2016

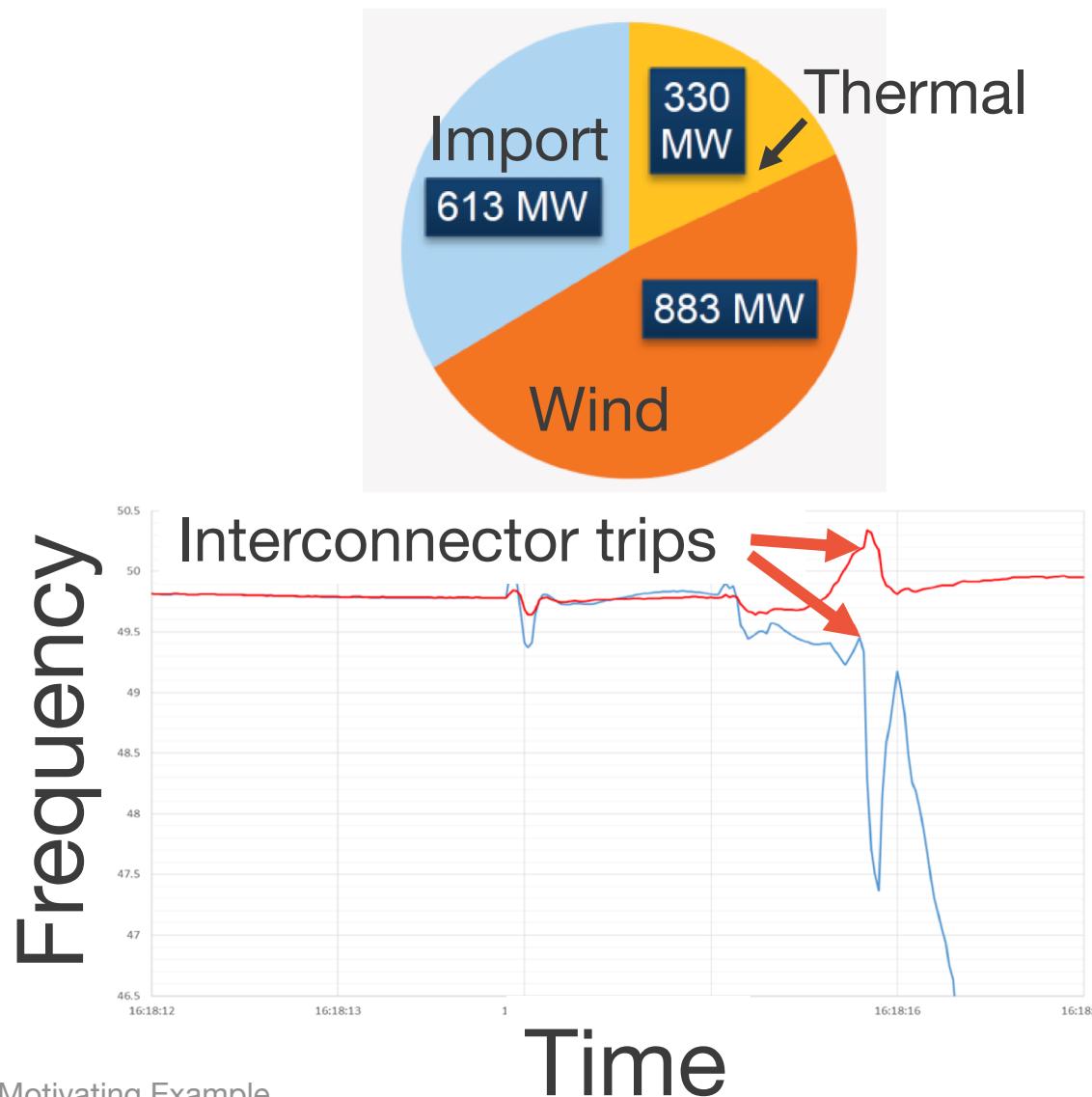


ABC News: Tom Fedorowitsch. [Accessed](#) 3-6-19



CNN Alison Daye. [Accessed](#) 3-6-19

South Australia Blackout – What Happened



South Australia Blackout – Who Cares?

Minister Josh Frydenberg, senator Nick Xenophon question renewables in wake of South Australia blackout

By Latika Bourke, Michael Koziol

Updated September 29, 2016 – 8.29am, first published September 28, 2016 – 11.31pm

Malcolm Turnbull criticises state governments for 'unrealistic' emissions targets over energy security

By political reporter [Stephanie Anderson](#)

Updated 28 Sep 2016, 10:45pm

The Sydney Morning Herald

Blackout report leaves renewables debate dangling in the breeze



David Washington

[@davidwashingto2](#)



Bension Siebert



Image credit: Dennis Schroeder / NREL. Inspecting Turbine Blade at NWTC. August 9, 2013



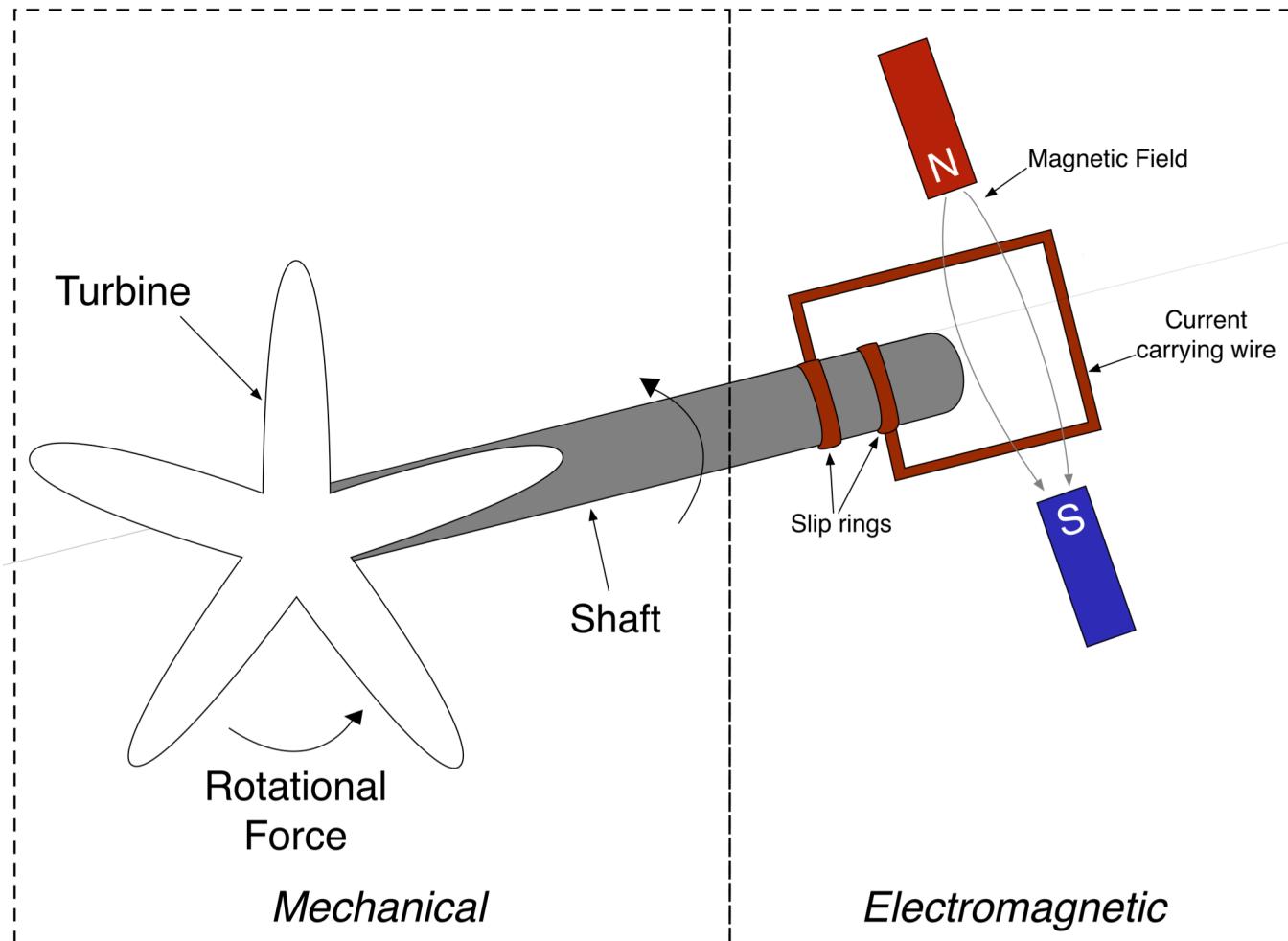
Image credit: Dennis Schroeder / NREL. Boulder rooftop PV. Jun 20, 2017.

Relationship between renewables and stability

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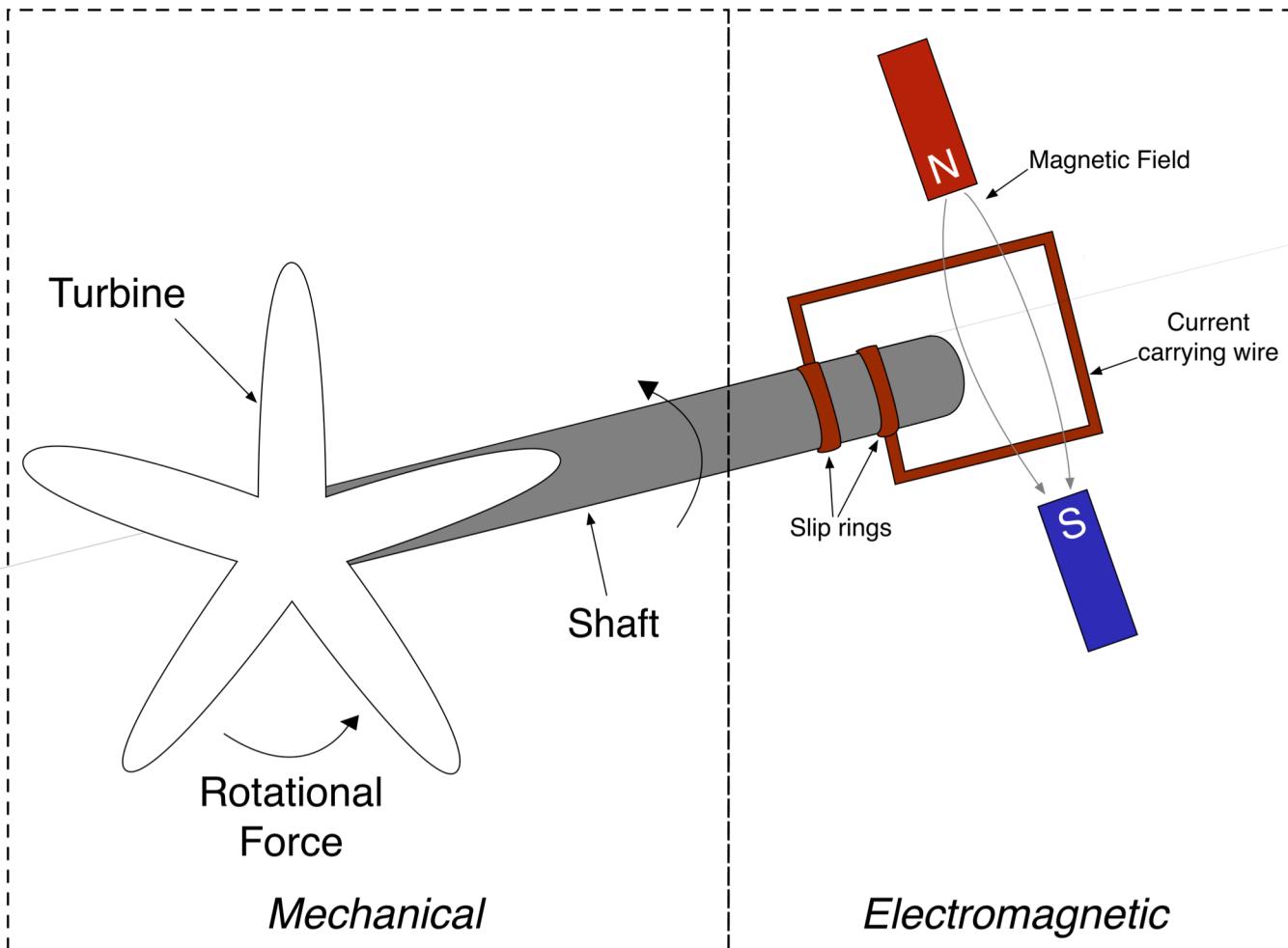
Power Generation



Traditional Generation

- Coal
- Nuclear
- Natural Gas
- Hydro

Power Generation



$$M_g \dot{\omega}_g + D_g \omega_g = P_g - P_e$$

$$\dot{\delta}_g = \omega_g$$

M_g Inertia Constant

D_g Damping Constant

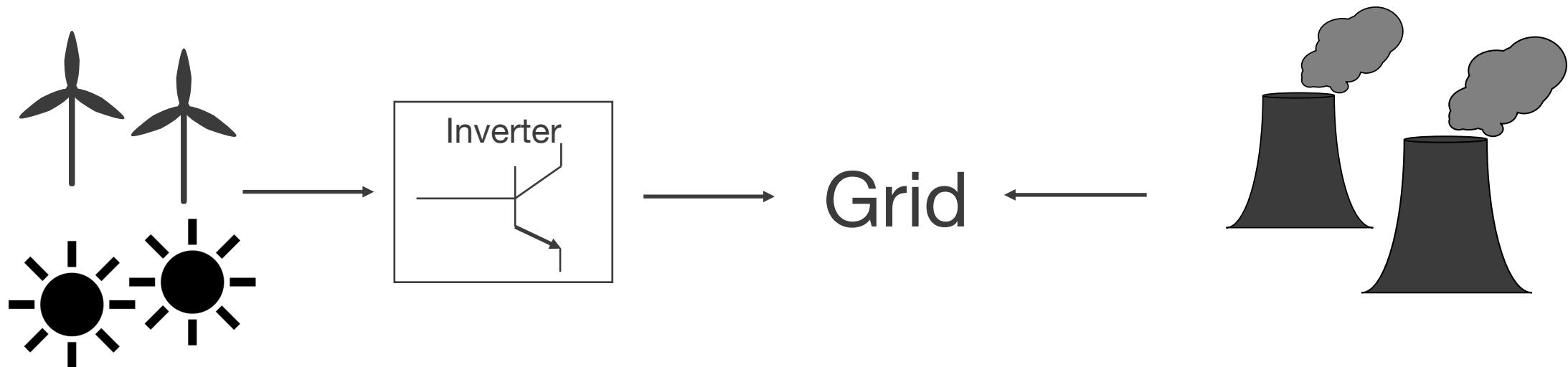
ω_g Rotational Speed

P_g Power Generation

P_e Power consumption

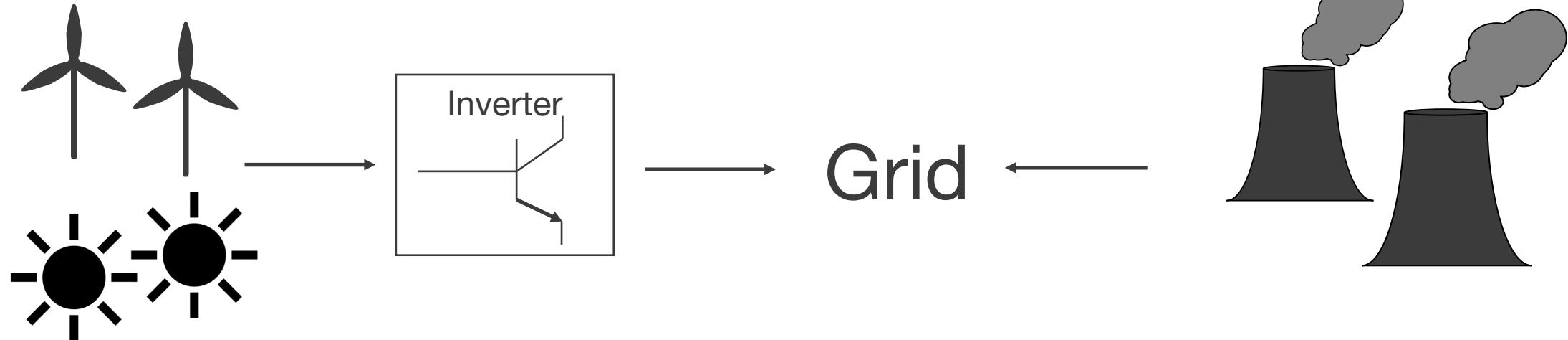
δ_g Voltage Angle

Traditional vs. Renewable



Traditional vs. Renewable

$$D_{RG} \dot{\delta}_{RG} = P_{RG} - P_e$$



$$M_g \dot{\omega}_g + D_g \omega_g = P_g - P_e$$

$$\dot{\delta}_g = \omega_g$$

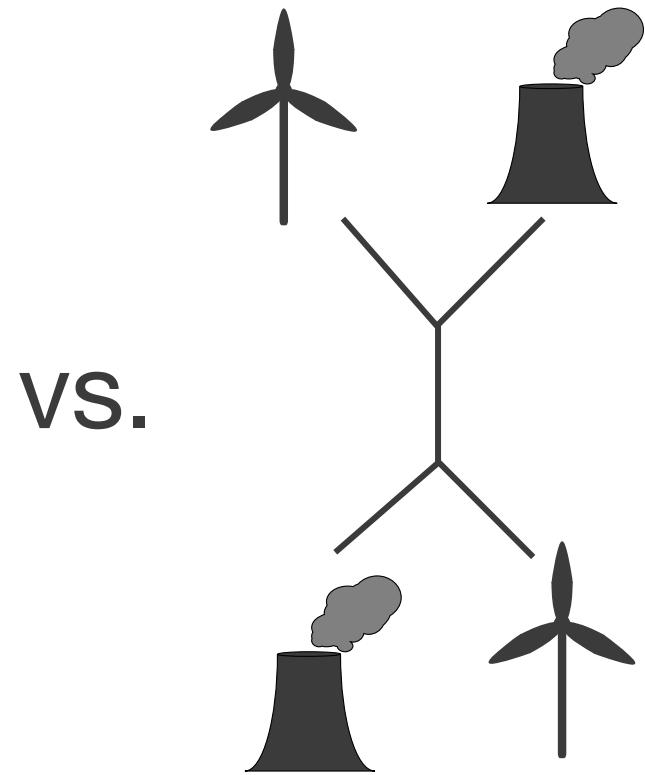
Important Aspects of Inertia

Total System Inertia

$$\begin{array}{c} \text{1} \\ | \\ \text{1} + \text{1} + \text{1} = 3 \end{array}$$

$$\begin{array}{c} \text{1} \\ | \\ \text{1} + \text{1} + \text{Wind Turbine} = 2 \end{array}$$

Structural Distribution of Inertia



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Previous Work—Power Systems

“Amount of inertia is important”

- Frequency deviations increase
- Maximum deviations occur faster

Limitations

- Small test cases
- Limited contingency or inertia scenarios
- Focus on inverter technologies
- Focus on market mechanisms

1. A. Ulbig, T. S. Borsche, and G. Andersson. “Impact of low rotational inertia on power system stability and operation.” IFAC Proceedings Volumes, 47:7290, 2014.
2. A. S. Ahmadyar et. al. “A Framework for Assessing Renewable Integration Limits With Respect to Frequency Performance,” 2018.
3. J. McLoughlin et. al. “Estimating the impact of reduced inertia on frequency stability due to large-scale wind penetration in Australian electricity network,” 2014.
4. N. W. Miller, M. Shao, S. Pajic, and R. D'aquila. “Western wind and solar integration study phase 3 frequency response and transient stability.” Technical report, National Renewable Energy Lab, Golden, CO, 2014.

Previous Work—Power Systems

“Location of inertia is important”

- Locational changes to inertia have a mostly local impact

Limitations

- Small number of contingency or inertia placement scenarios
- Little focus on network structure
- Focus on placing various control mechanisms placement not *differences in dynamics*

1. Xu, Ti et. al. "Metric development for evaluating inertia's locational impacts on system primary frequency response." 2018.
2. Xu, Ti, et. al. "Location-dependent impacts of resource inertia on power system oscillations." 2018.
3. B. K. Poolla, S. Bolognani, and F. Dorfler. "Optimal placement of virtual inertia in power grids." IEEE Transactions on Automatic Control, 62(12):6209, December 2017.
4. Y. Wang, H. Silva-Saravia, and H. Pulgar-Painemal. "Estimating inertia distribution to enhance power system dynamics." pages 1-6, 2017.

Previous Work—Complex Systems

Basin Stability and Synchronization

- Estimate basin of attraction
- “Tree-like” structures are less stable
- Find analytical expressions that guarantee synchronization

Limitations

- Unrealistic assumptions of power system parameters
 - “Assume homogenous coupling”
 - “Assume homogenous inertia values”
- No assessment of power system measures e.g. NADIR, RoCoF...
- Not assessing contingency behavior, only perturbation of oscillator state variables

1. P. Schultz, J. Heitzig, and J. Kurths. Detours around basin stability in power networks. *New Journal of Physics*, 16(12):125001, 2014.
2. P. J. Menck, J. Heitzig, N. Marwan, and J. Kurths. How basin stability complements the linear-stability paradigm. *Nature physics*, 9(2):89, 2013.
3. P. J. Menck, J. Heitzig, J. Kurths, and J. H. Schellnhuber. How dead ends undermine power grid stability. *Nature communications*, 5:3969, 2014.
4. F. Dorfler and F. Bullo. Synchronization and transient stability in power networks and nonuniform kuramoto oscillators. *SIAM J. Control Optim.*, 50(3):1616–1642, 2012.

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Contributions

Total System Inertia

- Estimate the functional relationship between total system inertia and stability metrics
- Explore the relationship between network *structure* and stability with changing inertia

Structural Distribution of Inertia

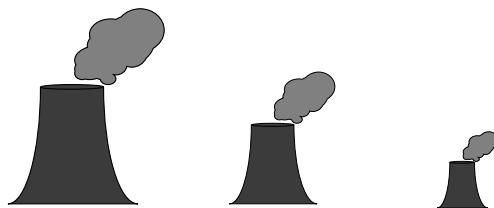
- How does network structure contribute or inhibit frequency propagation
 - Motif analysis -> Which structures enhance frequency propagation
 - Basin stability -> How does changing inertia location alter the stability of particular nodes?

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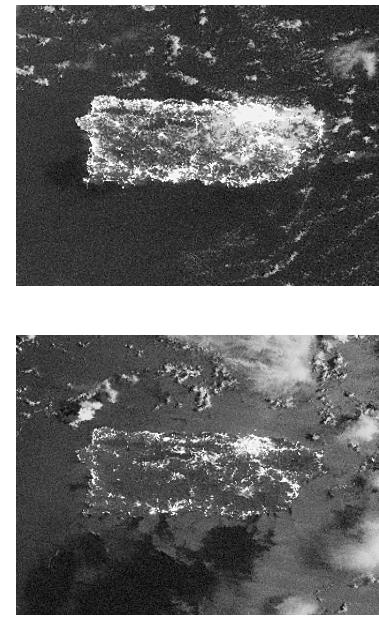
Experiment

Setup Inertia



$$M_{tot} = \sum_{g=1}^{n_g} M_g$$

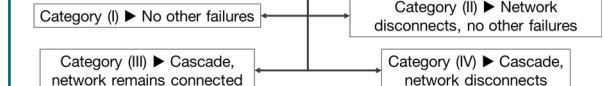
Simulate Cascade



Analyze Results

$$f = \frac{\sum_{g=1}^{n_g} M_g \omega_g}{M_{tot}}$$

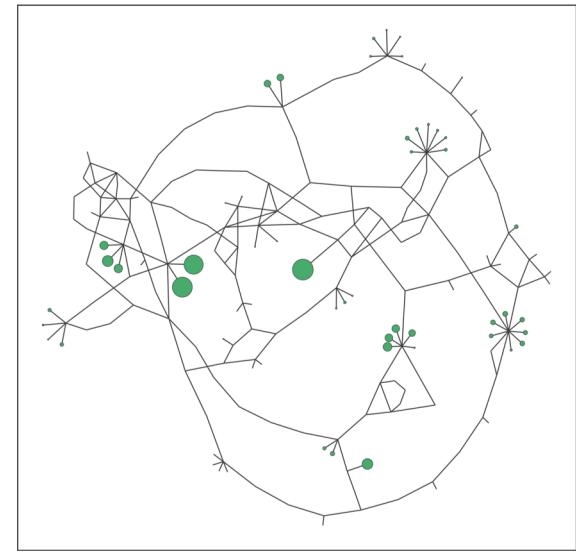
Initial Contingency



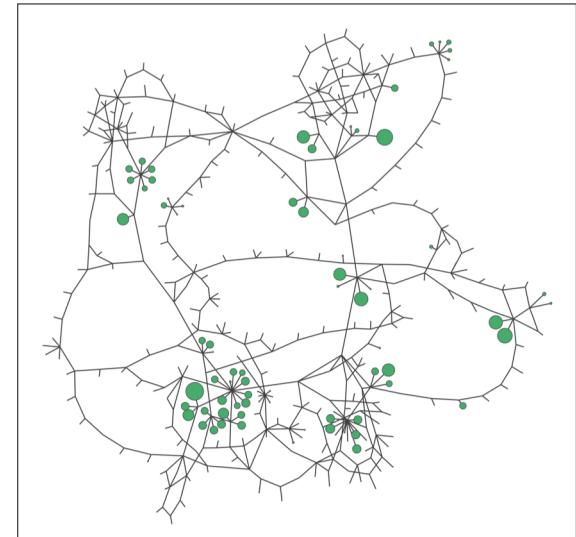
Power System Test Cases

- Topology
 - Delauney Triangulation and minimum spanning tree
- Load
 - Population size \propto Power Consumption
- Generation
 - Amount and type from EIA
- Line Parameters
 - Statistically pick radius and conductor type
- Dynamical Parameters
 - Draw from distributions of known cases

Central Illinois



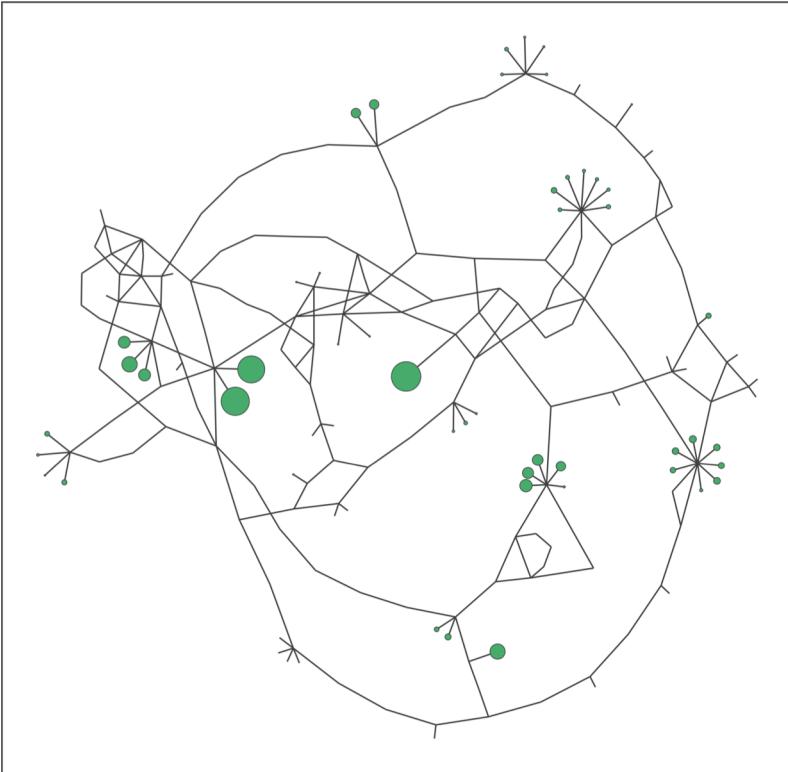
South Carolina



1. T. Xu, A. B Bircheld, K. S Shetye, and T. J Overbye. Creation of synthetic electric grid models for transient stability studies. In IREP Symposium Bulk Power System Dynamics and Control, 2017.
2. T. Xu, A. B. Bircheld, and T. J. Overbye. Modeling, tuning, and validating system dynamics in synthetic electric grids. IEEE Transactions on Power Systems, 33(6):6501–6509, 2018.
3. A. B. Bircheld, Ti Xu, K. M. Gegner, K. S. Shetye, and T. J. Overbye. Grid structural characteristics as validation criteria for synthetic networks. IEEE Transactions on Power Systems, 32(4):3258{3265, 2017.

Power System Test Cases

Central Illinois



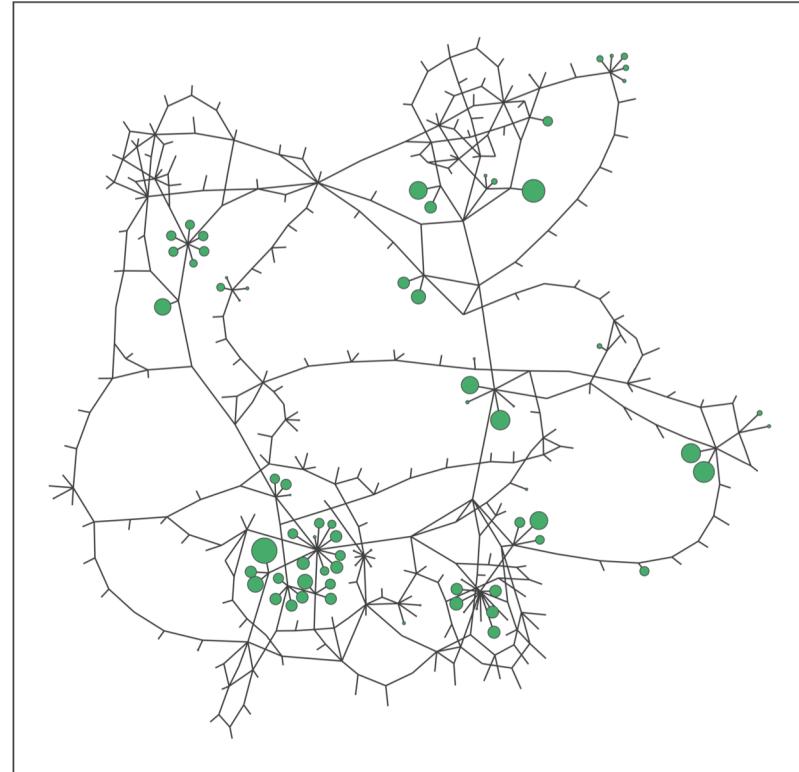
$$M_{tot} = 29.61$$

$$n_b = 200$$

$$n_g = 49$$

$$n_l = 245$$

South Carolina



$$M_{tot} = \sum_{g=1}^{n_g} M_g$$

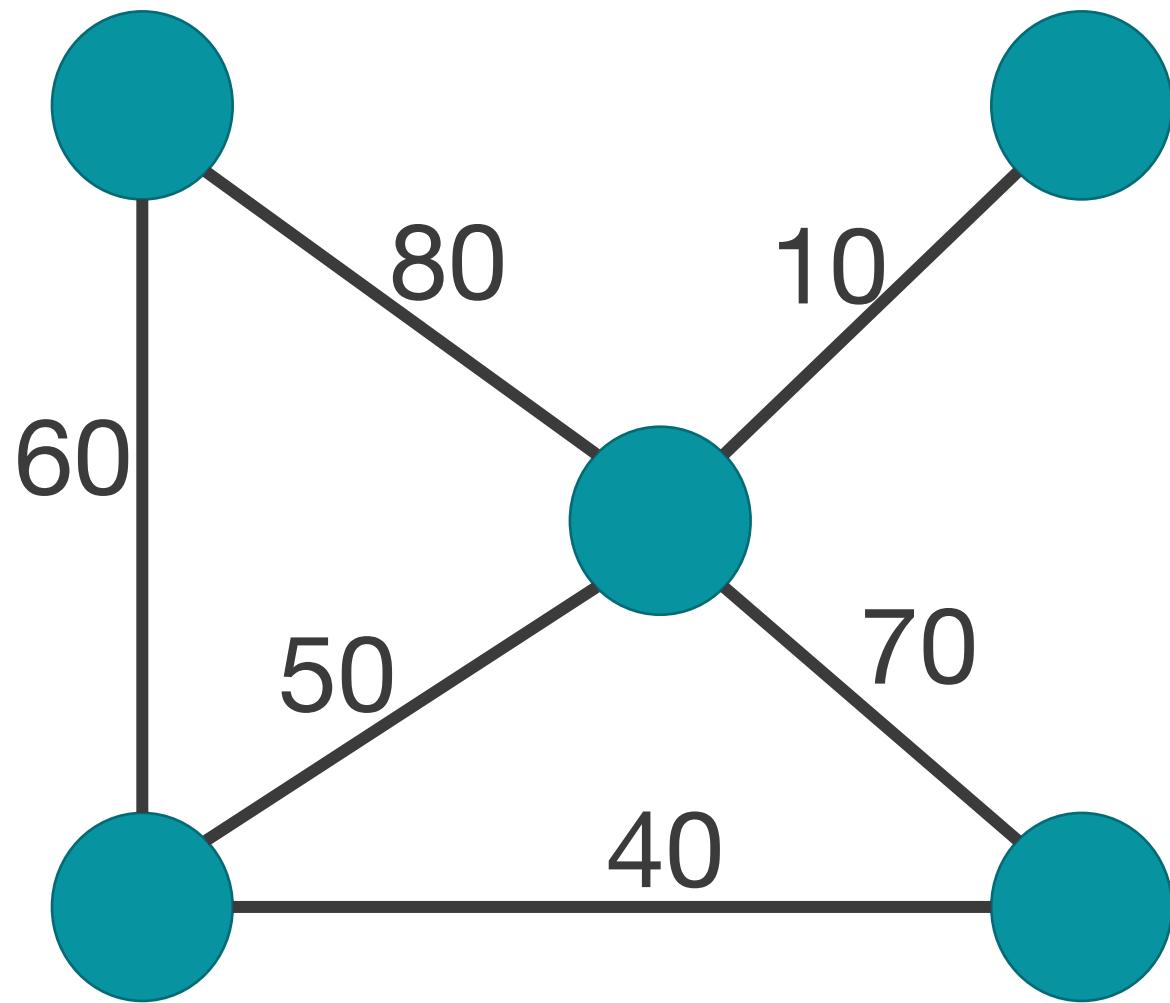
$$M_{tot} = 139.13$$

$$n_b = 500$$

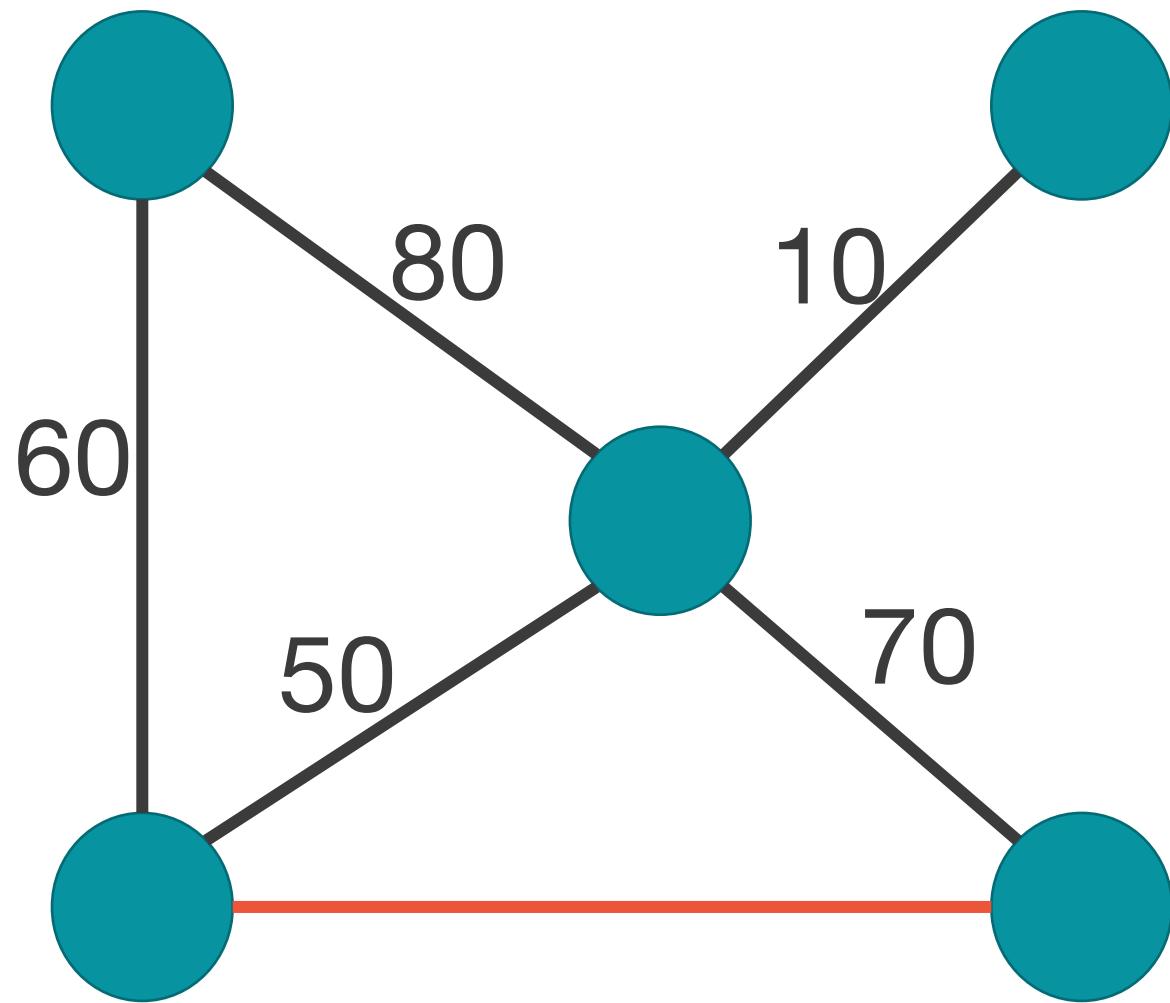
$$n_g = 90$$

$$n_l = 584$$

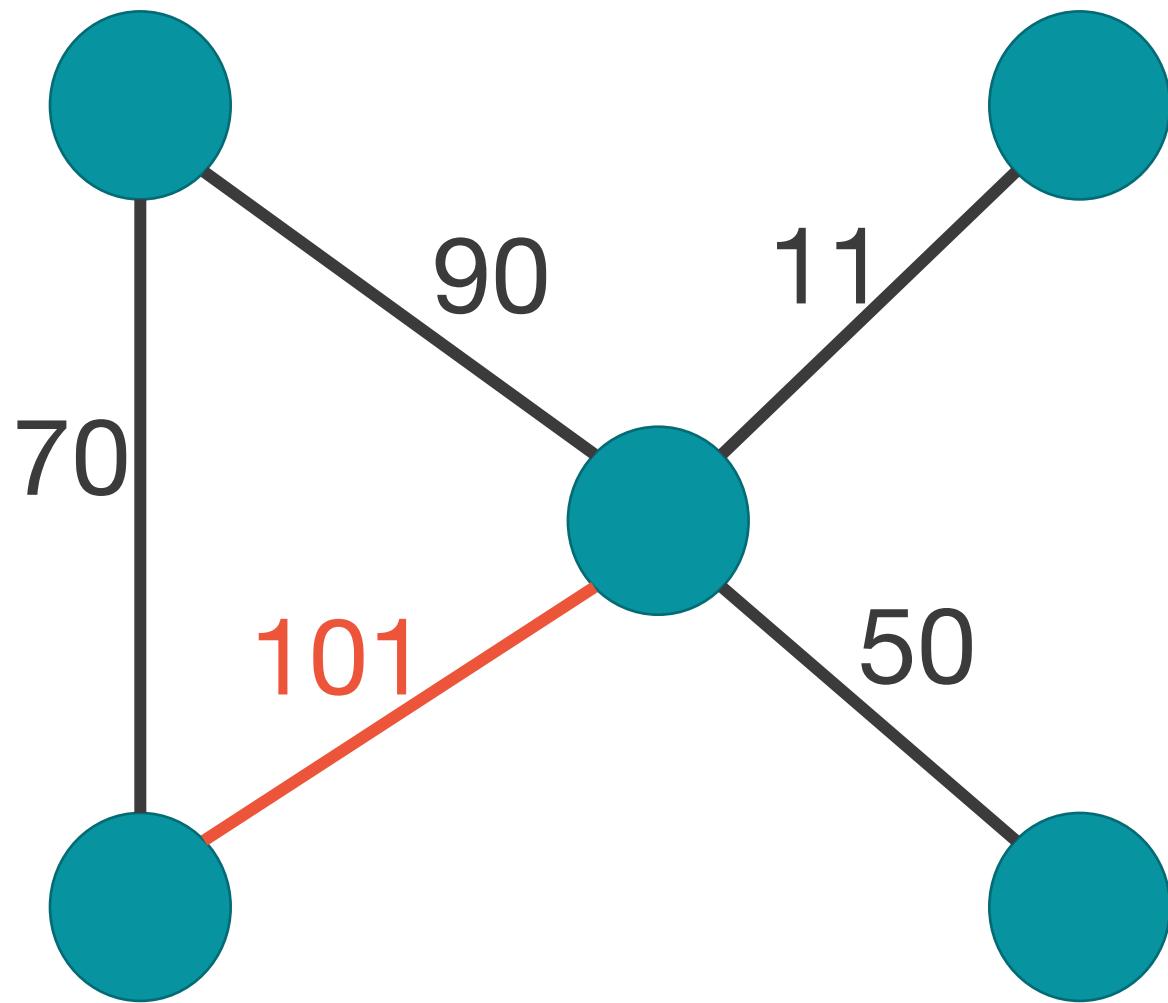
Cascading Failures—Definition



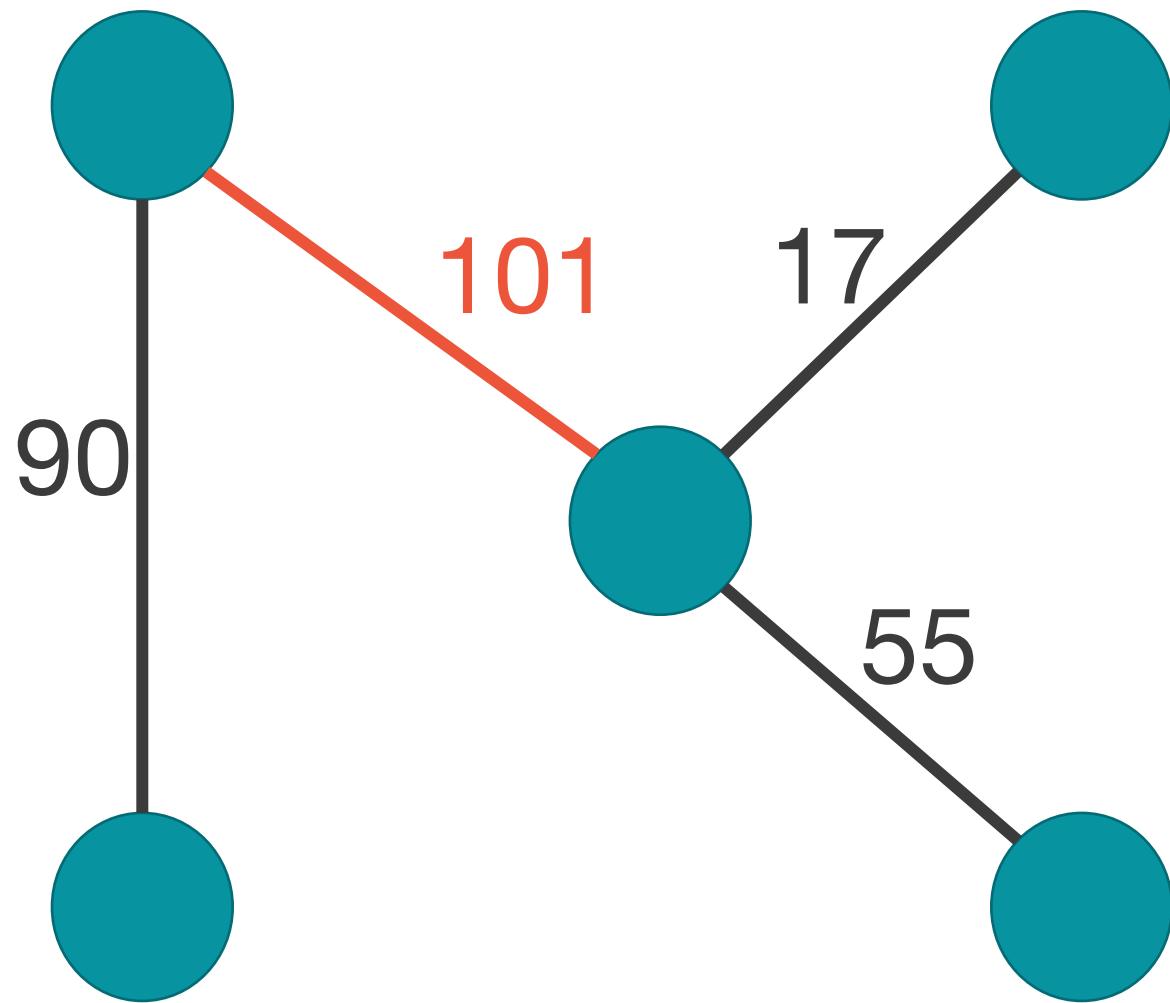
Cascading Failures—Definition



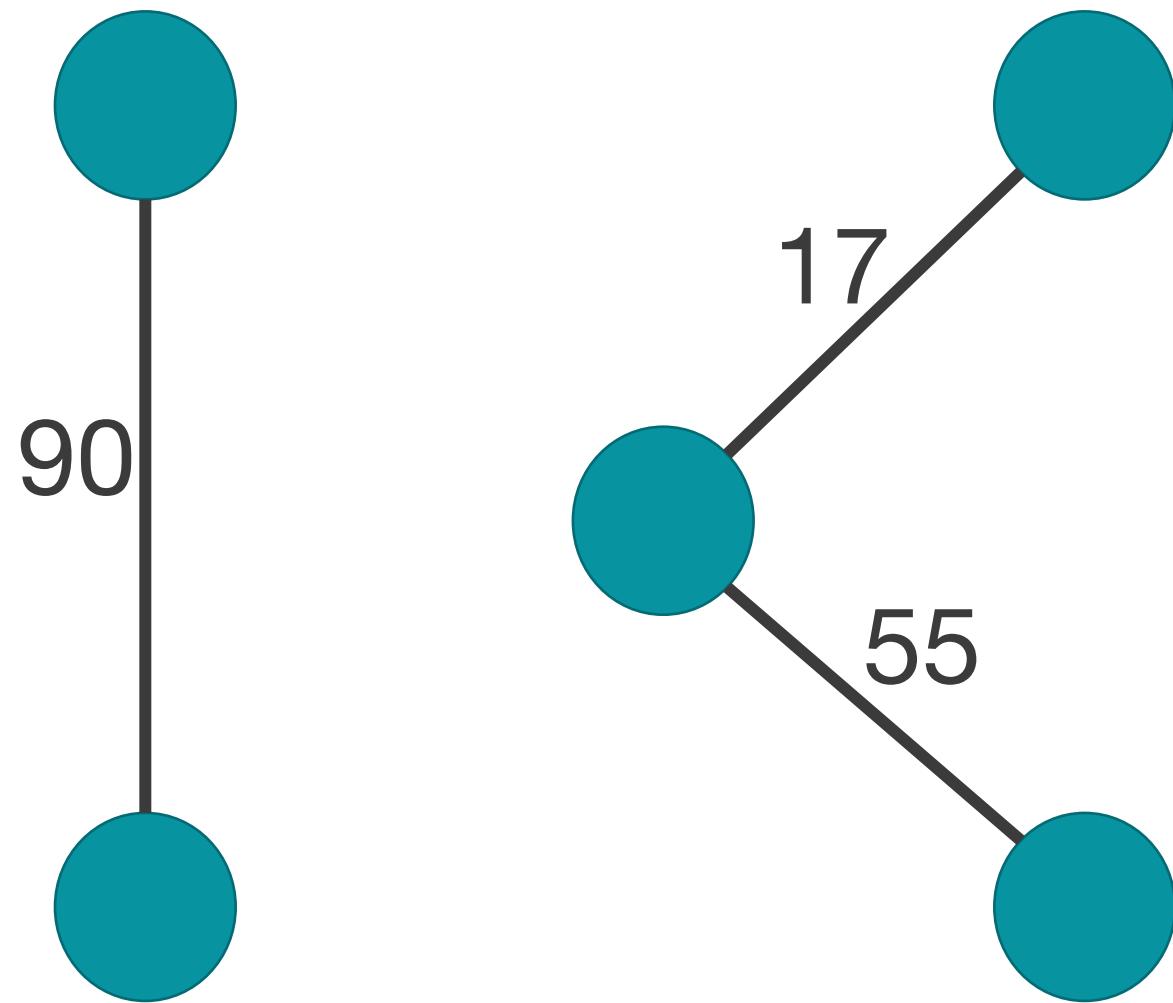
Cascading Failures—Definition



Cascading Failures—Definition



Cascading Failures—Definition



Cascading Failures - Model

$$\forall g \in Gens \quad \begin{cases} \dot{\omega}_g = -\frac{D_g}{M_g} \omega_g - \frac{1}{M_g} (P_g + \sum_{\forall i \notin G} B_{gi} \sin(\delta_g - \delta_i)) \\ \dot{\delta}_g = \omega_g - \omega_1 \end{cases}$$

$$\forall RG \in Gens \quad \dot{\delta}_{RG} = -\frac{1}{D_{RG}} (P_{RG} + \sum_{j=1}^{n_b} B_{RGj} \sin(\delta_{RG} - \delta_j)) - \omega_1$$

Power on lines connected to node

$$\forall i \notin Gens \quad \dot{\delta}_i = -\frac{1}{D_i} (P_i + \sum_{j=1}^{n_b} B_{ij} \eta_{ij} \sin(\delta_i - \delta_j)) - \omega_1$$

Line status

$$\forall i, j \in E \quad \dot{\eta}_{ij} = 10(f(\eta_{ij}) - \frac{B_{ij}(1 - \cos(\delta_i - \delta_j))}{W_{ij}})$$

Current line capacity

Maximum line capacity

i, j Buses
δ Voltage Angle
ω_1 Reference Frequency
P_i Power consumption or generation at bus i
B_{ij} Line Susceptance
D_i Damping Constant
M_g Inertia Constant

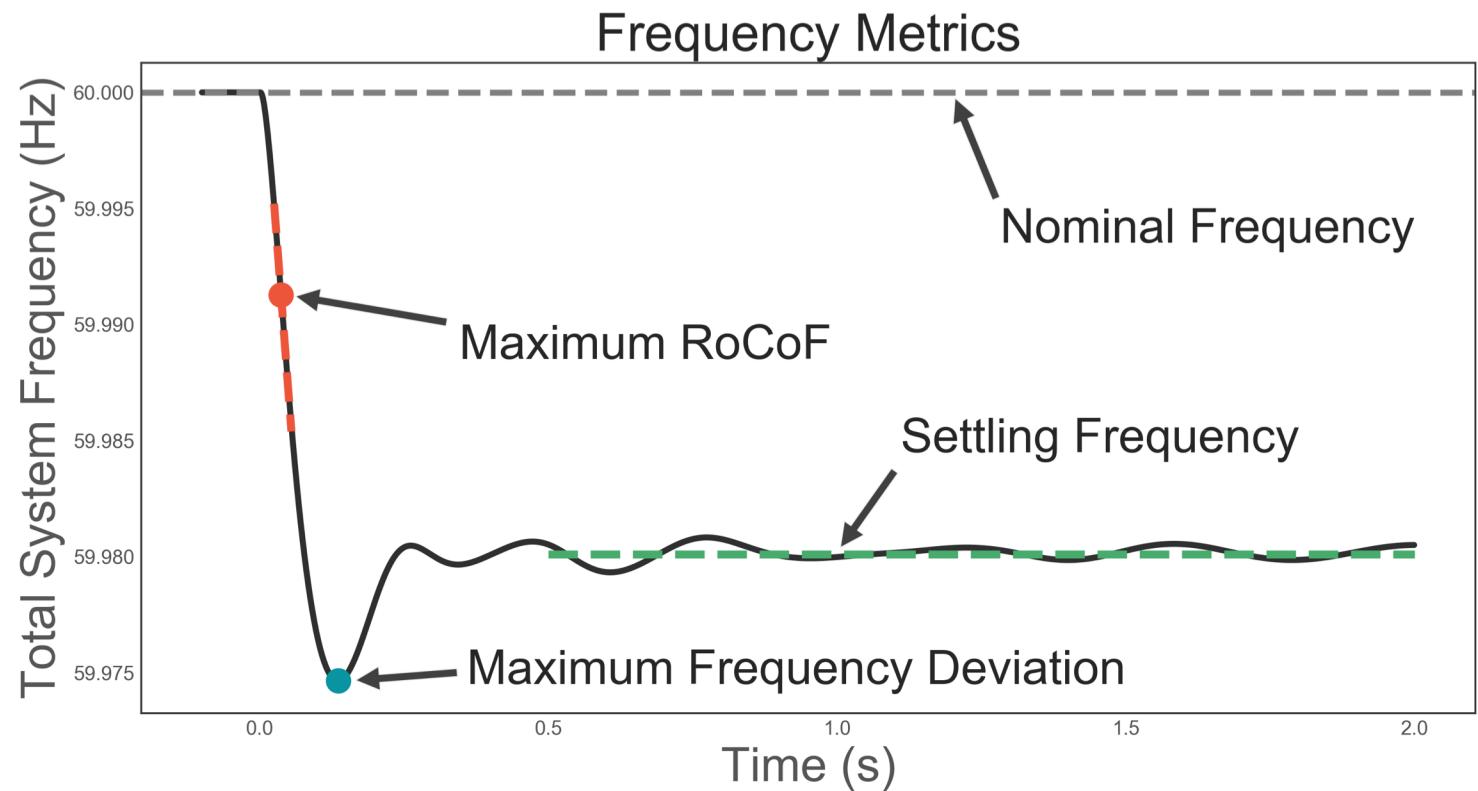
Cascading Failures - Model

Assumptions

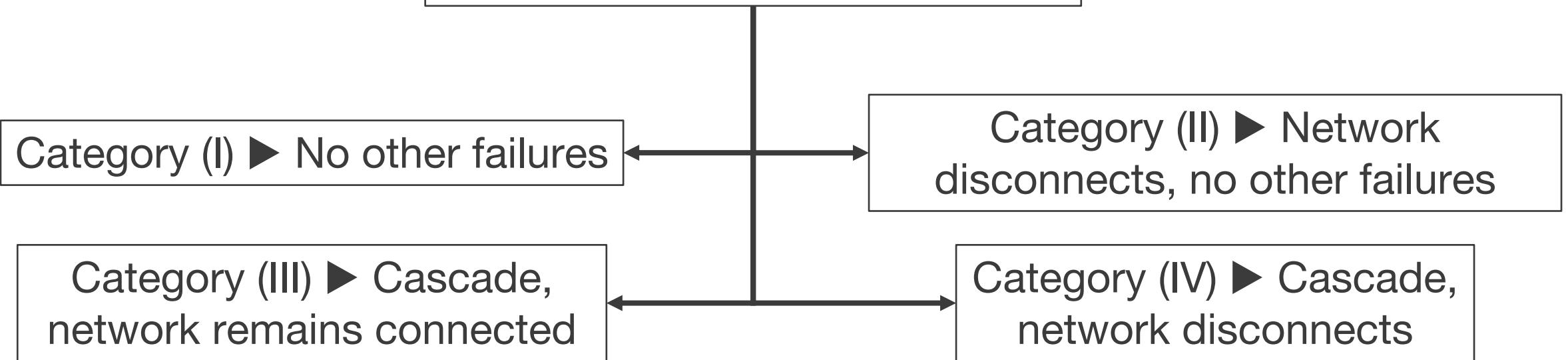
- Voltage magnitudes ≈ 1
- Transmission lines have no resistance
- Renewable generation is constant
- Not solving for reactive power
- No ancillary services
- Only limitations are line capacities

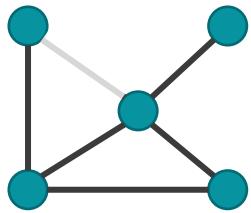
Frequency Stability

$$f = \frac{\sum_{g=1}^{n_g} M_g \omega_g}{2\pi \sum_{g=1}^{n_g} M_g}$$



Initial Contingency





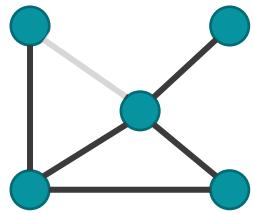
Initial Contingency

Category (I) ► No other failures

Category (II) ► Network disconnects, no other failures

Category (III) ► Cascade, network remains connected

Category (IV) ► Cascade, network disconnects



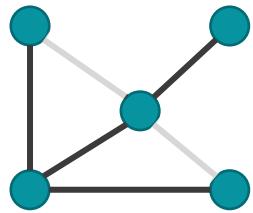
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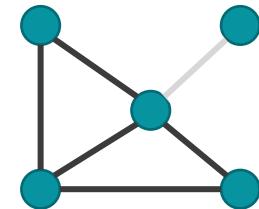
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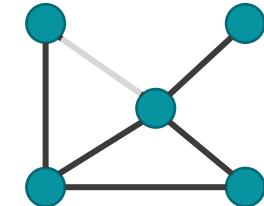
Initial Contingency

Category (I) ► No other failures

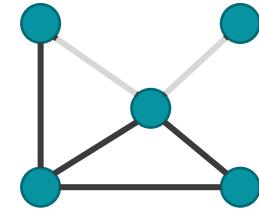
Category (II) ► Network disconnects, no other failures

Category (III) ► Cascade, network remains connected

Category (IV) ► Cascade, network disconnects



Initial Contingency



Category (I) ► No other failures

Category (II) ► Network disconnects, no other failures

Category (III) ► Cascade, network remains connected

Category (IV) ► Cascade, network disconnects

Initial Contingency

More Stable

Category (I) ► No other failures

Less Stable

Category (II) ► Network disconnects, no other failures

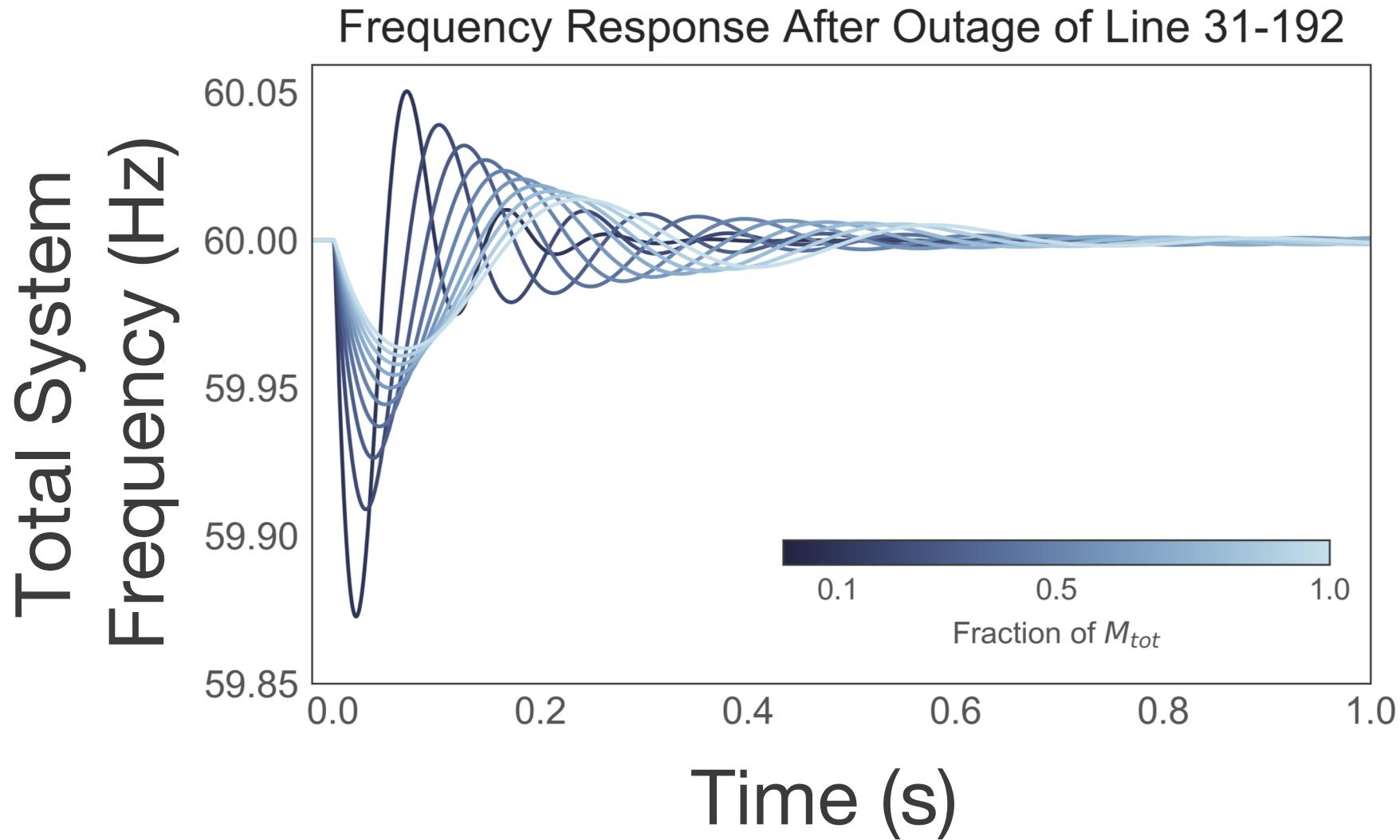
Category (III) ► Cascade, network remains connected

Category (IV) ► Cascade, network disconnects

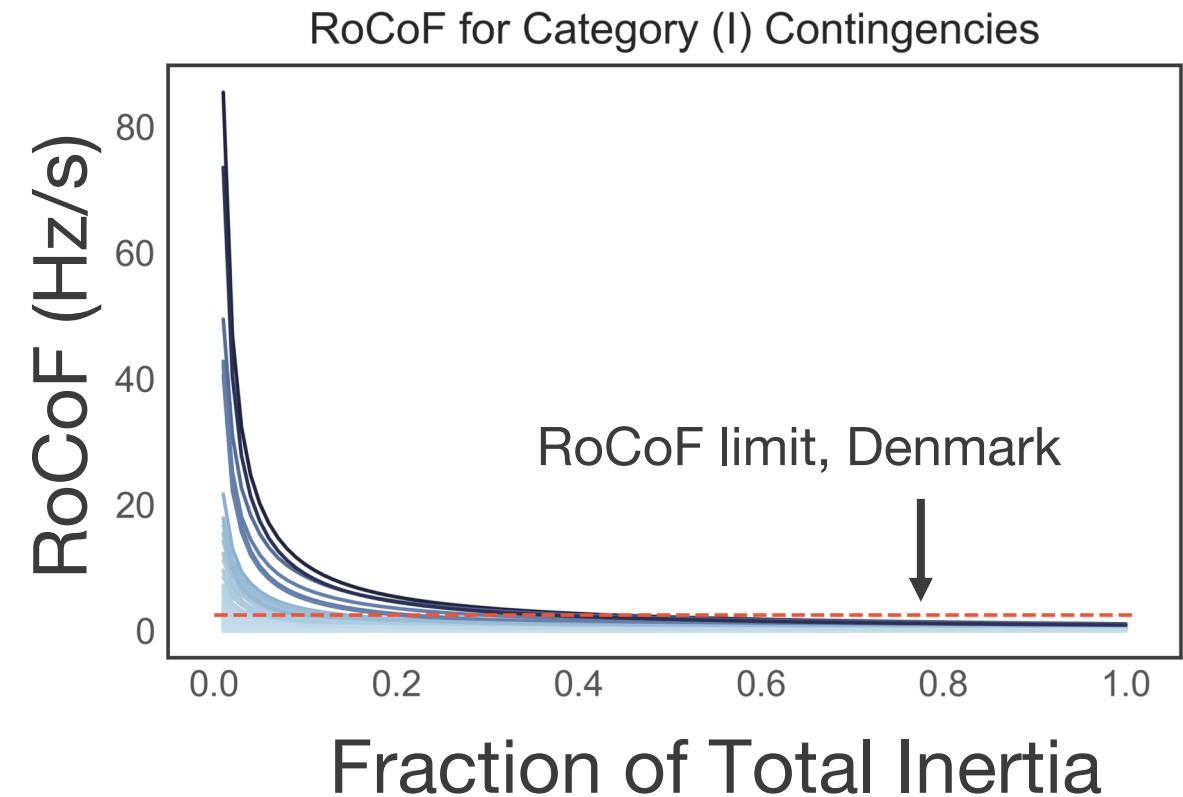
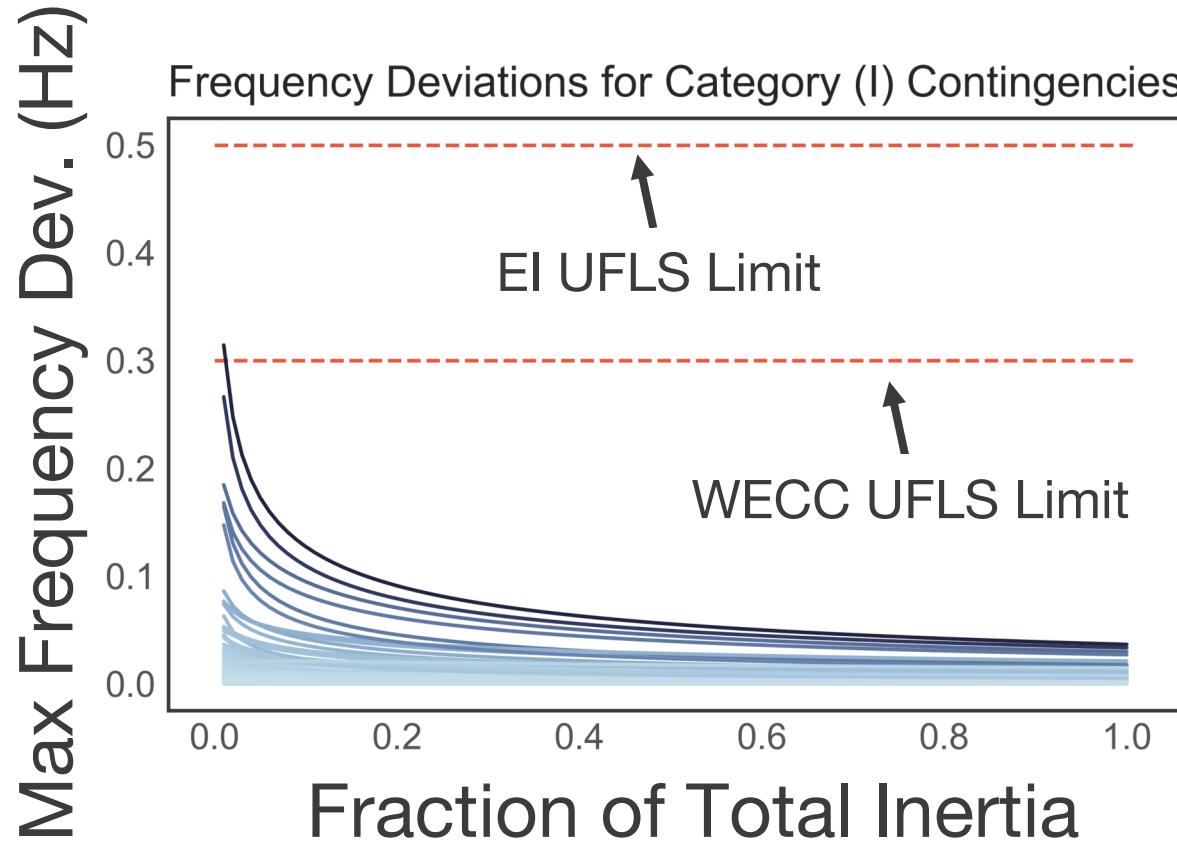
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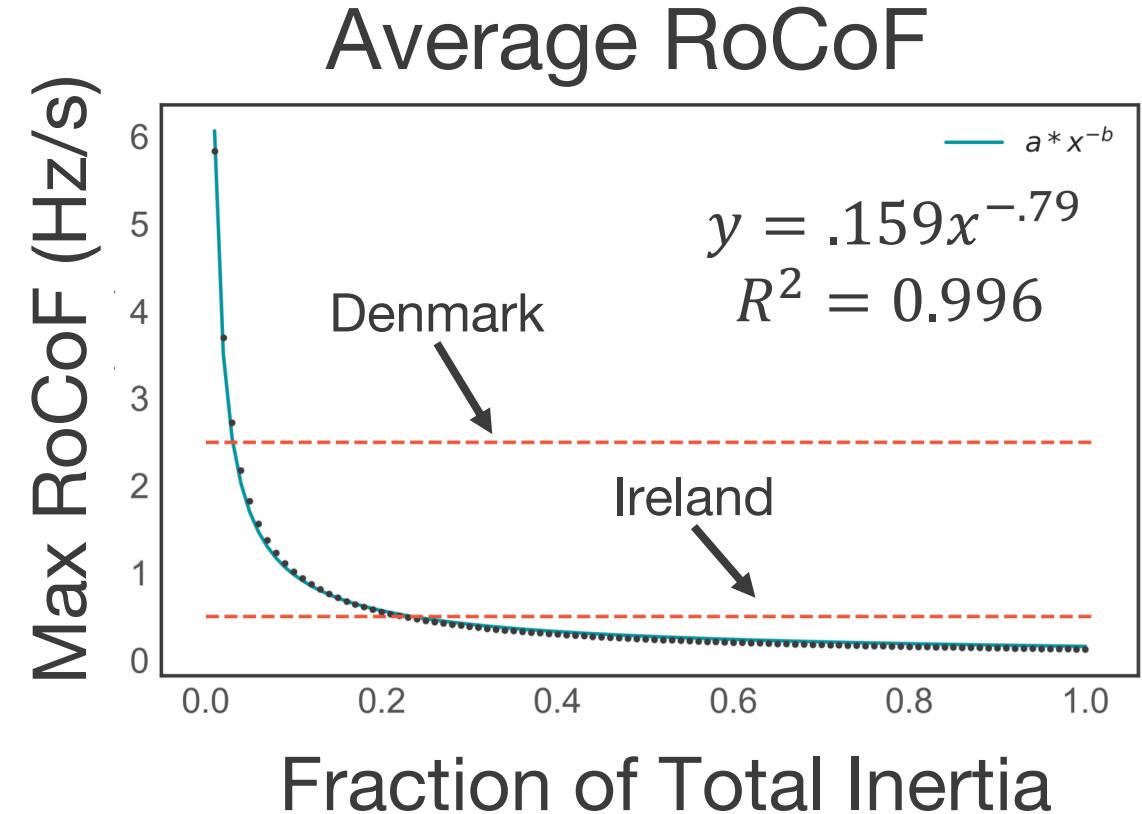
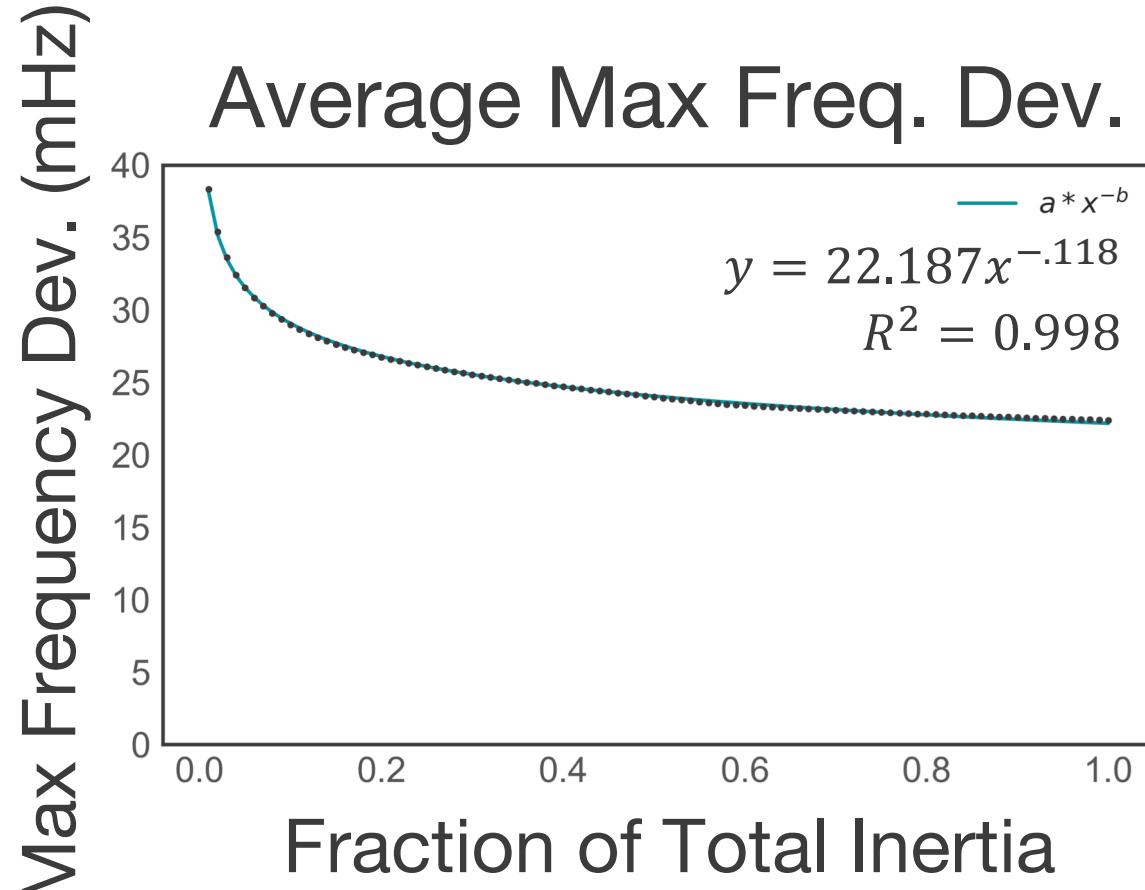
Category (I) – Illinois



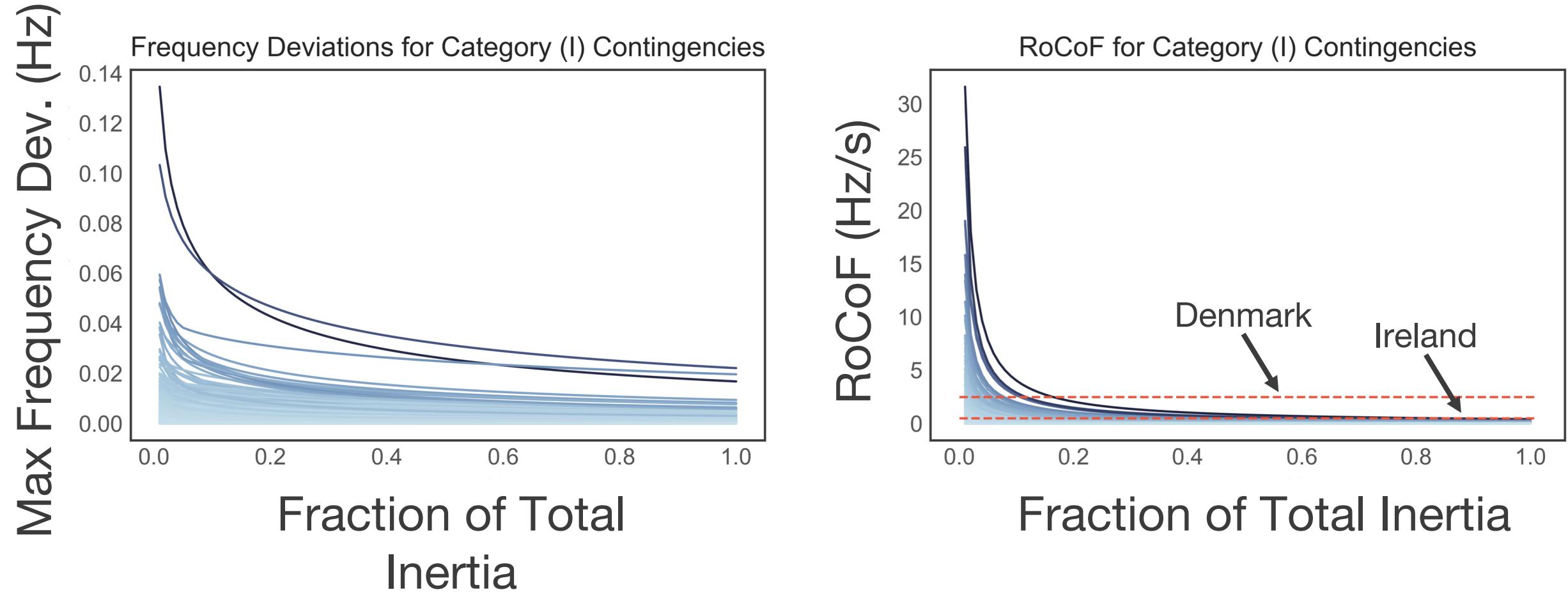
Category (I) – Illinois



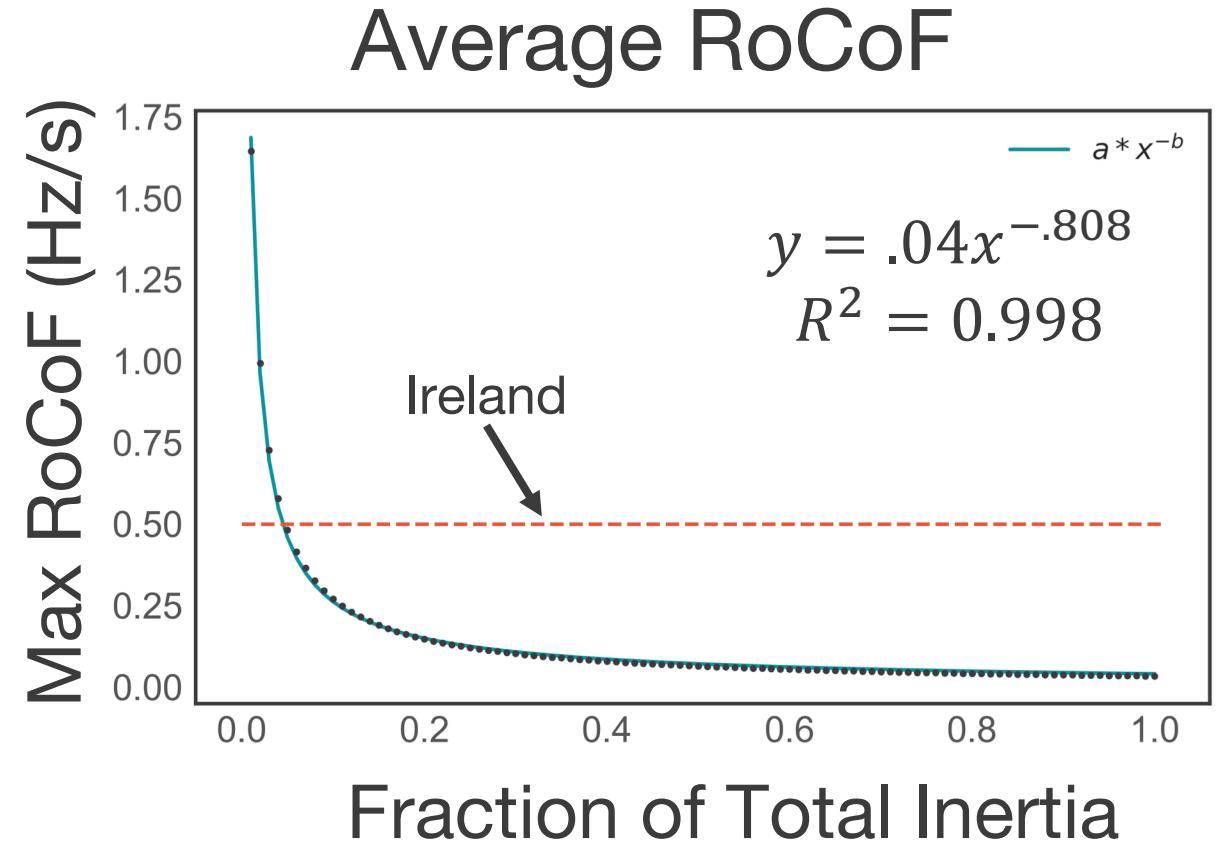
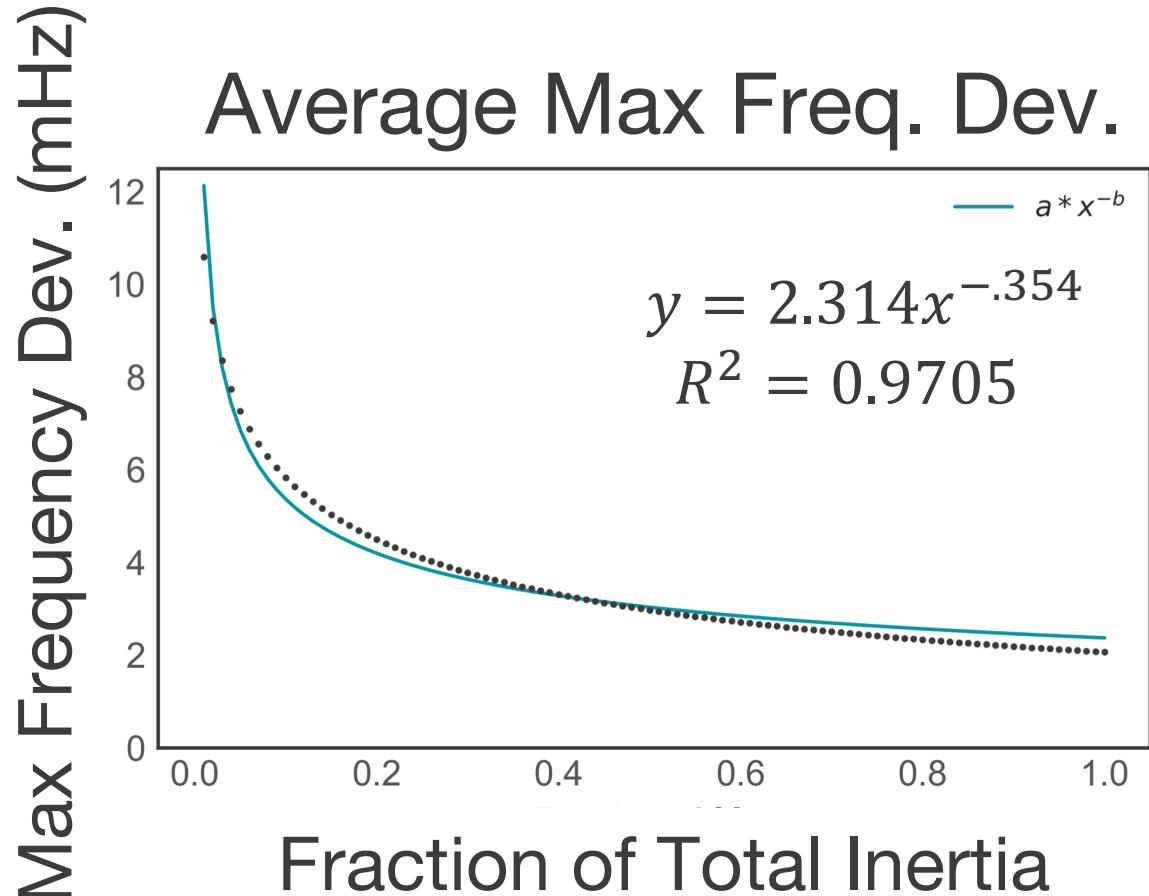
Category (I) – Illinois



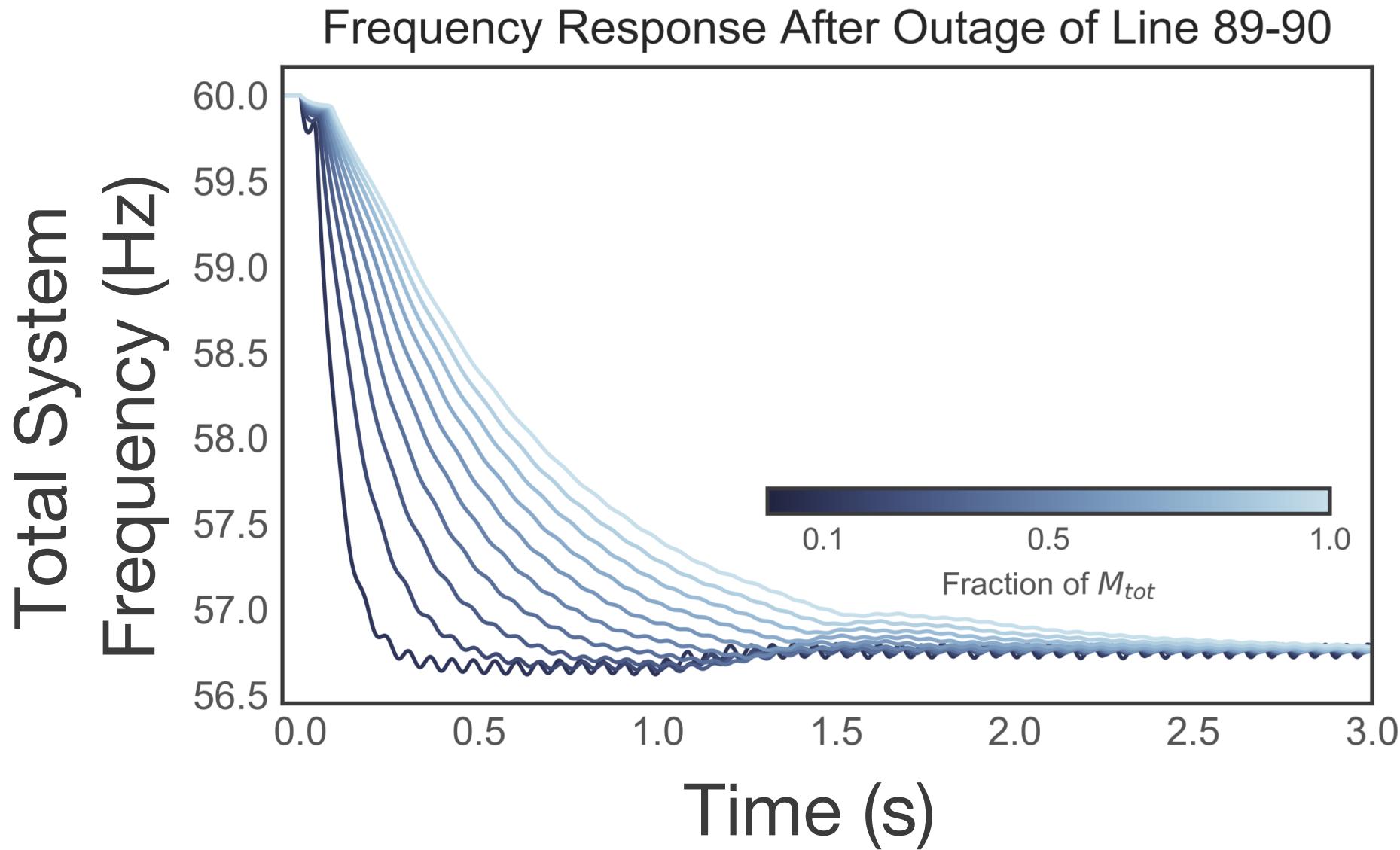
Category (I) – South Carolina



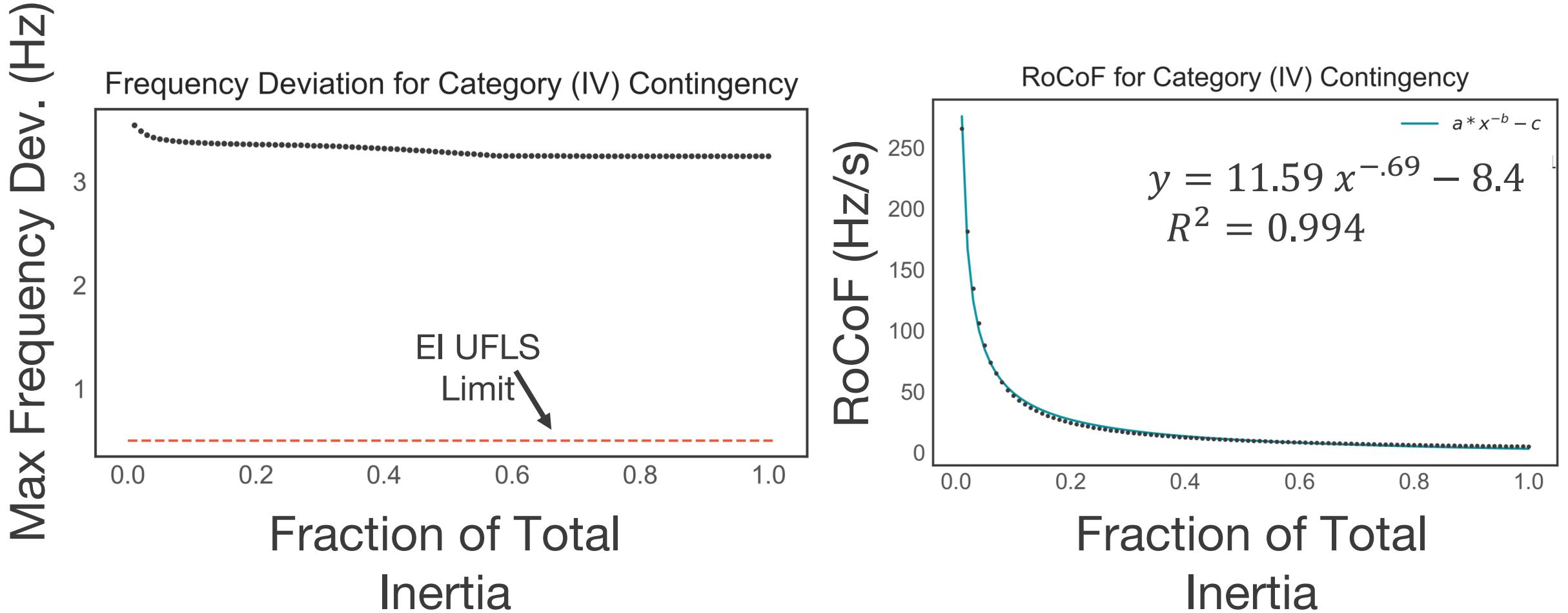
Category (I) – South Carolina



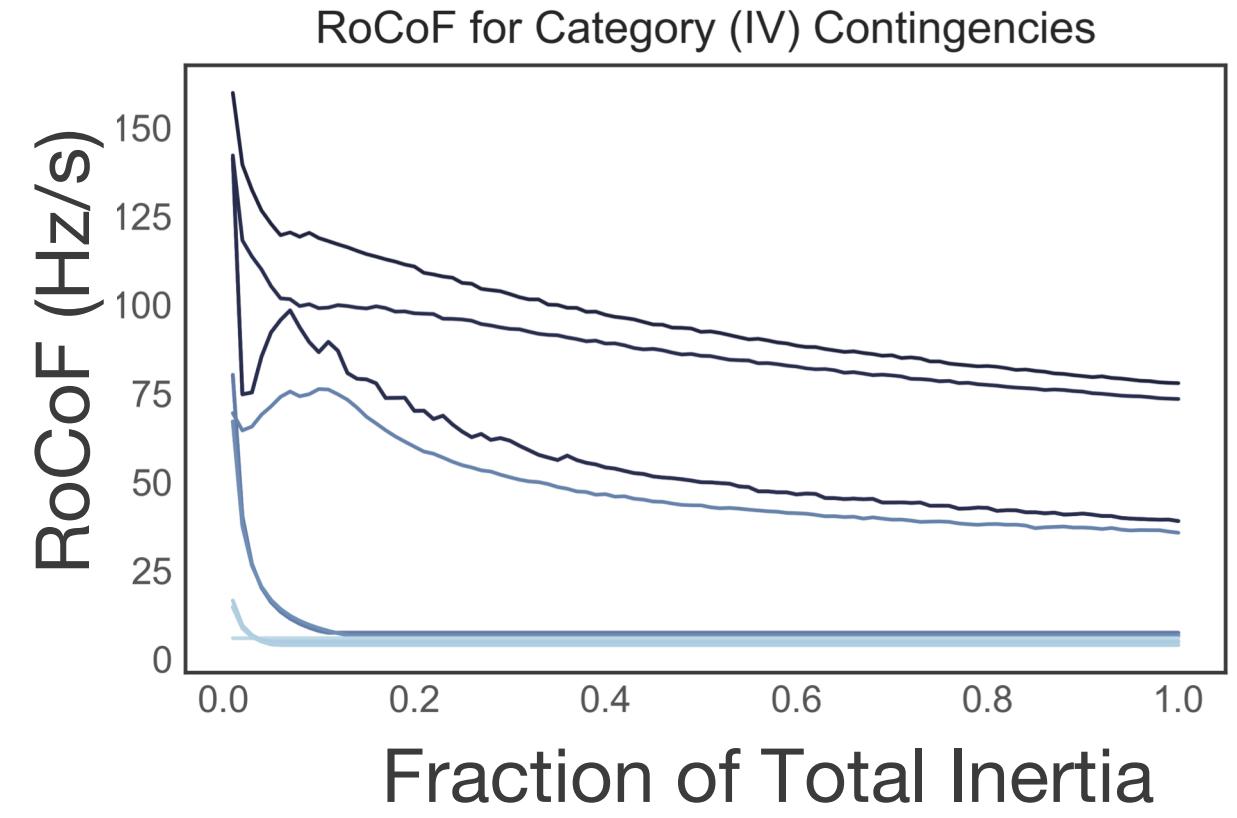
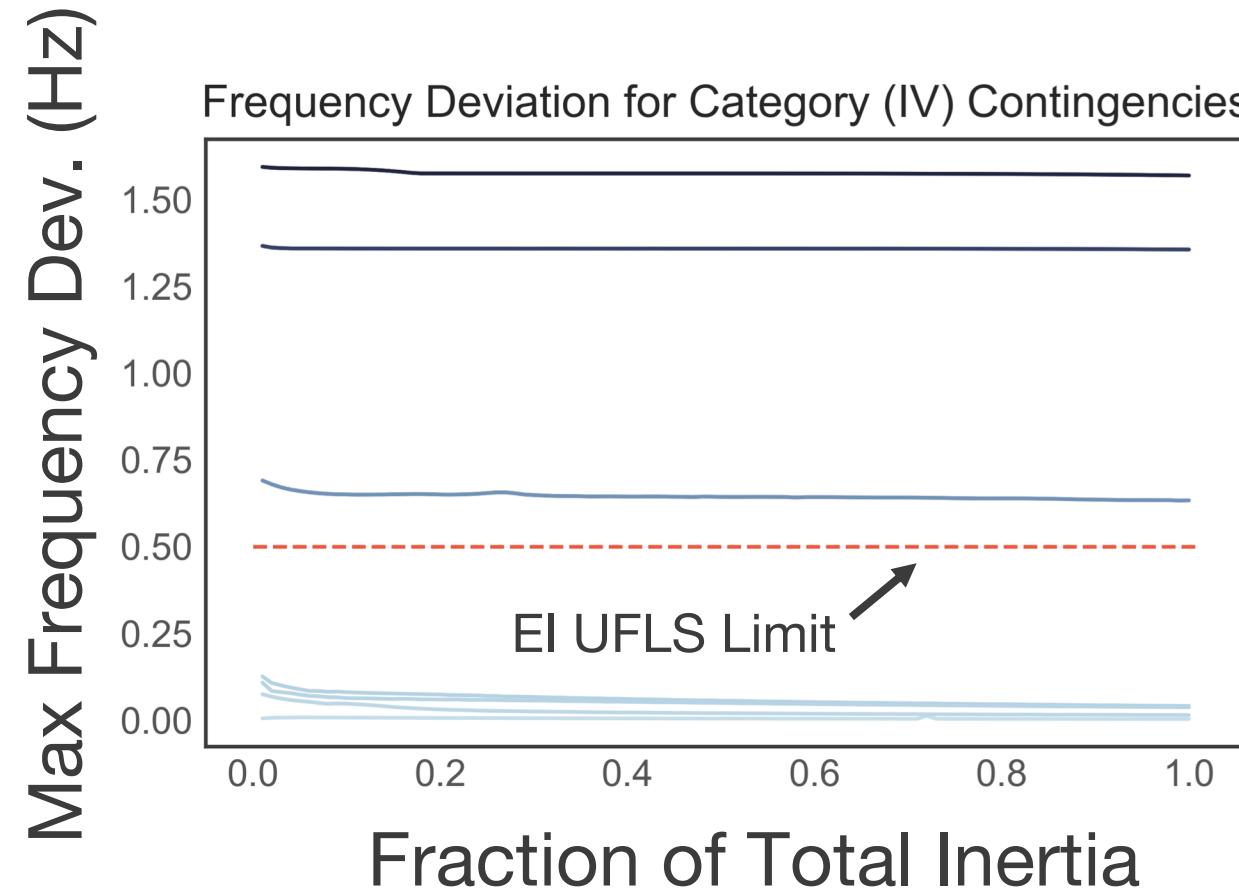
Category (IV) – Illinois



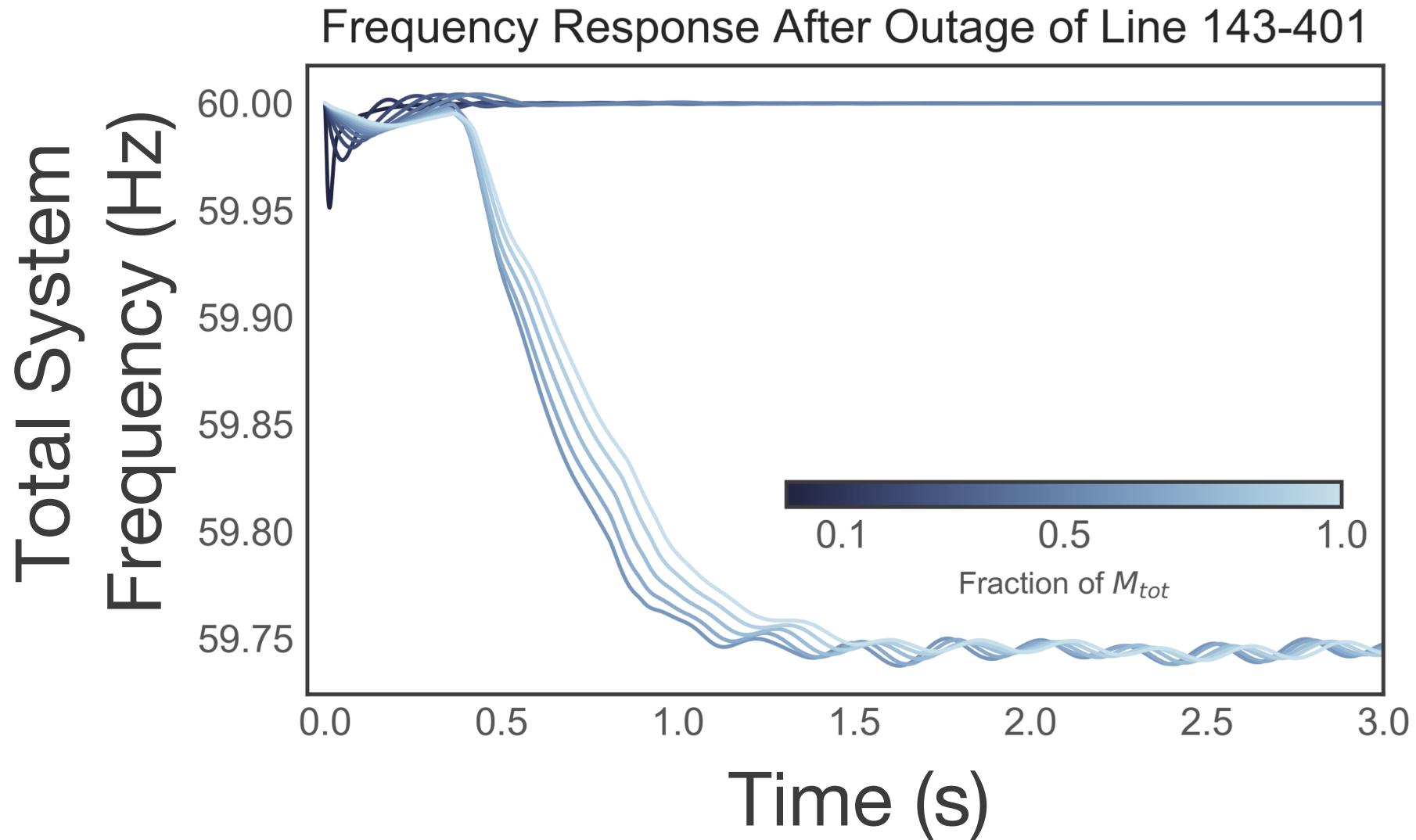
Category (IV) – Illinois



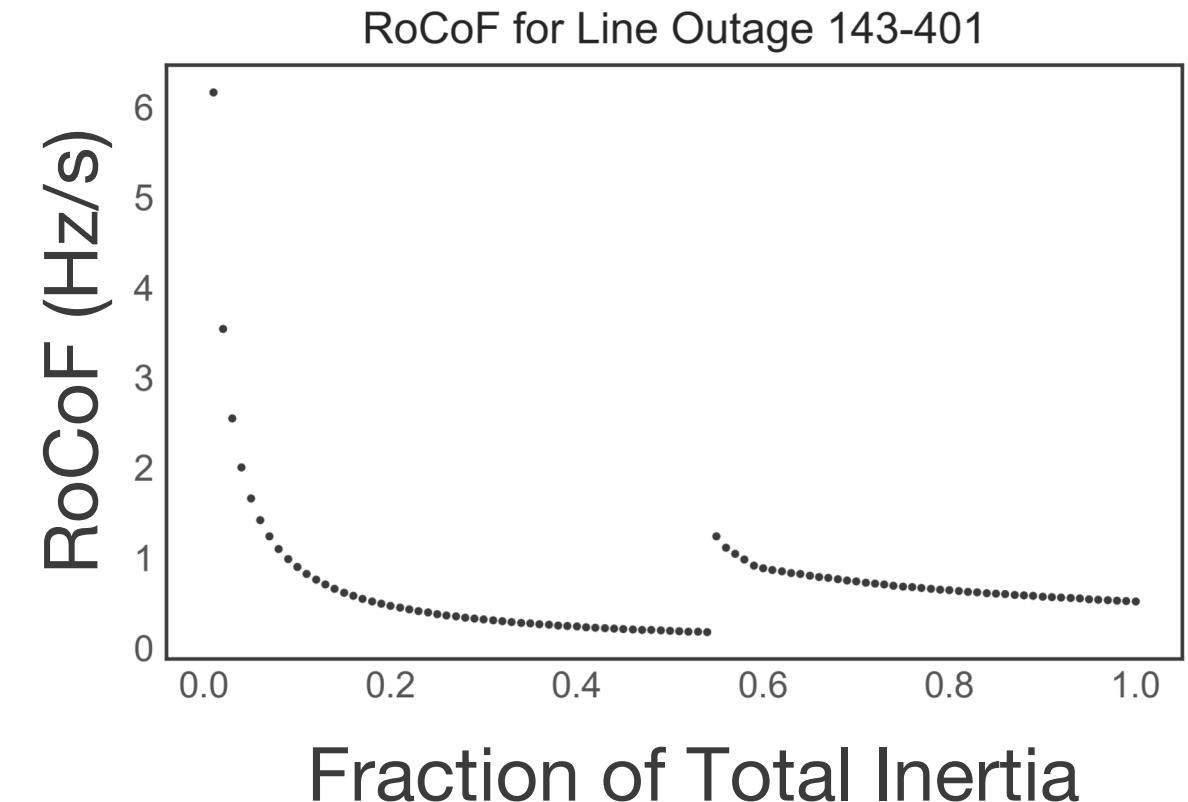
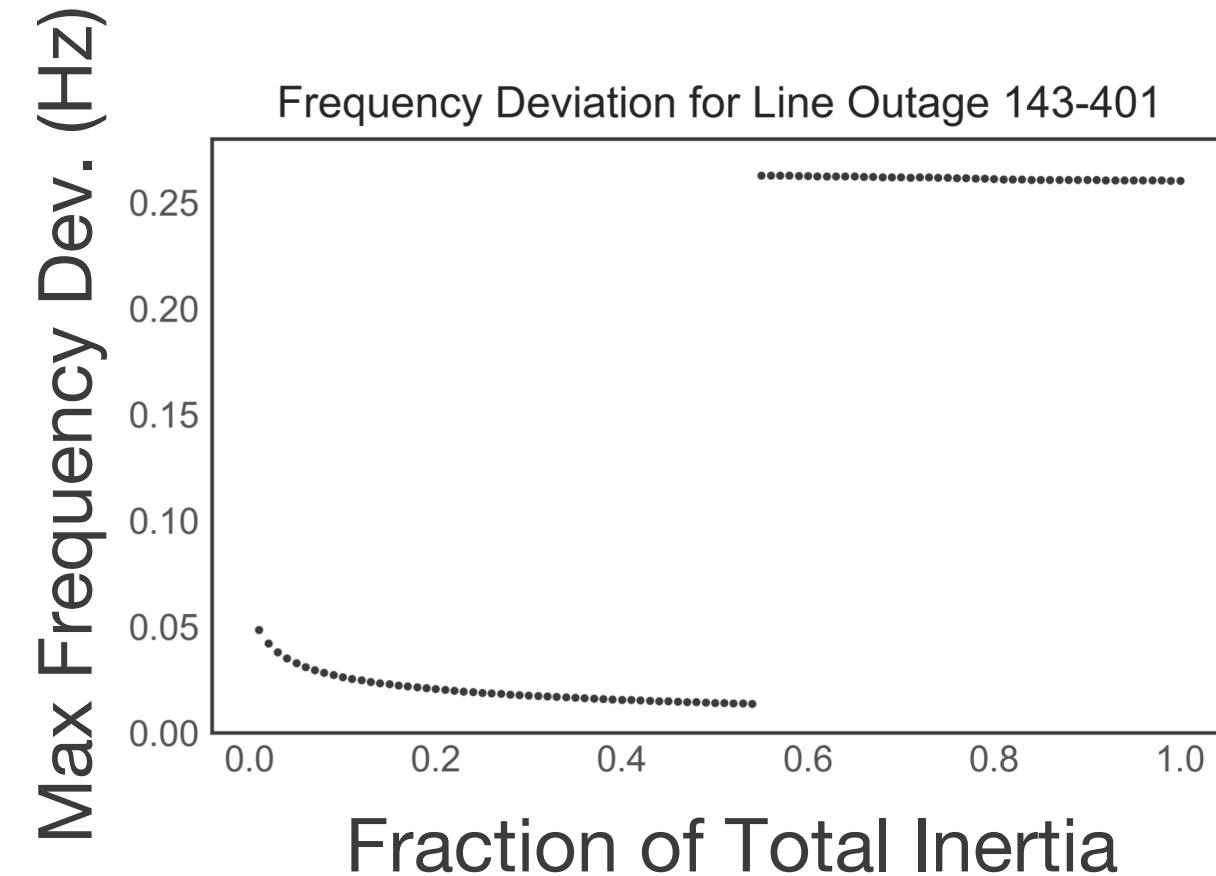
Category (IV) – South Carolina



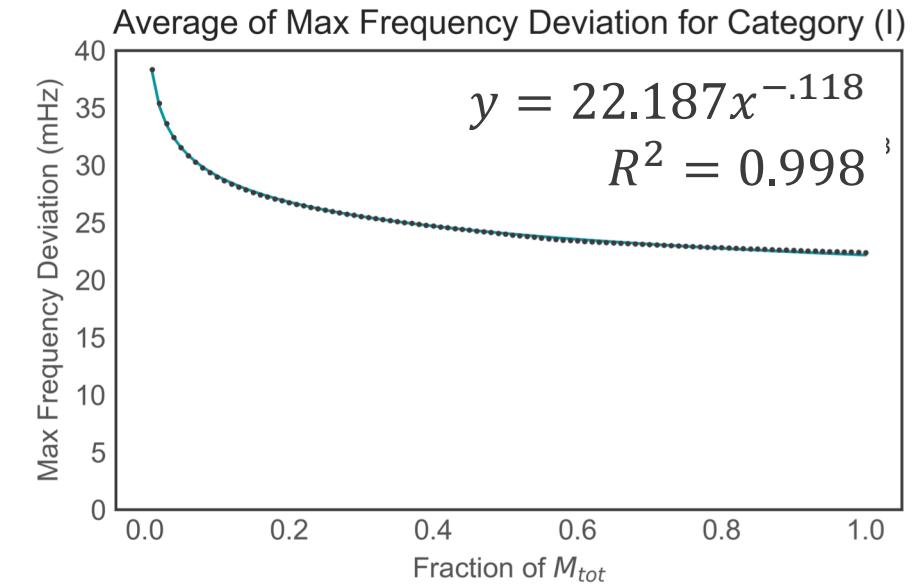
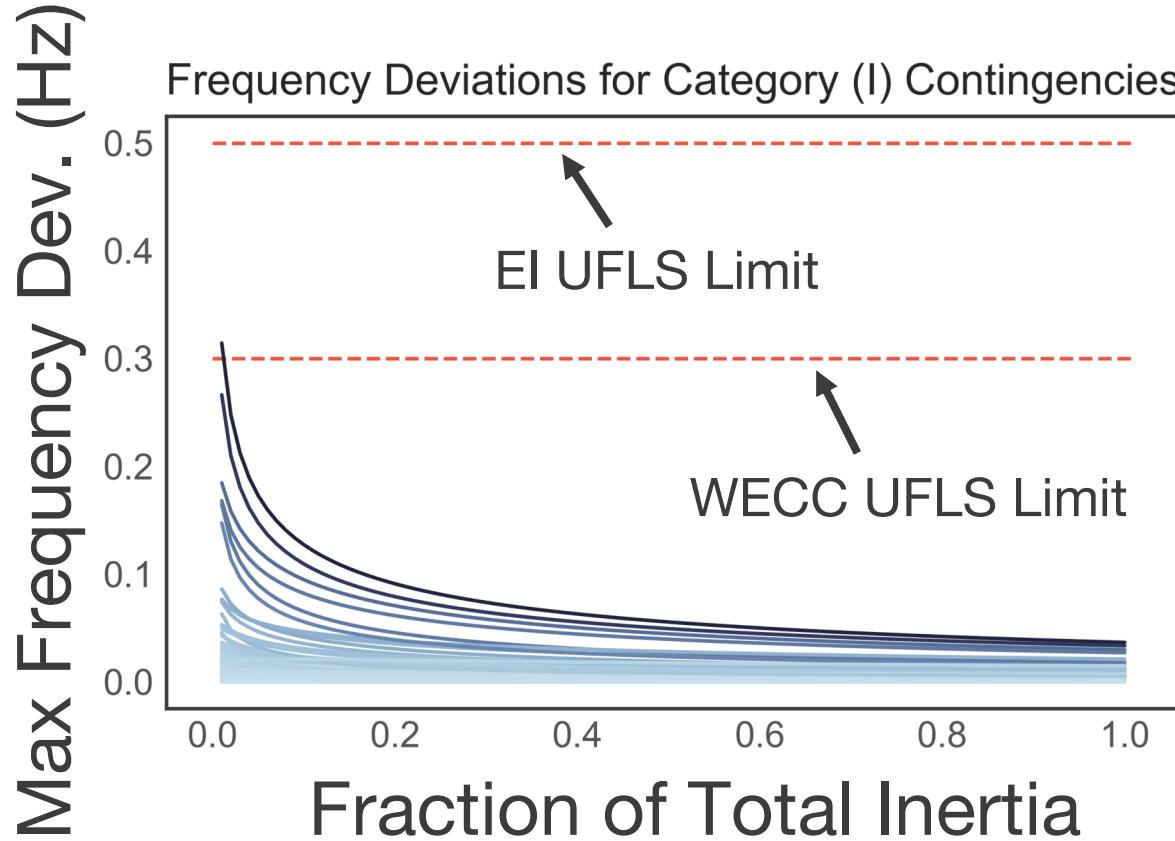
South Carolina—Bifurcations?



South Carolina—Bifurcations?

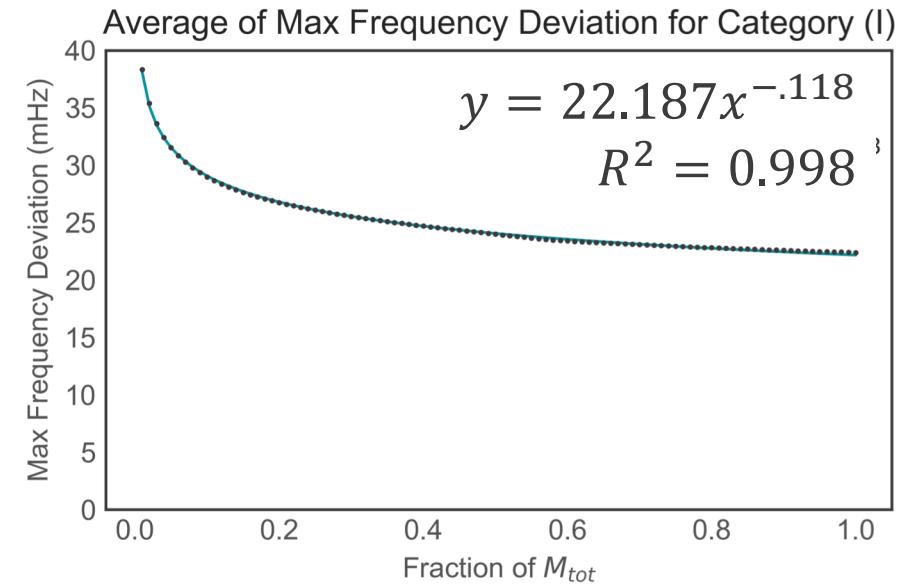
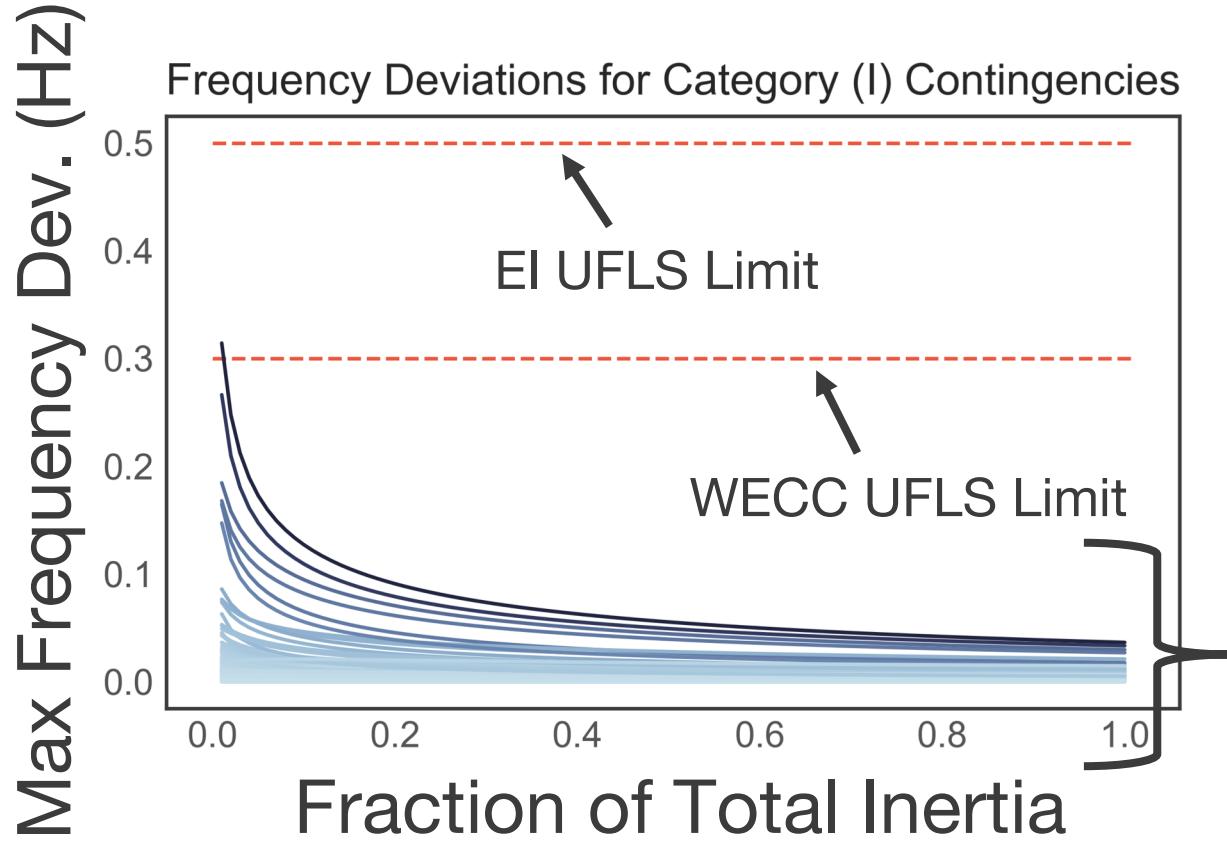


How metrics change



Frequency metrics as a
function of total system inertia

Why Contingencies Differ



Why do some contingencies cause larger deviations than others?

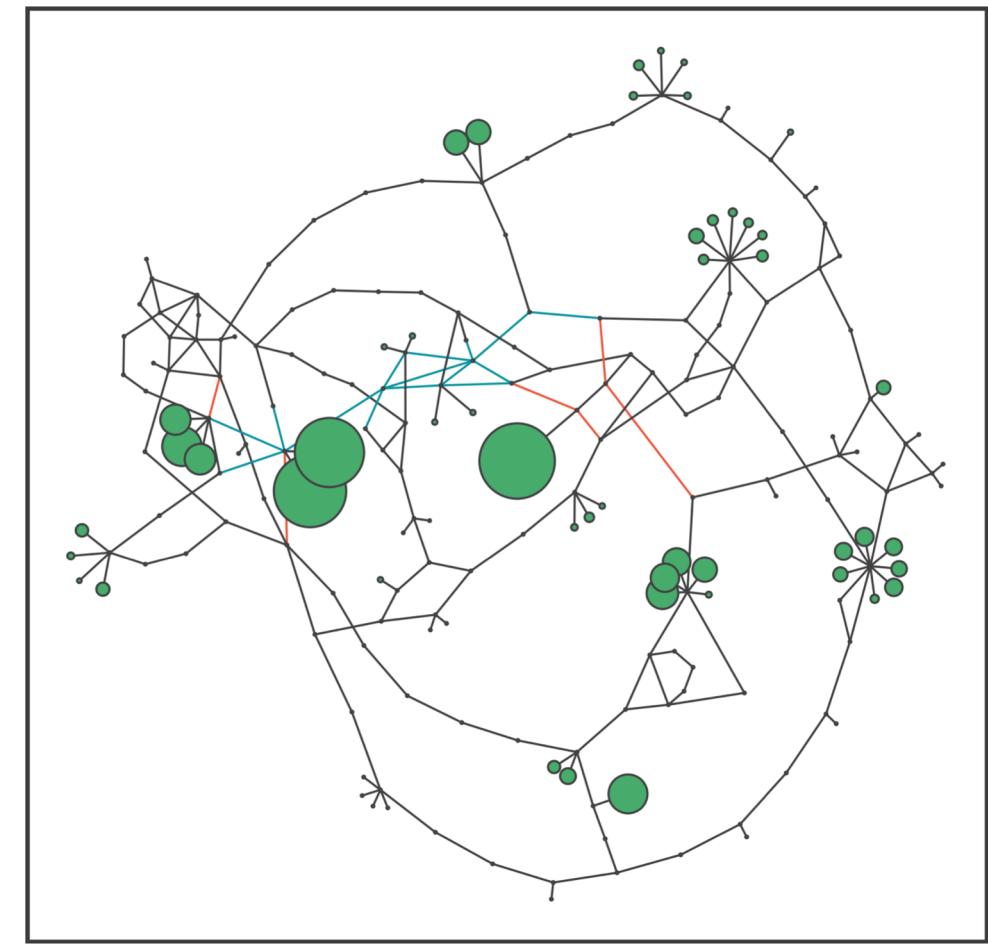
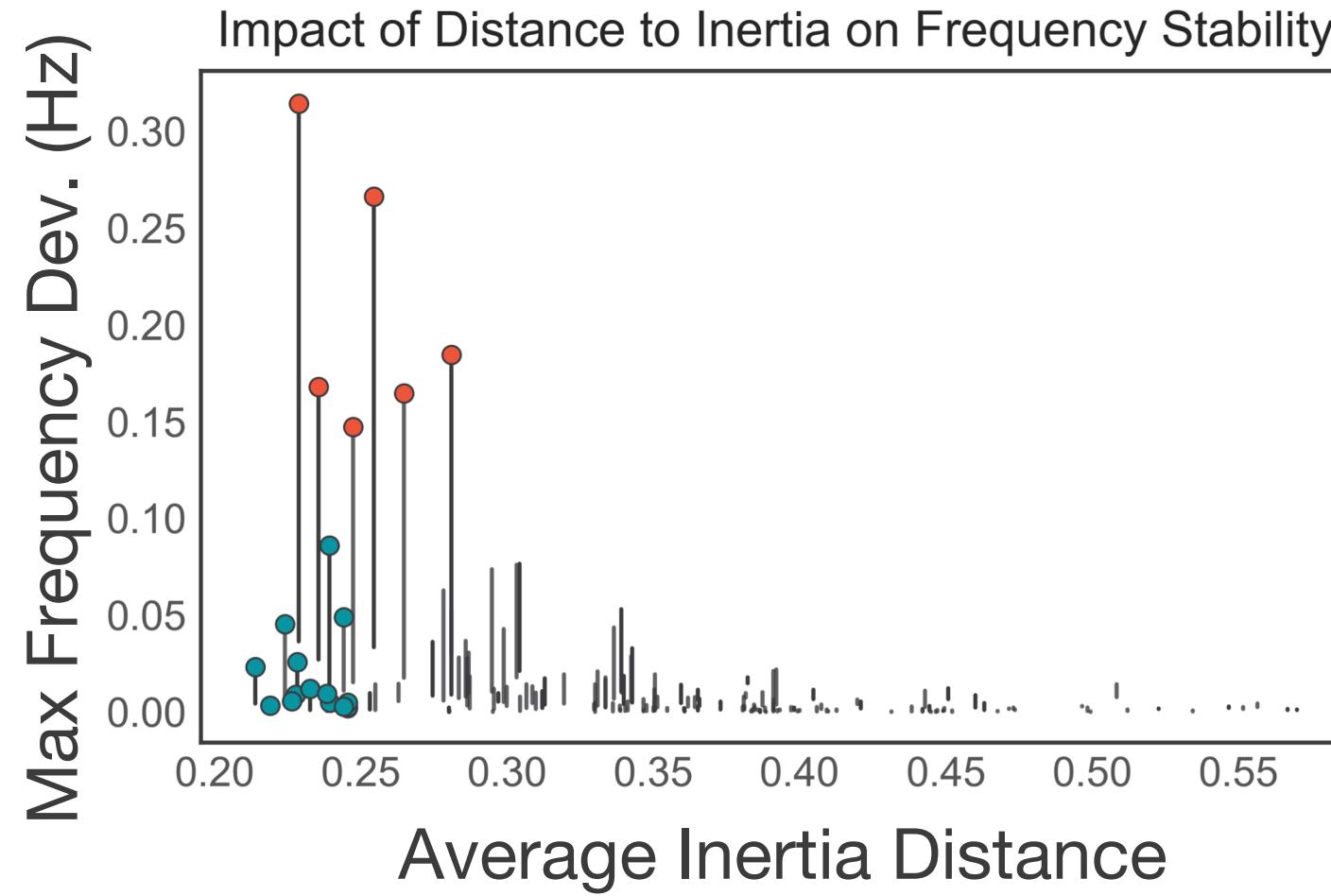
Average Inertia Distance

$$p(\ell_{i,j}) = \frac{1}{M_{tot}} \sum_{g=1}^{n_g} M_g \frac{d(\ell_{i,j}, g)}{\text{diam}(G)}$$

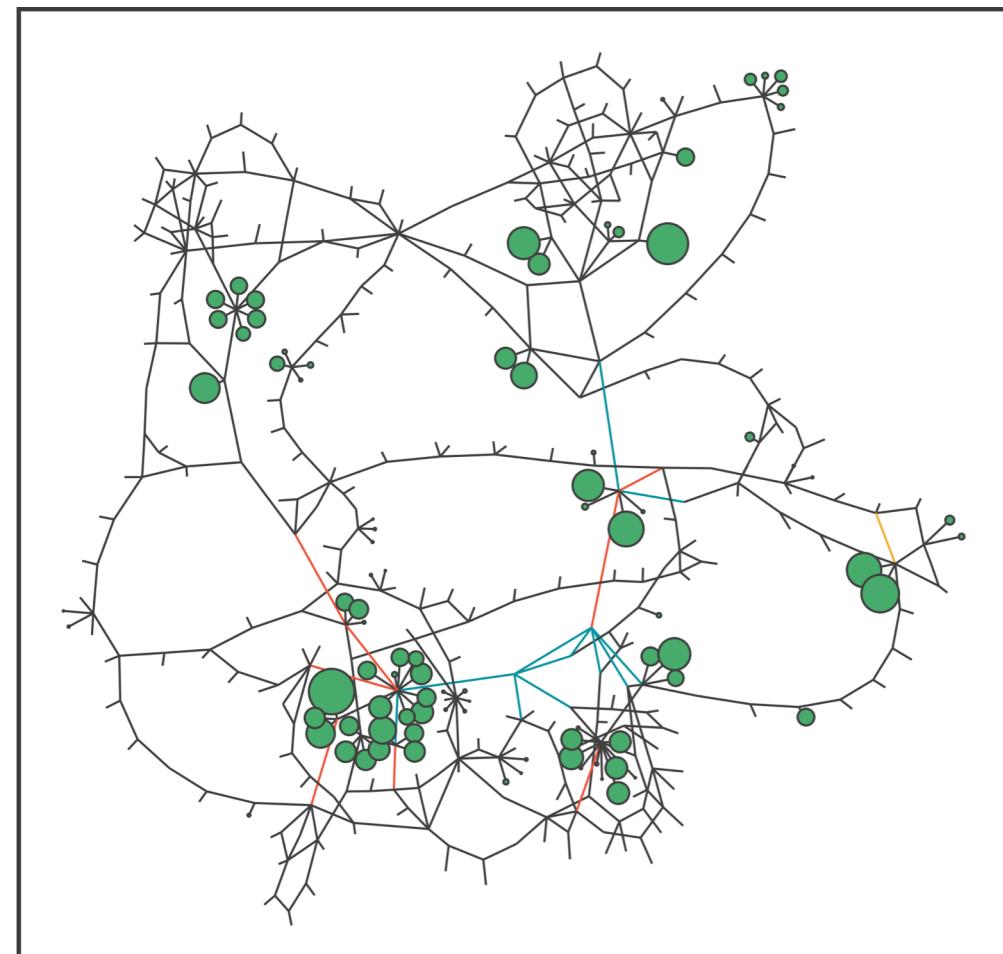
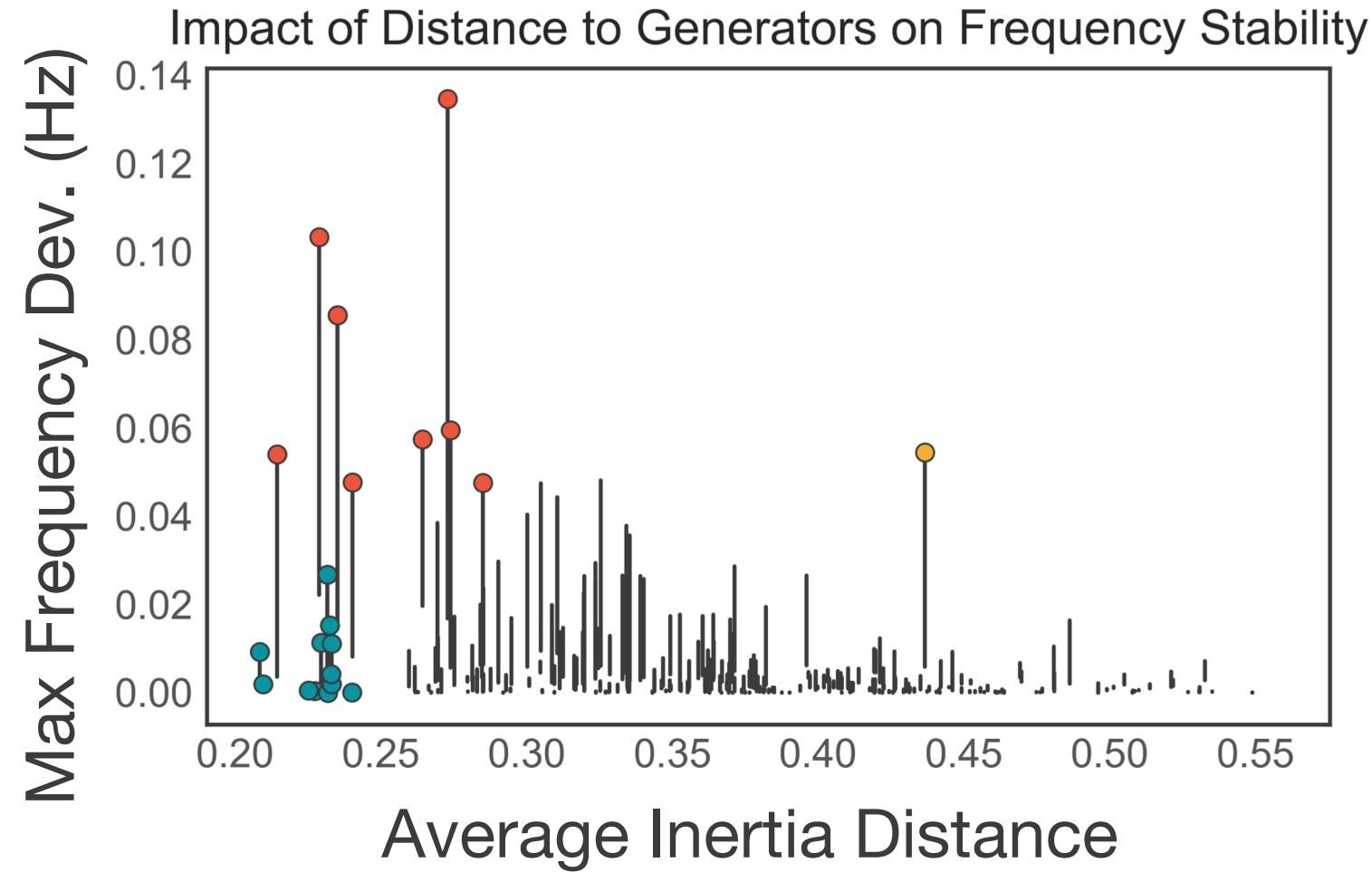
Shortest distance to generator

Diameter of network

Average Inertia Distance—Illinois



Average Inertia Distance—South Carolina

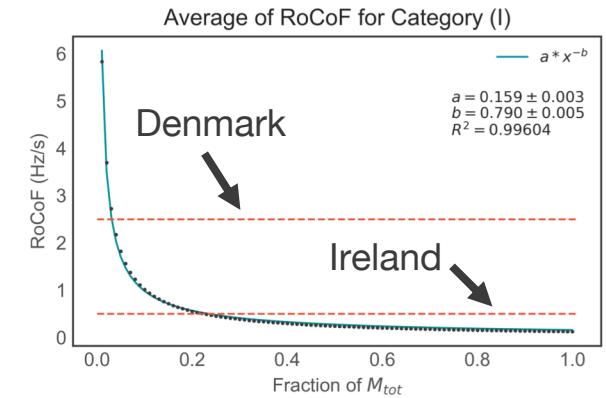
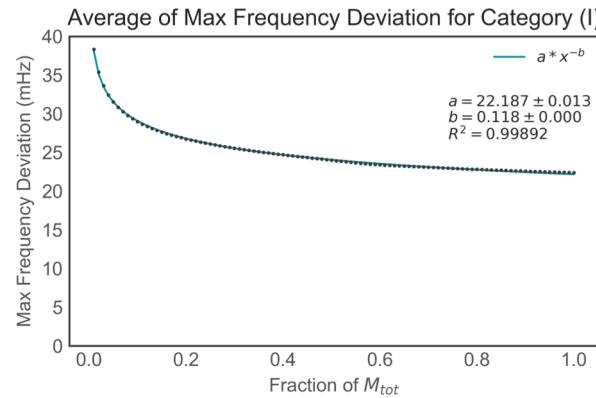


Outline

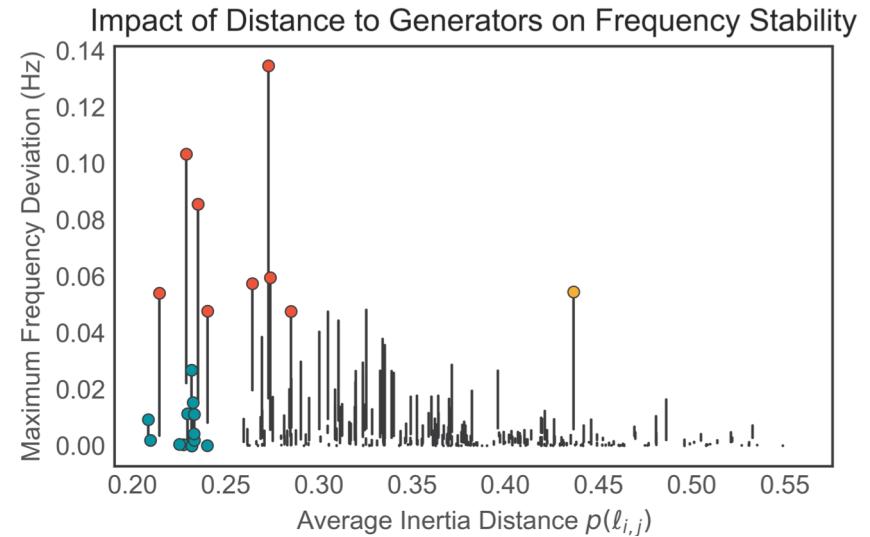
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Conclusions

- Showed the functional relationship between frequency metrics and total system inertia

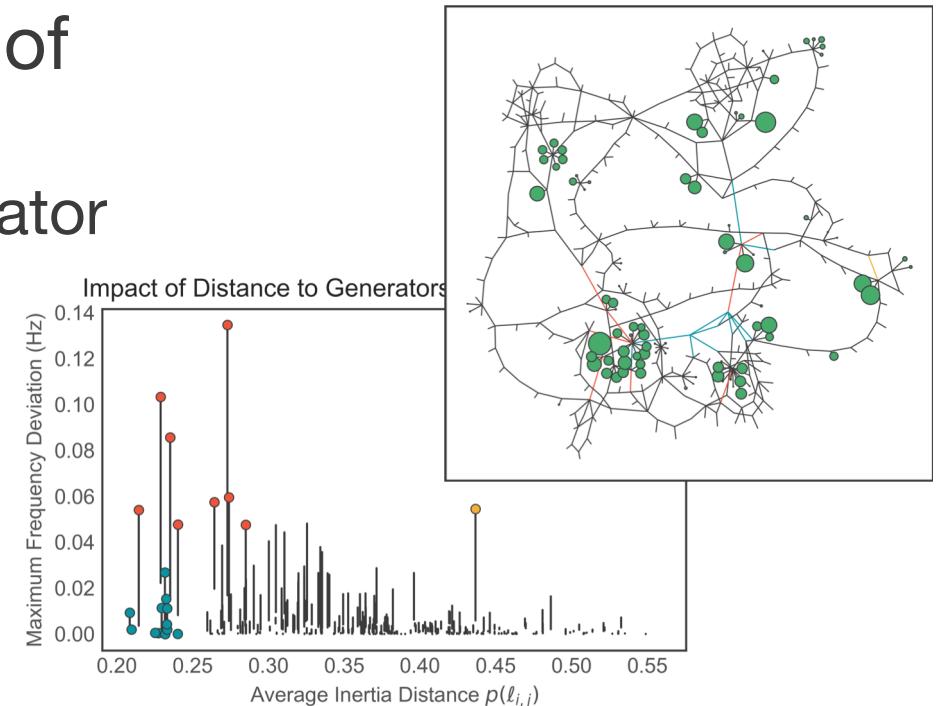
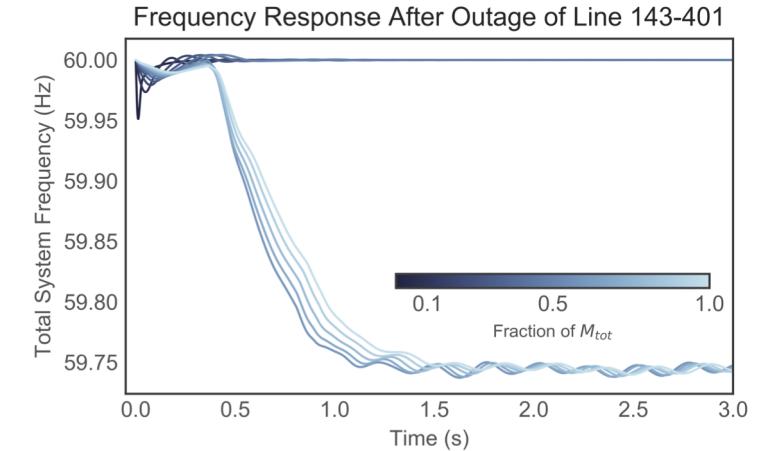


- Initial description of relationship between structure and frequency metrics



Future Work

- Use time series of nodes to study inertia as a bifurcation parameter
- Investigation of structural distribution of inertia
 - Replacement of each generator or generator hubs with renewable generators





Questions?



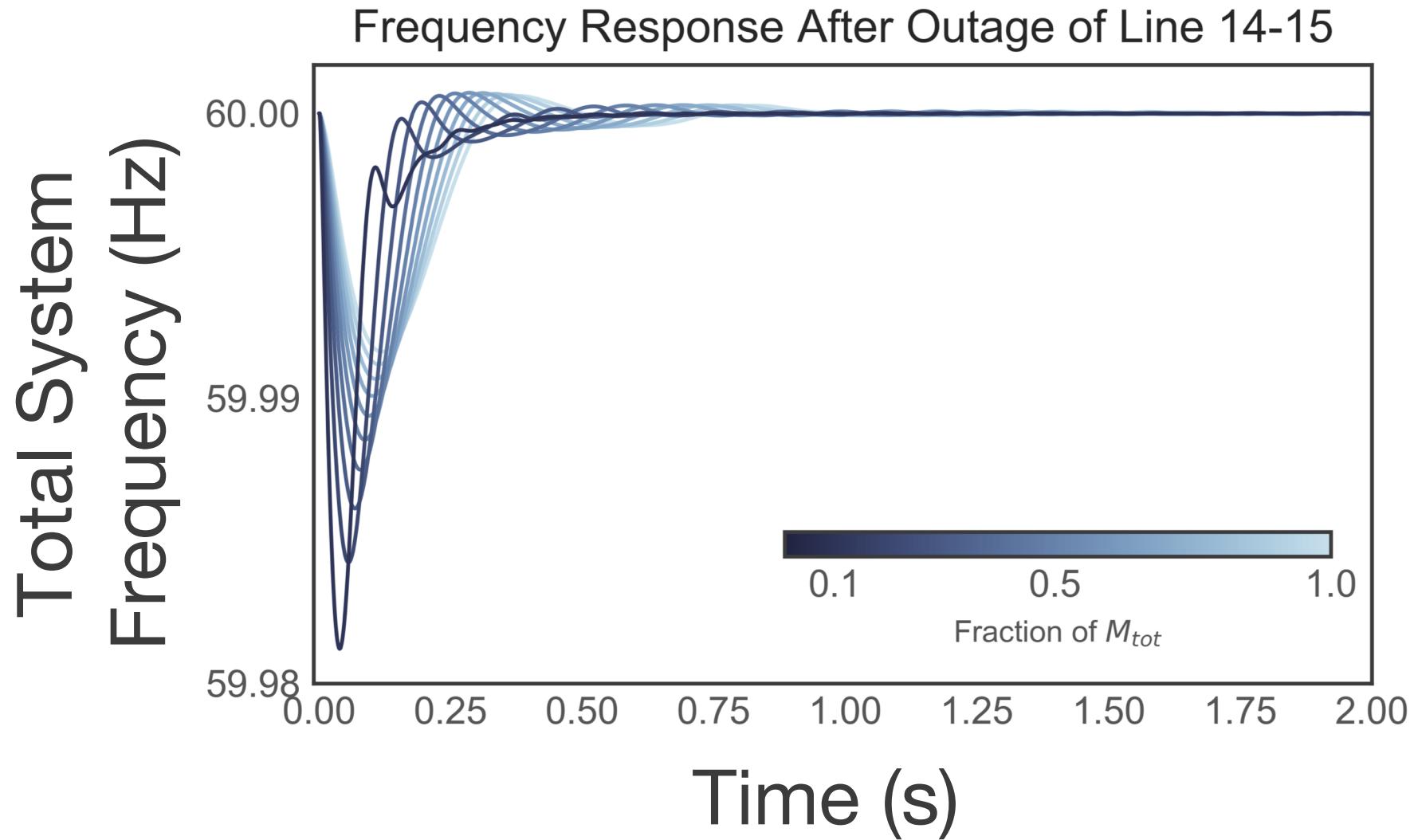
Wait...a wind generator spins!

- 4 Types of wind turbines
 - Types 1 and 2 are *fixed speed*
 - Turbines always spin at same speed, but might not produce optimal amount of power given a particular wind speed
 - Types 3 and 4 are *variable speed*
 - Turbine speed changes based on wind speed to produce maximum amount of power
 - Have to be connected to a power inverter

Creation of Synthetic Topologies

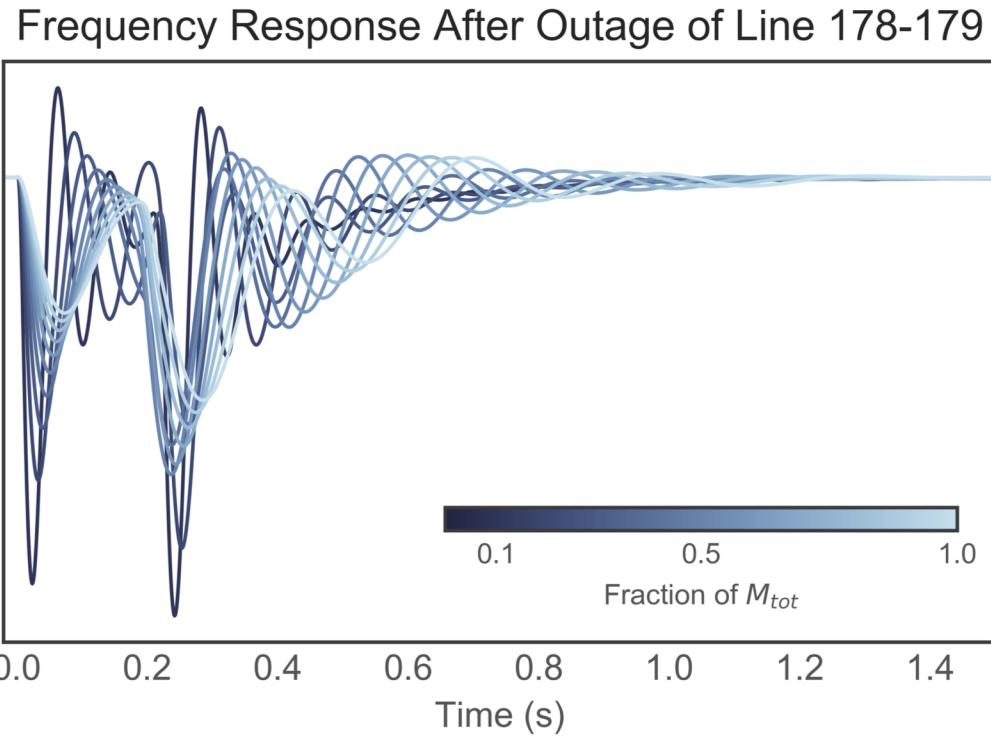
1. Cluster zip codes, each cluster gets a load substation
2. Delauney triangulation of all buses
3. Find Euclidean minimum spanning tree
4. Need an additional $0.22n$ transmission lines to be selected from triangulation: do 10 iterations of the following
 - a) DC PF solutions where each unassigned line of Delauney triangulation compute expected power flow based on distance and voltage angles
 - b) Each iteration pick $0.022n$ lines with highest expected power flow and do not share nodes

Category (I) – South Carolina

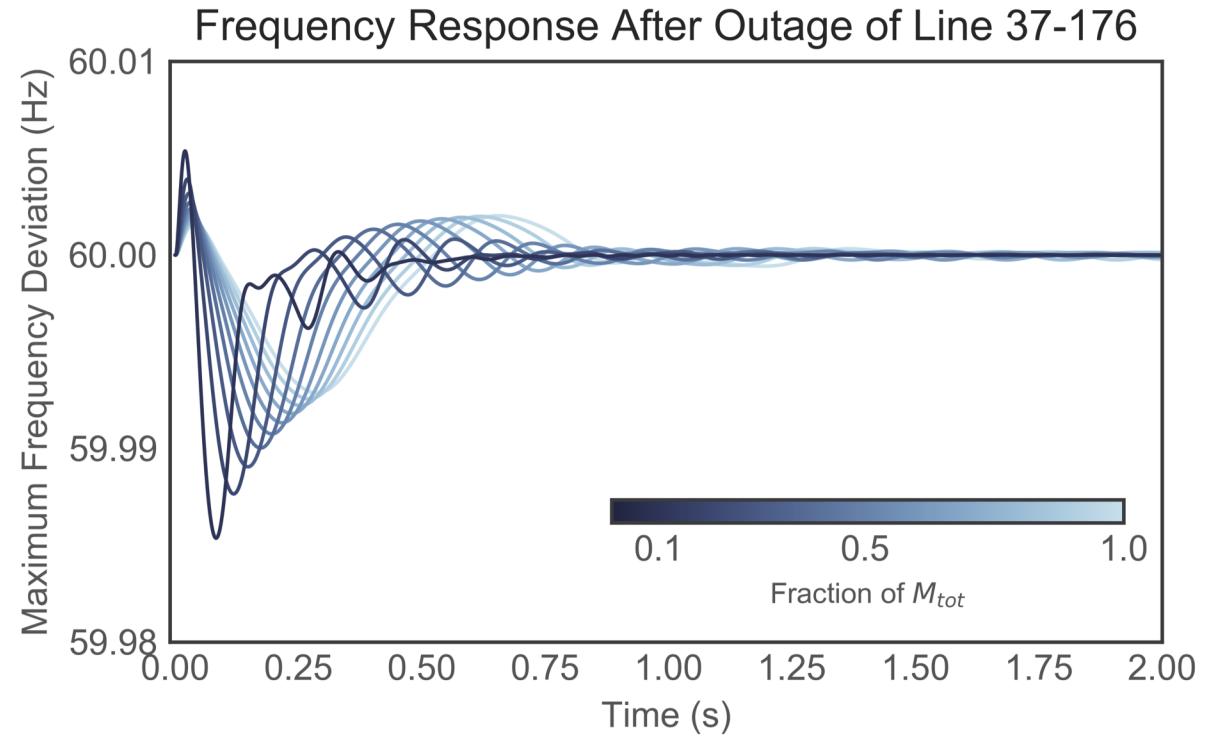


Category (III) – Cascade no disconnect

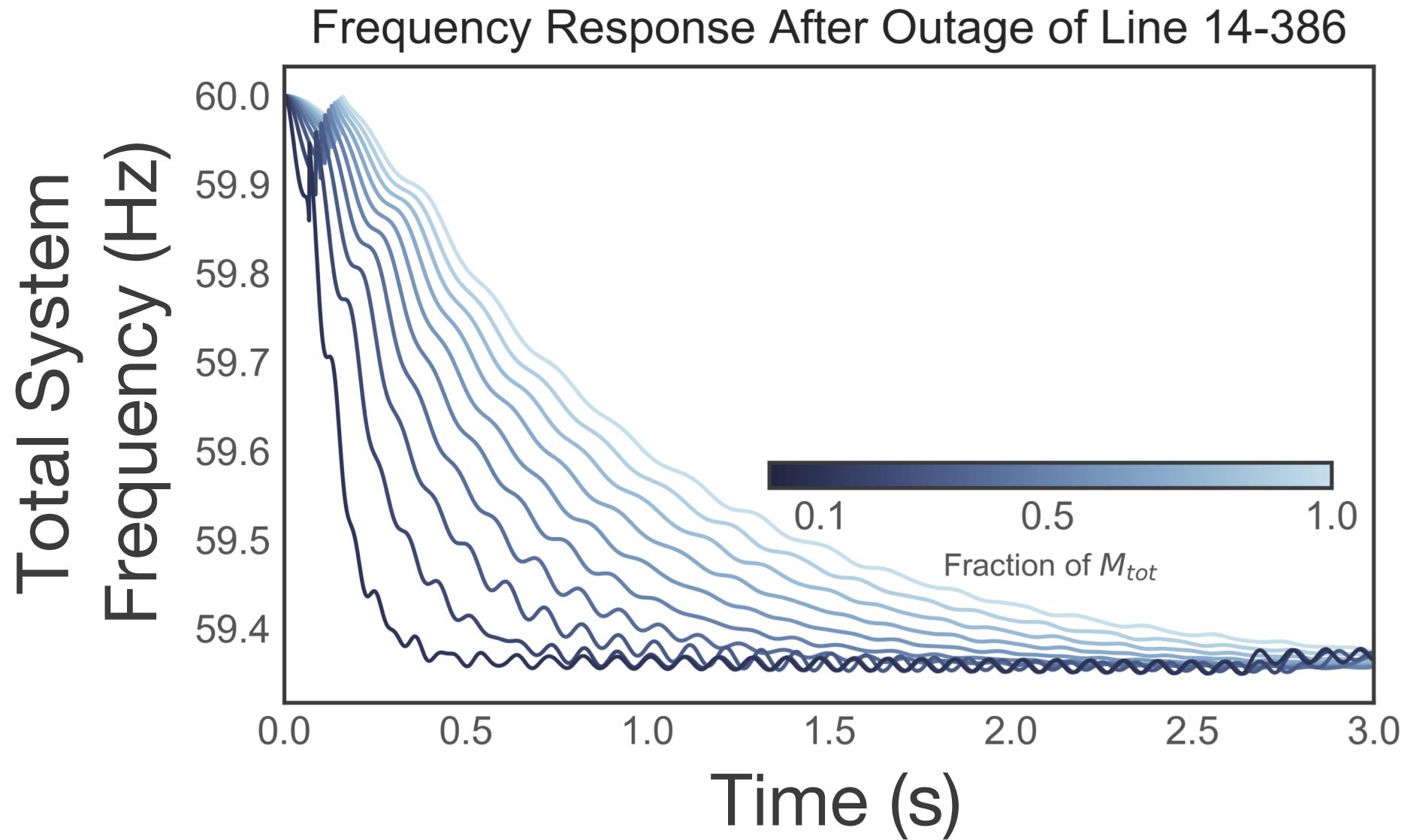
Central Illinois



South Carolina

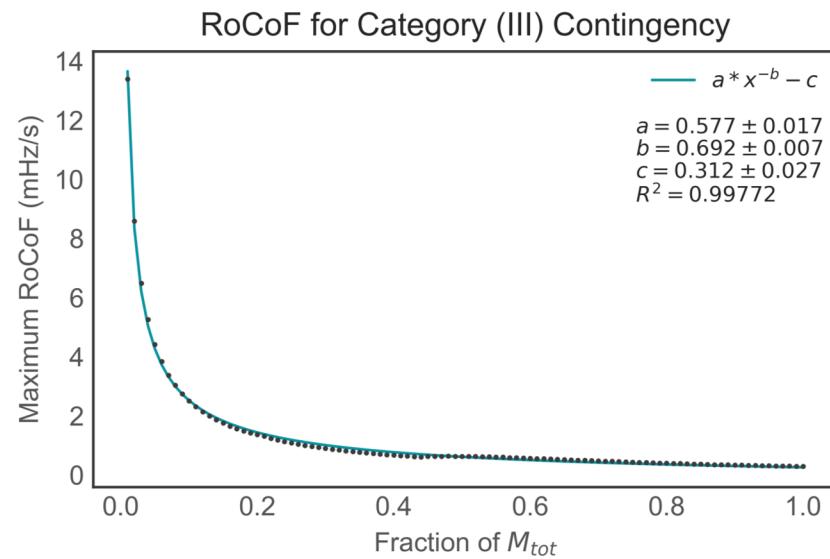
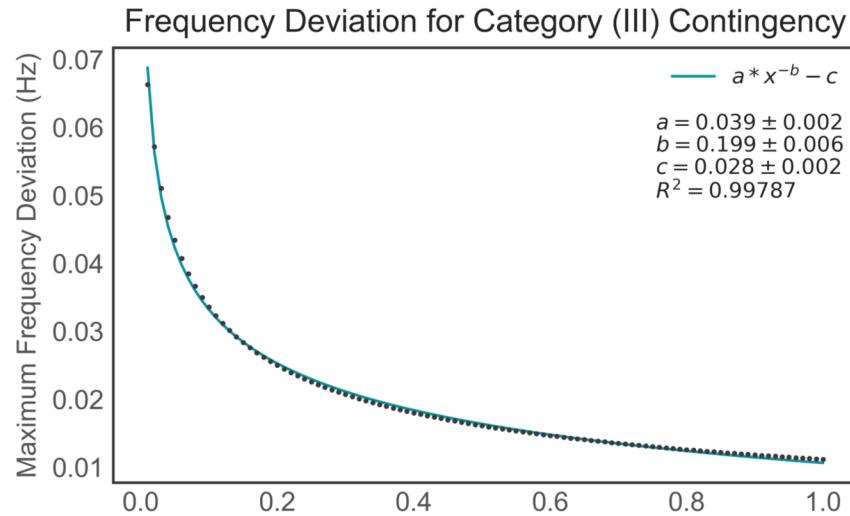


Category (IV) – South Carolina

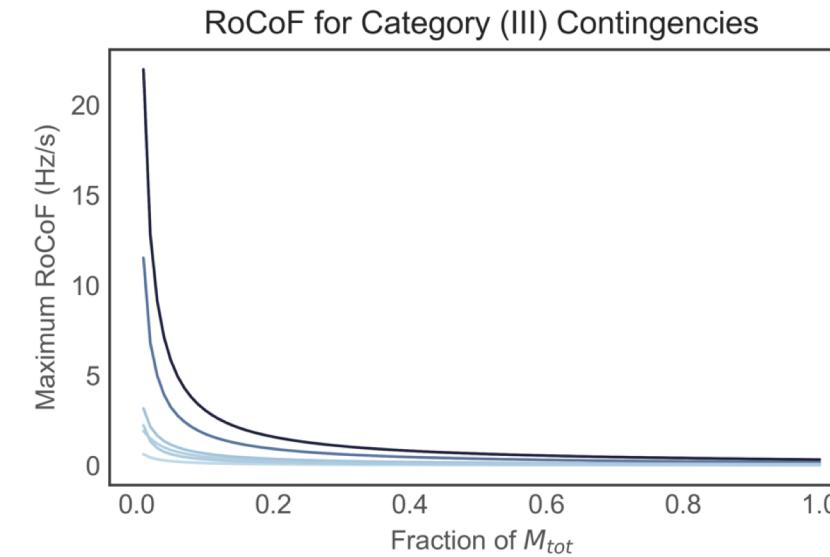
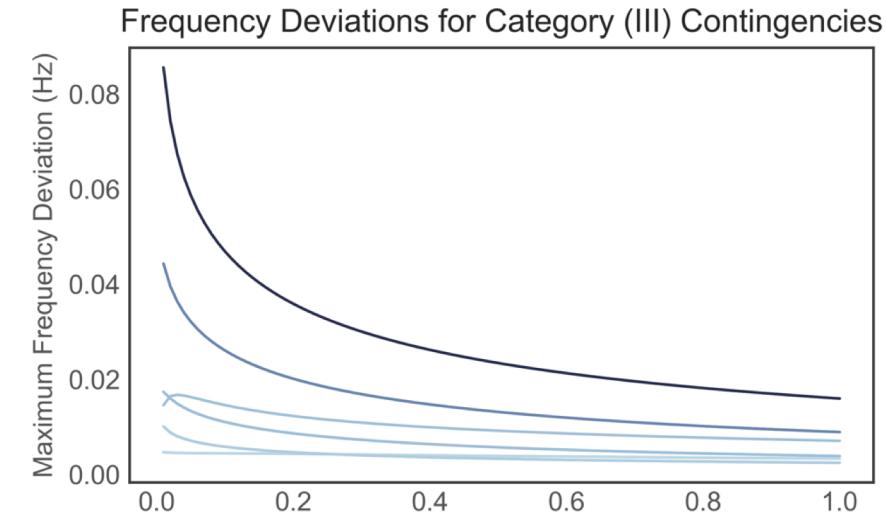


Category (III) – Cascade no disconnect

Central Illinois

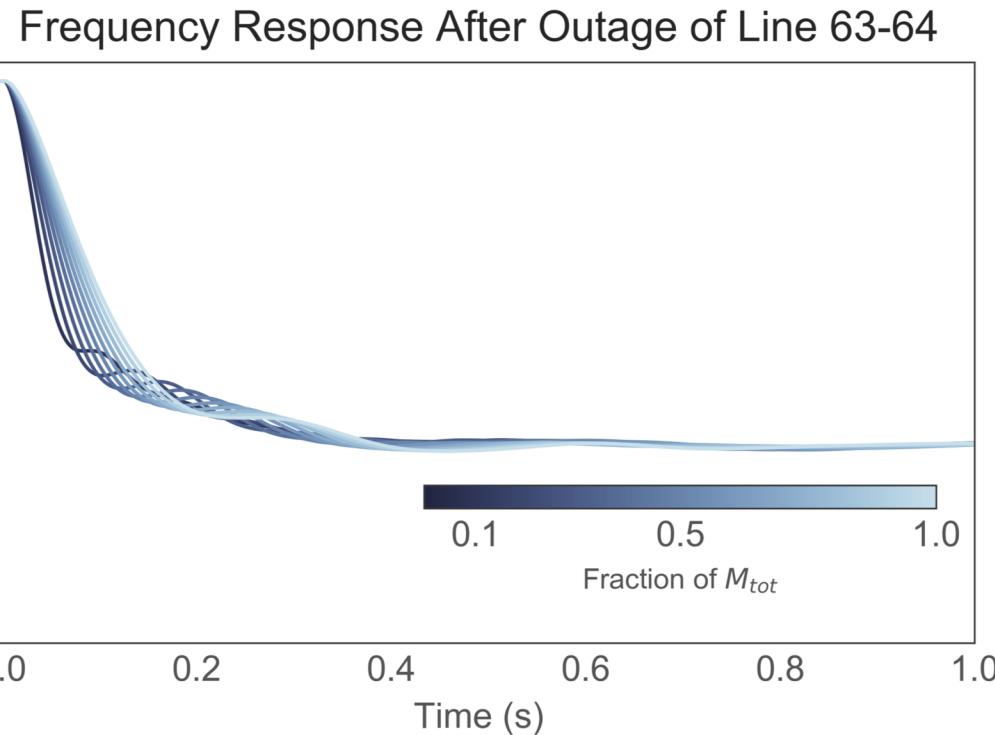


South Carolina

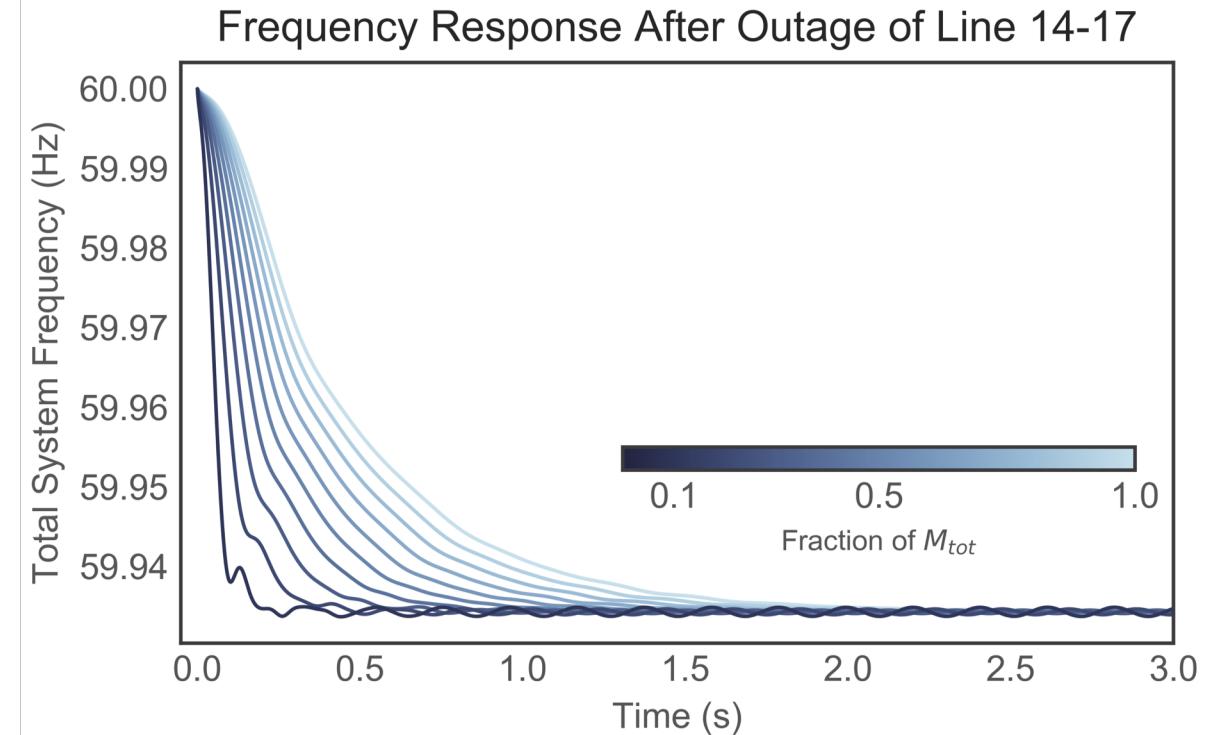


Category (II) – Disconnect

Central Illinois

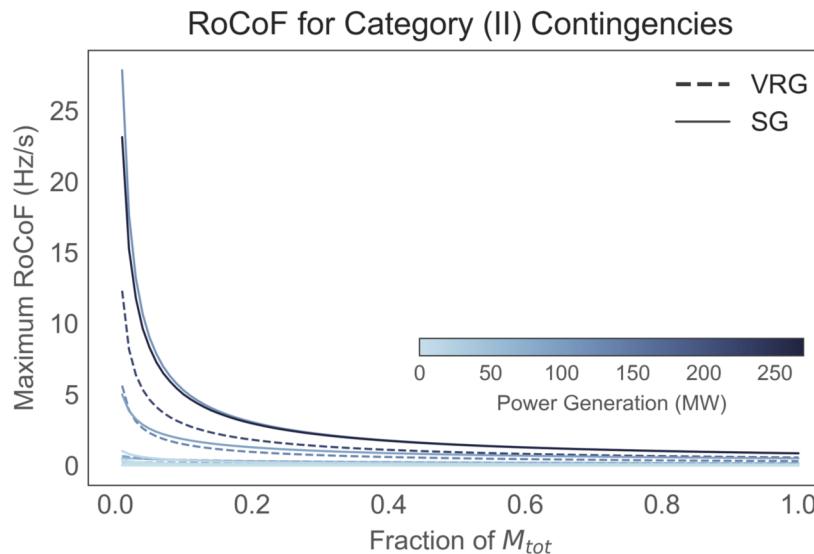
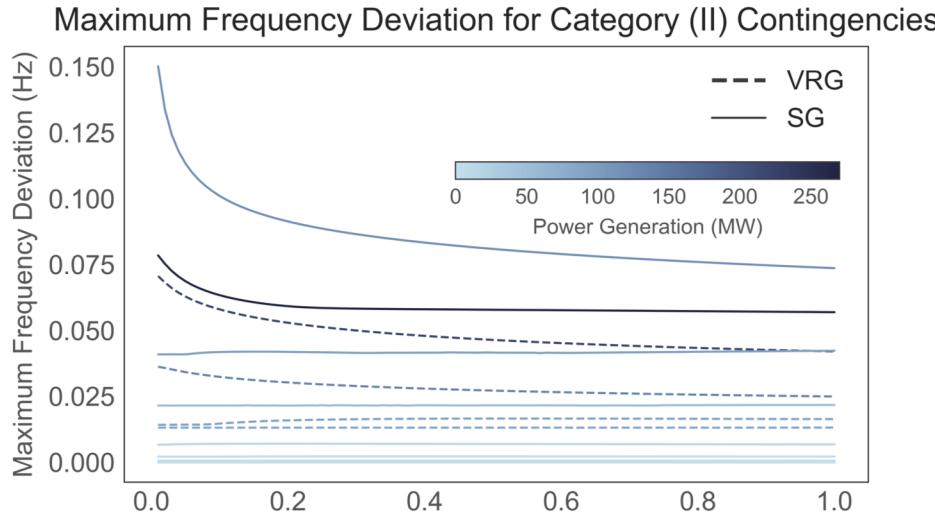


South Carolina



Category (II) – Disconnect

Central Illinois



South Carolina

