The Role of Inertia in Power System Dynamics during Cascading Failures

Sam Molnar

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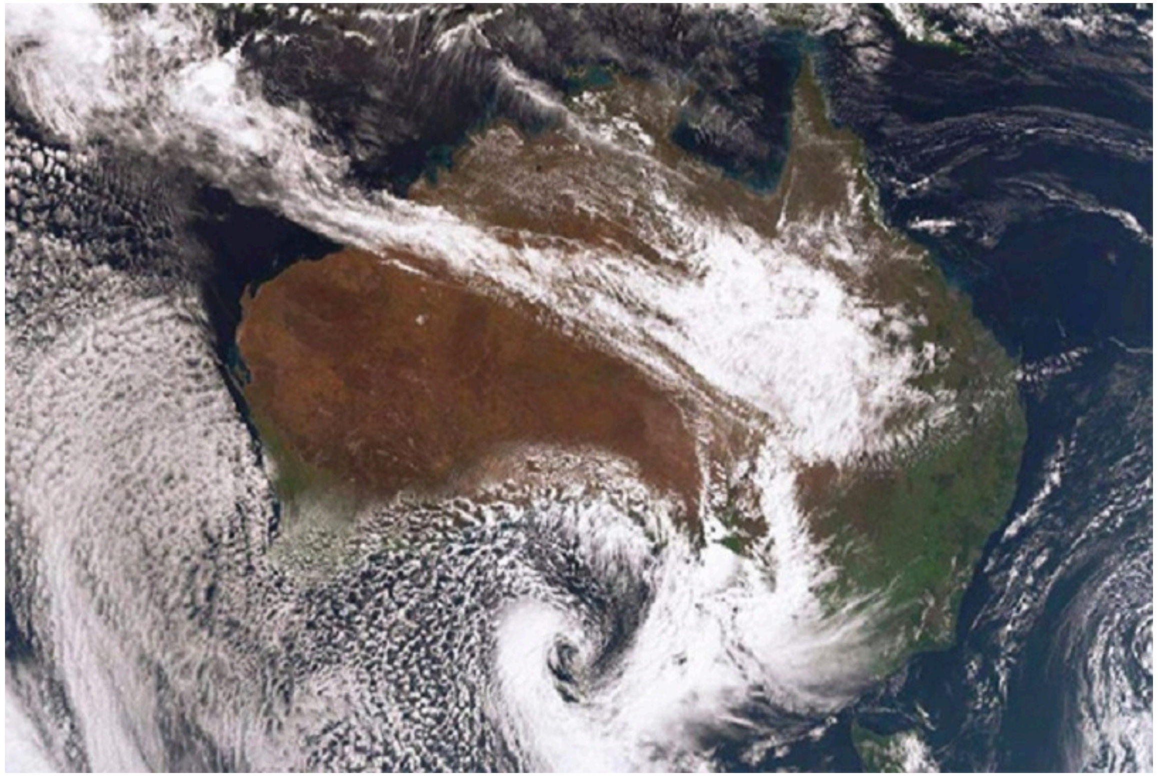
Outline

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

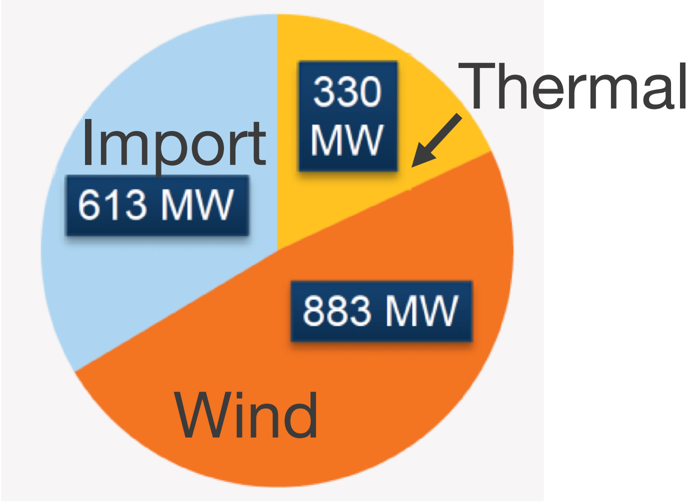
@NinaNewsAdelaid Nine News Adelaide Acessed 3-9-19

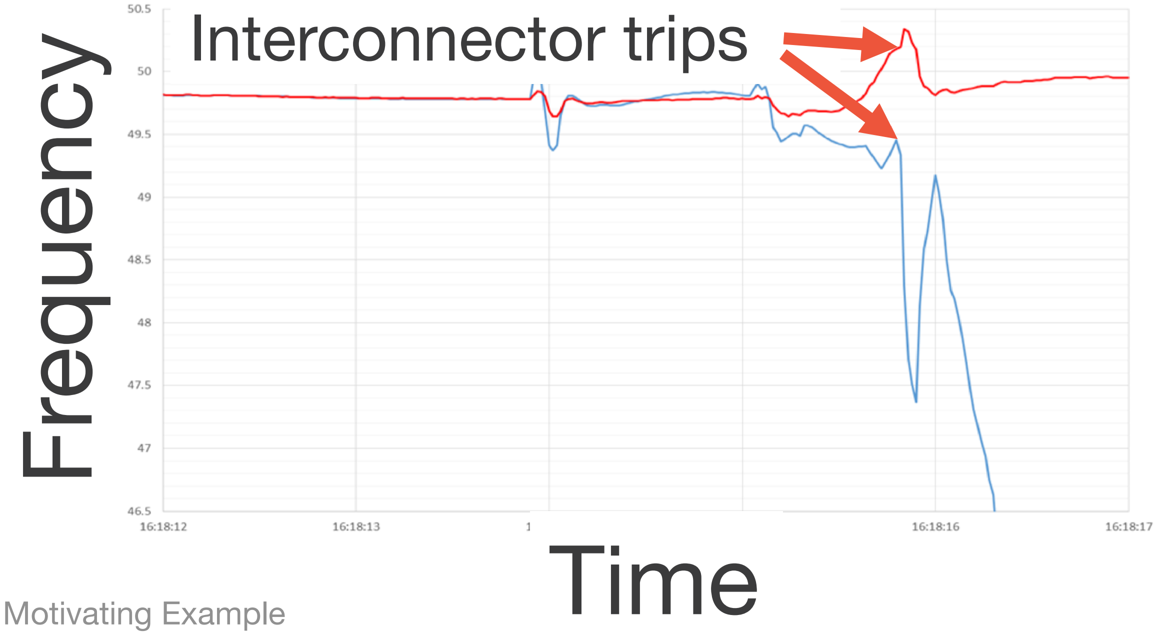
South Australia Blackout – September 2016

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

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

South Australia Blackout – What Happened





AEMO. Preliminary Report – Black System Event in South Australia on 28 September 2016. October 2016.

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

The Sydney Morning Herald

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

By political reporter Stephanie Anderson
Updated 28 Sep 2016, 10:45pm

Blackout report leaves renewables debate dangling in the breeze

INDAILY

David Washington
@davidwashingto2

Bension Siebert

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

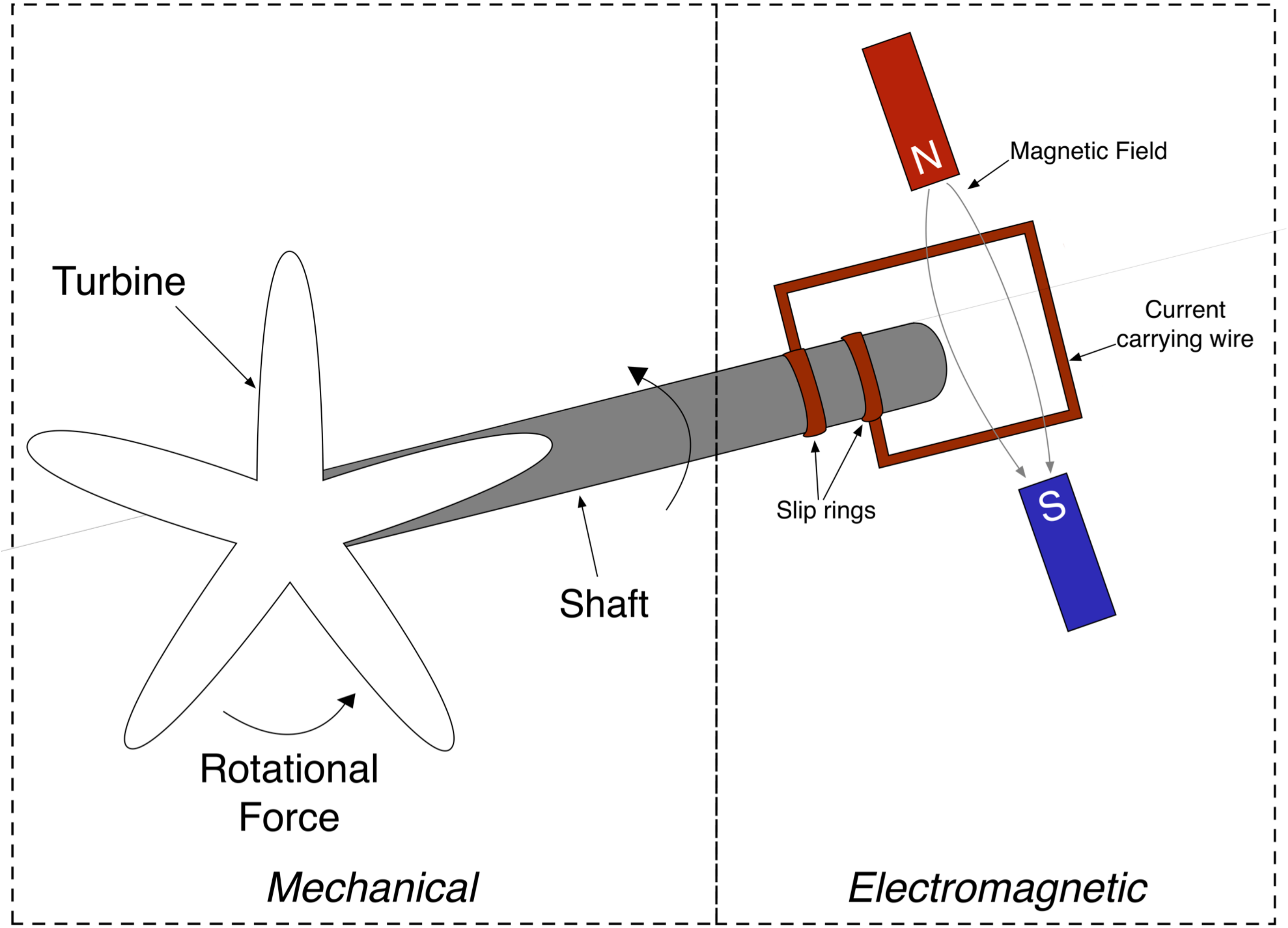
Image credit: Dennis Schroeder / NREL. Boulder rooftop PV. Jun 20, 2017.

How do renewables impact power system stability?

Outline

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

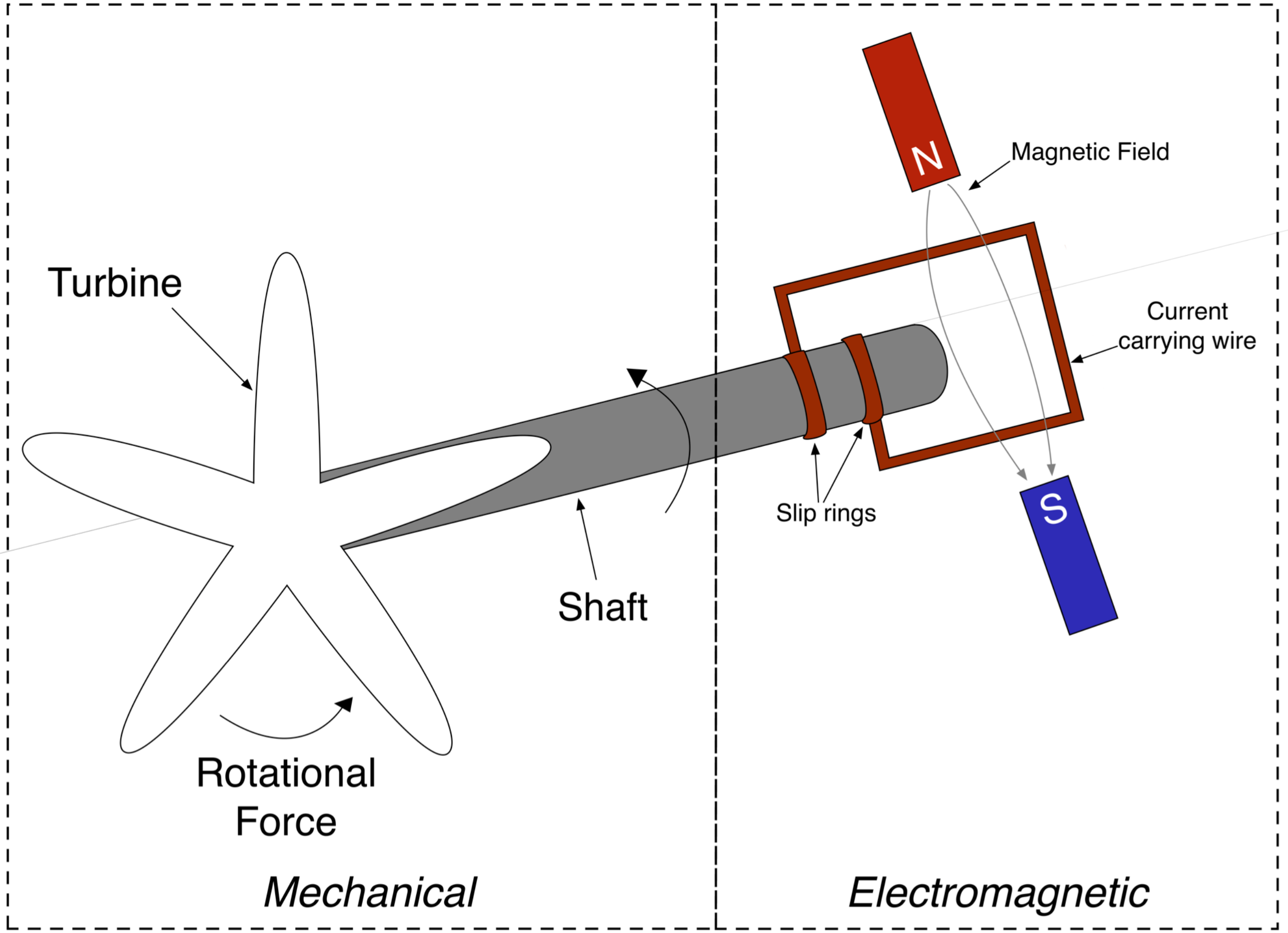
Power Generation



Traditional Generation

- Coal
- Nuclear
- Natural Gas
- Hydro

Power Generation

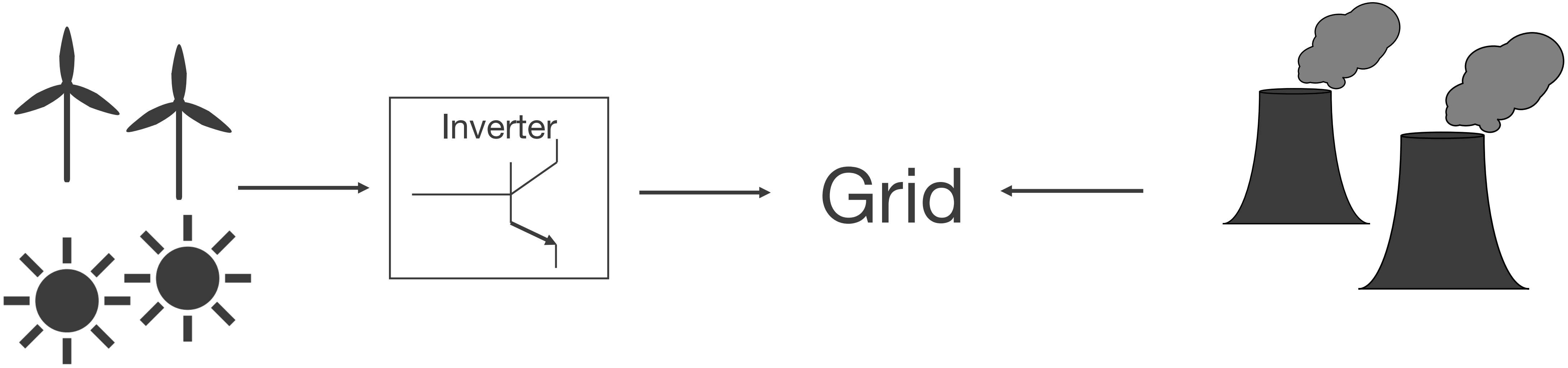


$$M_g \dot{\omega}_g + D_g \omega_g = P_g - P_e$$

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

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

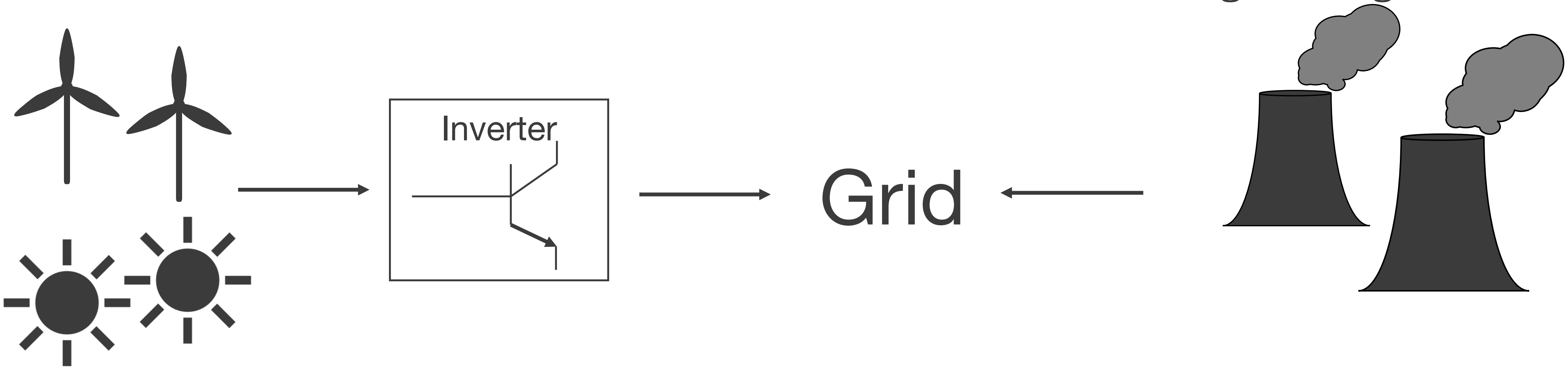


Traditional vs. Renewable

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

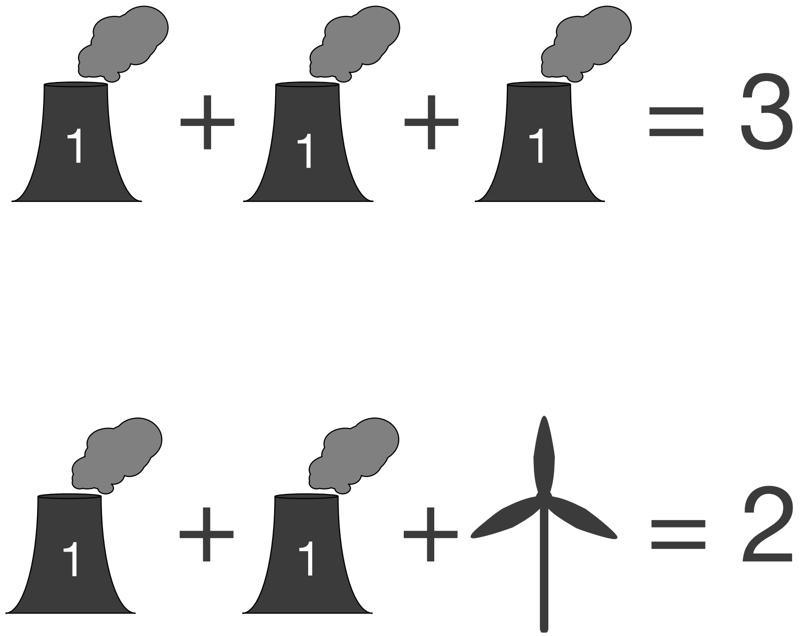
$$D_{RG} \dot{\delta}_{RG} = P_{RG} - P_e$$

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



Important Aspects of Inertia

Total System Inertia



Structural Distribution of Inertia

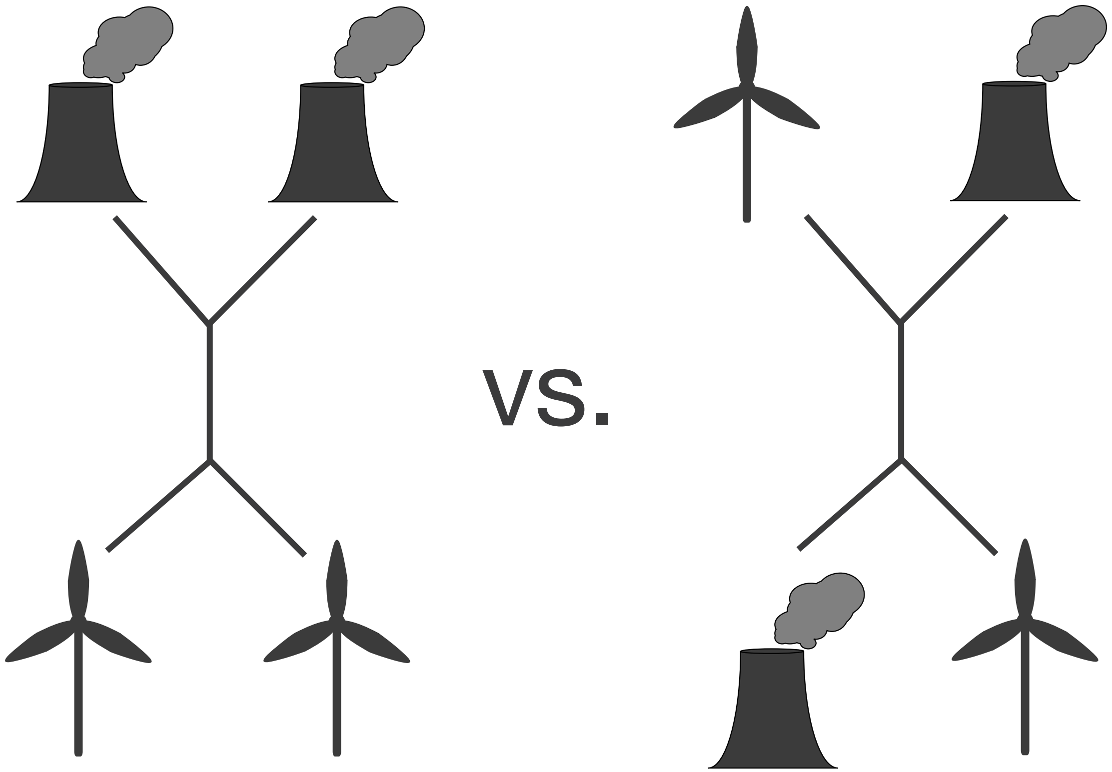


Image credit: Dennis Schroeder / NREL. Inspecting Turbine Blade at NWTC. August 9, 2013

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

~~How do renewables impact power system stability?~~

How does inertia impact power system stability?

Outline

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 contingencies or inertia placement scenarios
- Little focus on network structure
- Focus on placement of various control mechanisms 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 the volume of the 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.

Outline

Contributions

How does inertia impact power system stability?

Total System Inertia

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

Structural Distribution of Inertia

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

Outline

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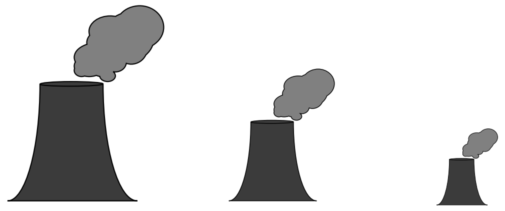
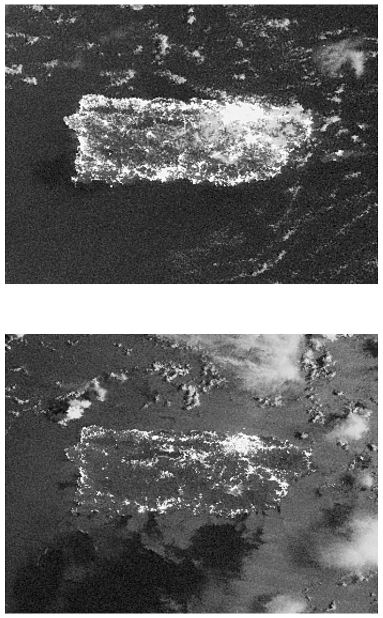
Experiment

Set up Inertia



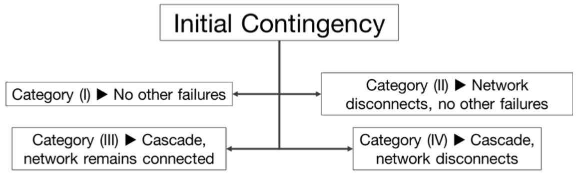
$$M_{tot} = \sum_{g=1}^{n_g} M_g$$

Simulate Cascade



Analyze Results

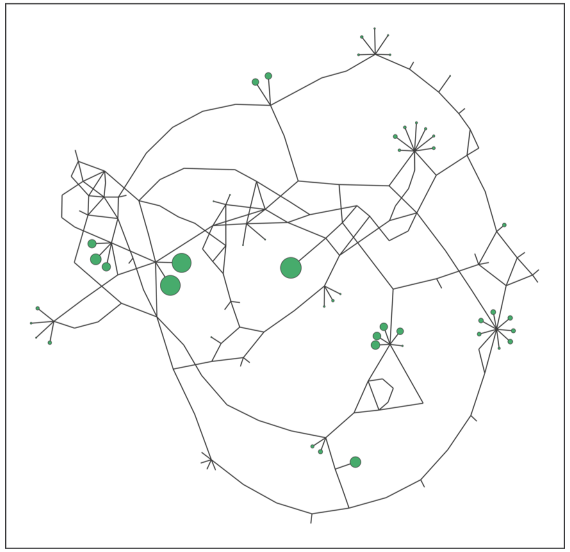
$$f = \frac{\sum_{g=1}^{n_g} M_g \omega_g}{M_{tot}}$$



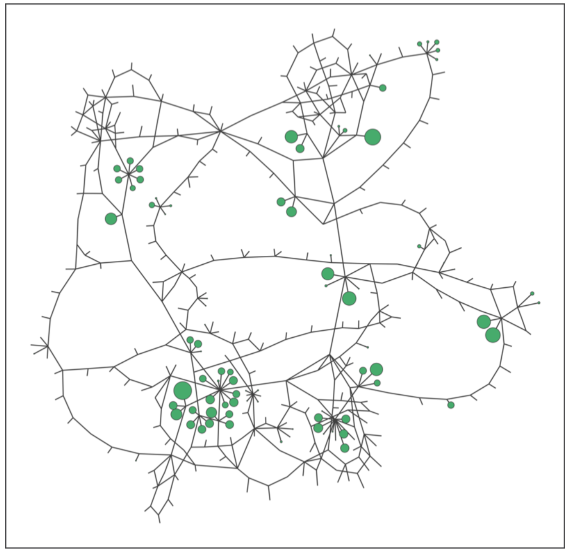
Power System Test Cases

- Topology
  - Delauney Triangulation and minimum spanning tree
- Load
  - Population size ∝ 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



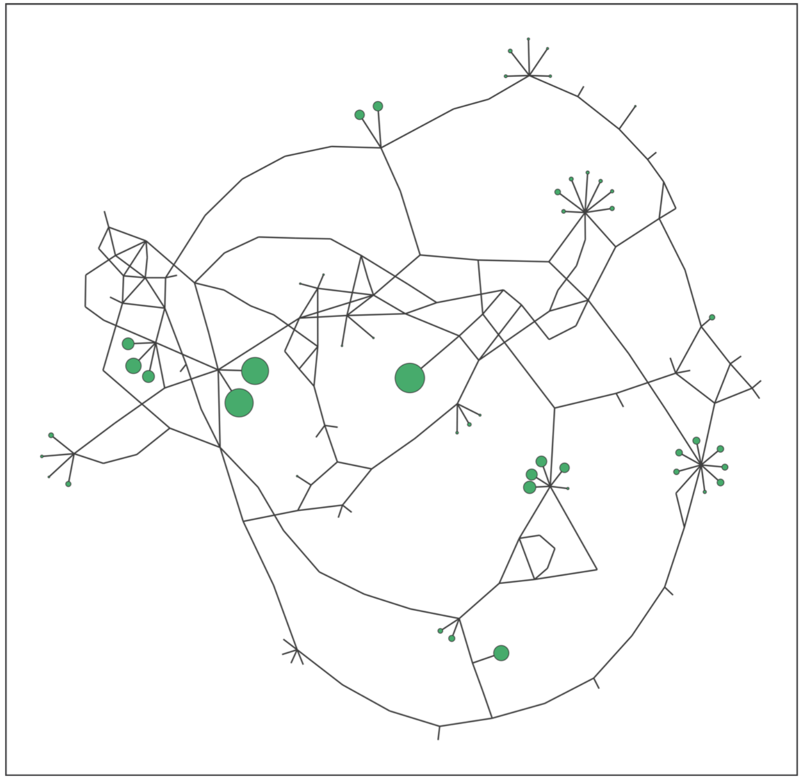
South Carolina



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

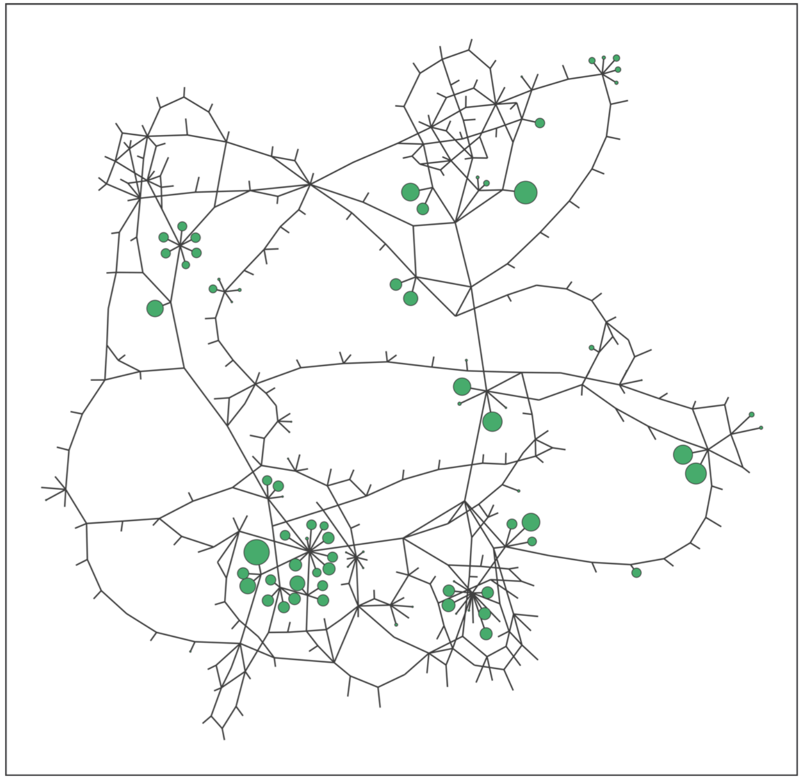
Central Illinois



$$M_{tot} = 29.61$$
$$n_b = 200$$
$$n_g = 49$$
$$n_l = 245$$

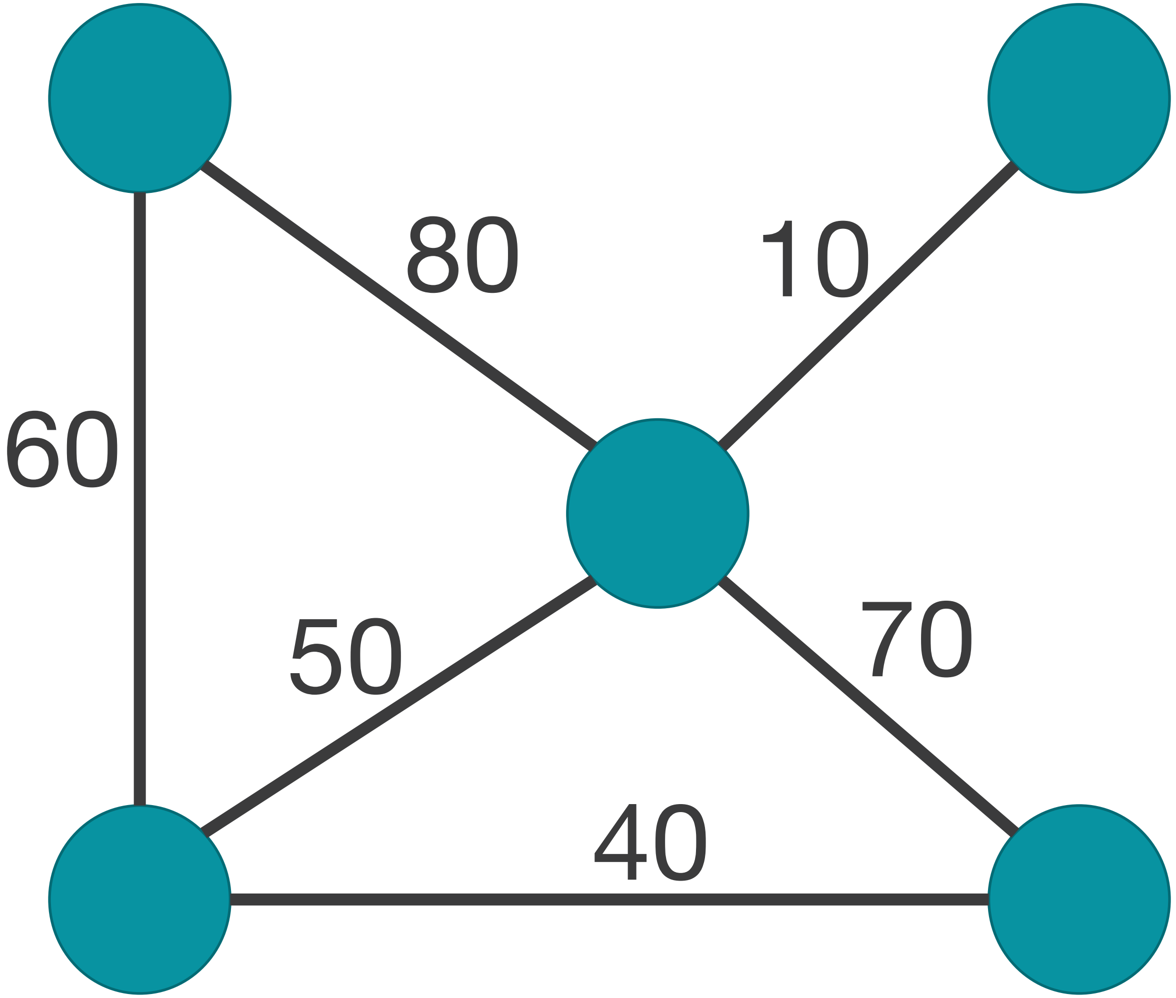
$$M_{tot} = \sum_{g=1}^{n_g} M_g$$

South Carolina

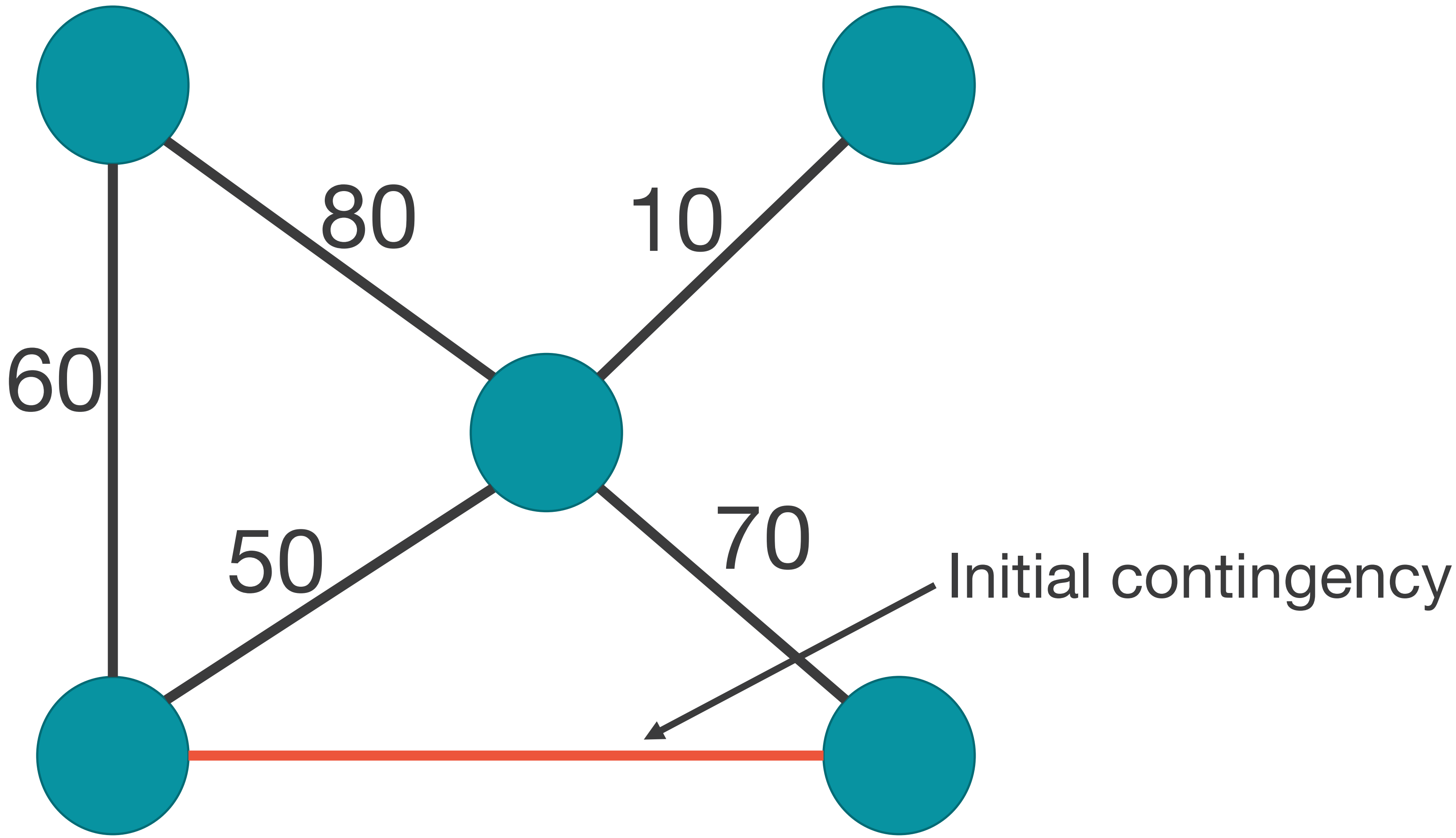


$$M_{tot} = 139.13$$
$$n_b = 500$$
$$n_g = 90$$
$$n_l = 584$$

Cascading Failures—Definition



Cascading Failures — Definition



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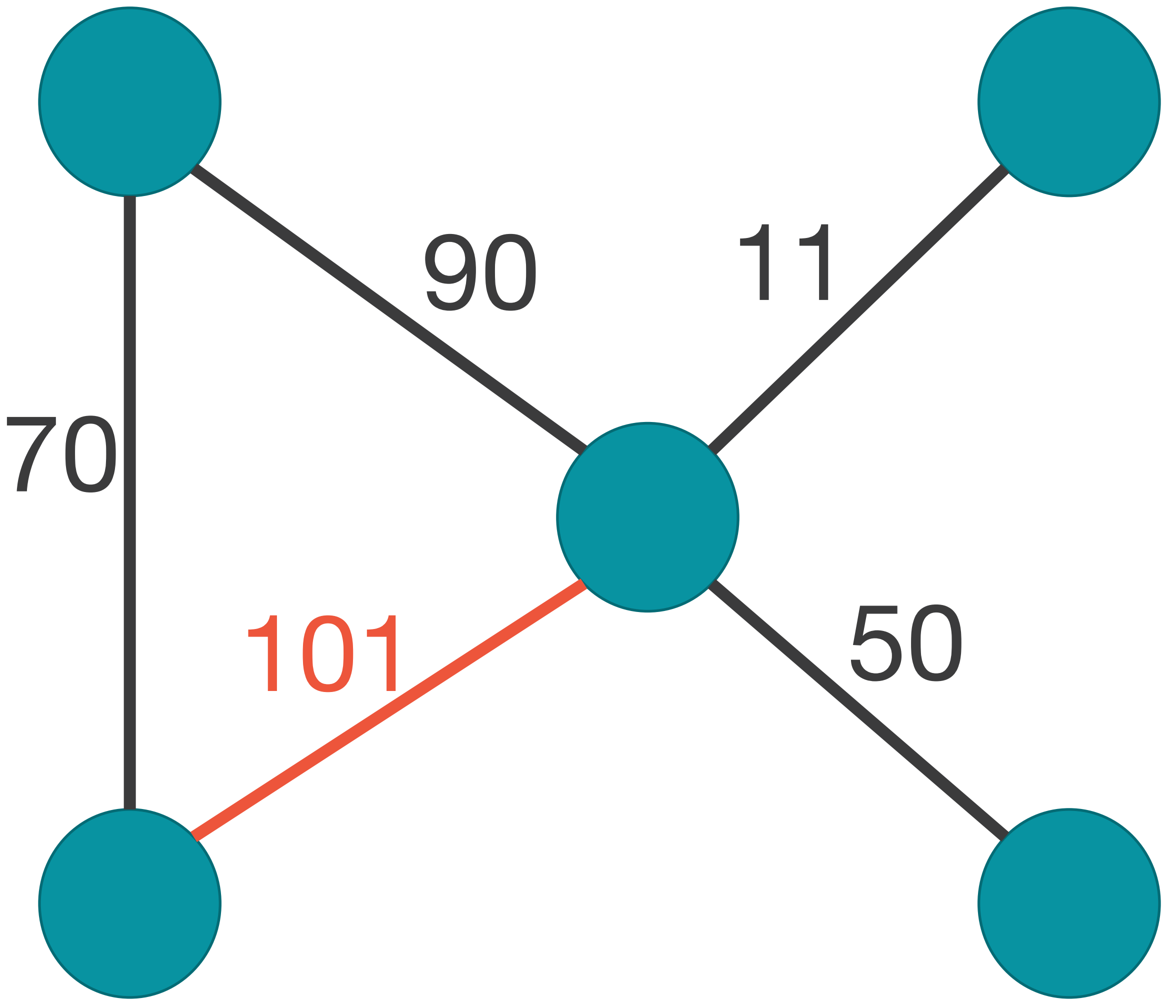

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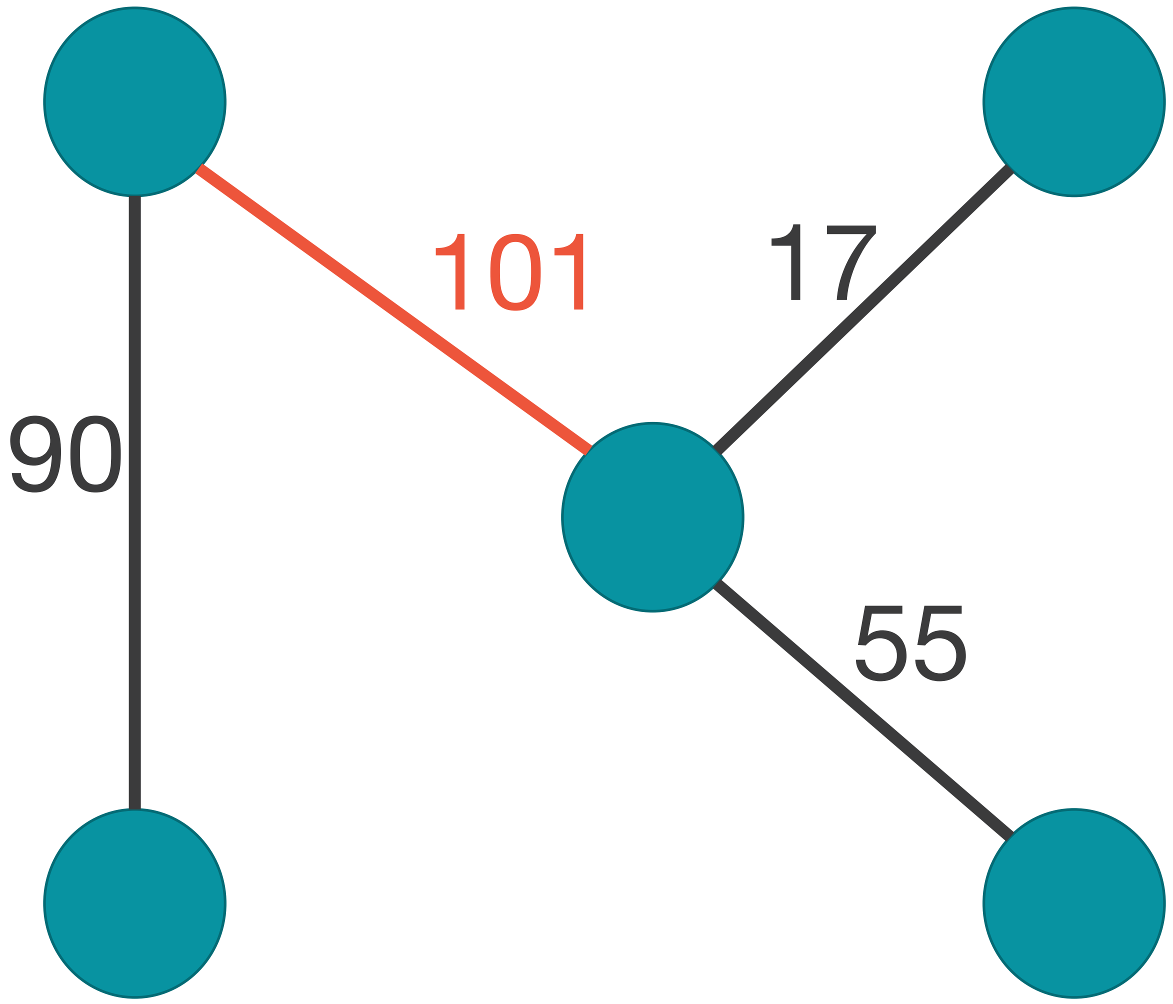

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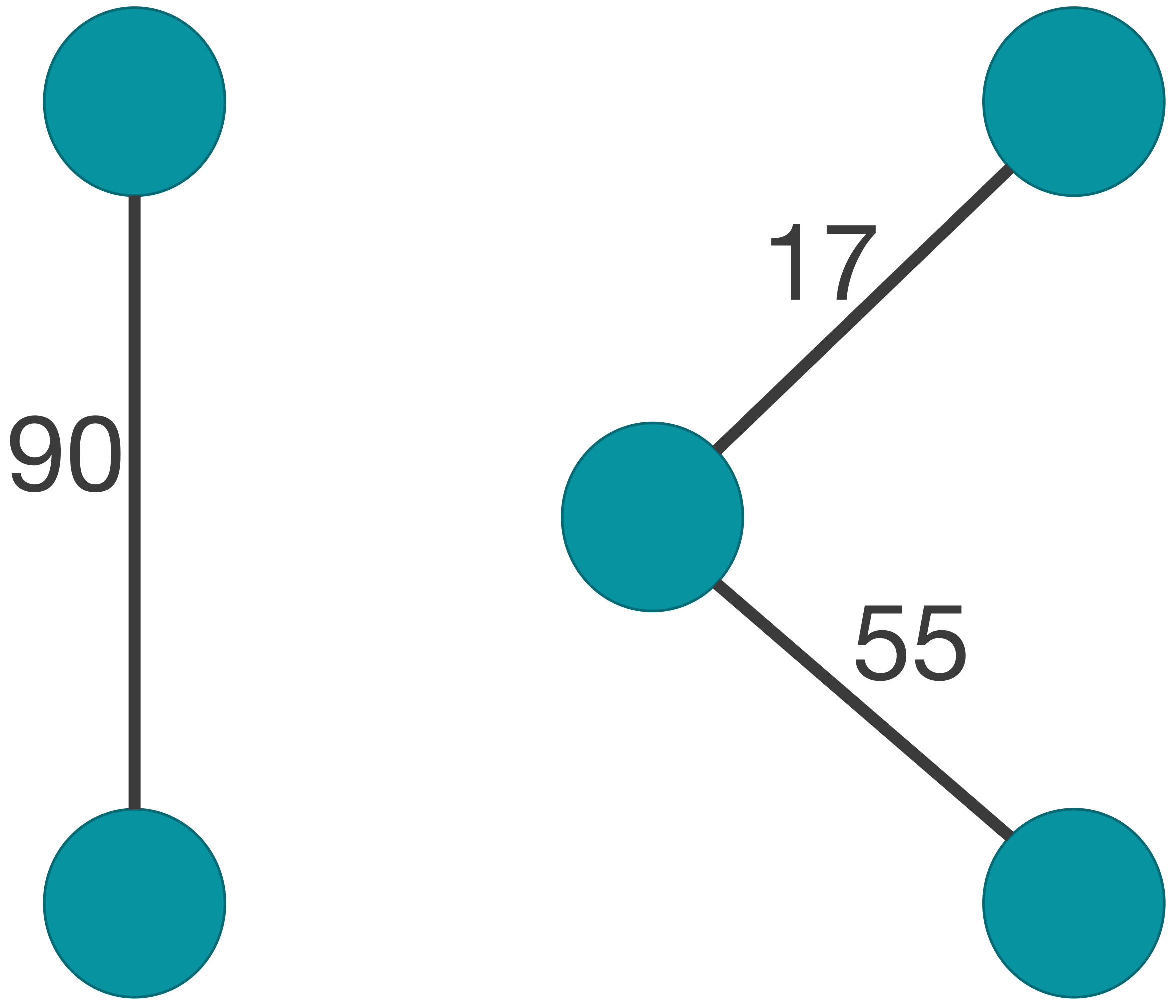
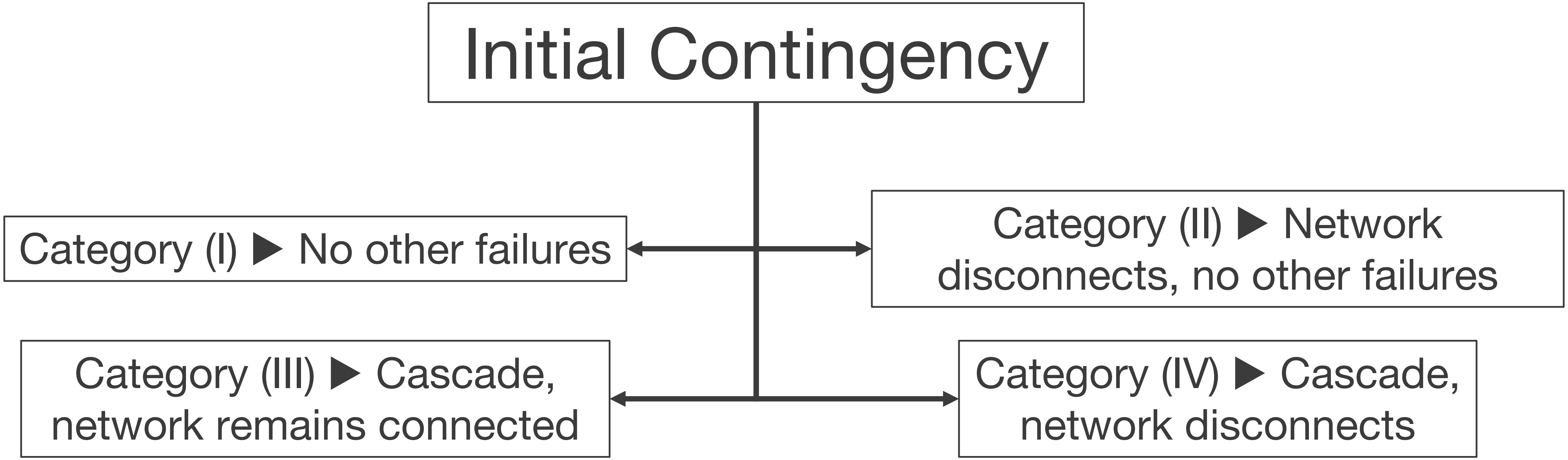



Initial Contingency
Category (I) ▶ No other failures
Category (II) ▶ Network disconnects, no other failures
Category (III) ▶ Cascade, network remains connected
Category (IV) ▶ Cascade, network disconnects

Initial Contingency

"More Stable"

Category (I) ▶ No other failures

Category (III) ▶ Cascade, network remains connected

"Less Stable"

Category (II) ▶ Network disconnects, no other failures

Category (IV) ▶ Cascade, network disconnects

Cascading Failures - Model

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

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

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

Power on lines connected to node

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

Line status

Current line capacity

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

Maximum line capacity

Y. Yang and A. E. Motter. Cascading failures as continuous phase-space transitions. Phys. Rev. Lett., 119(24):248{302, 2017.

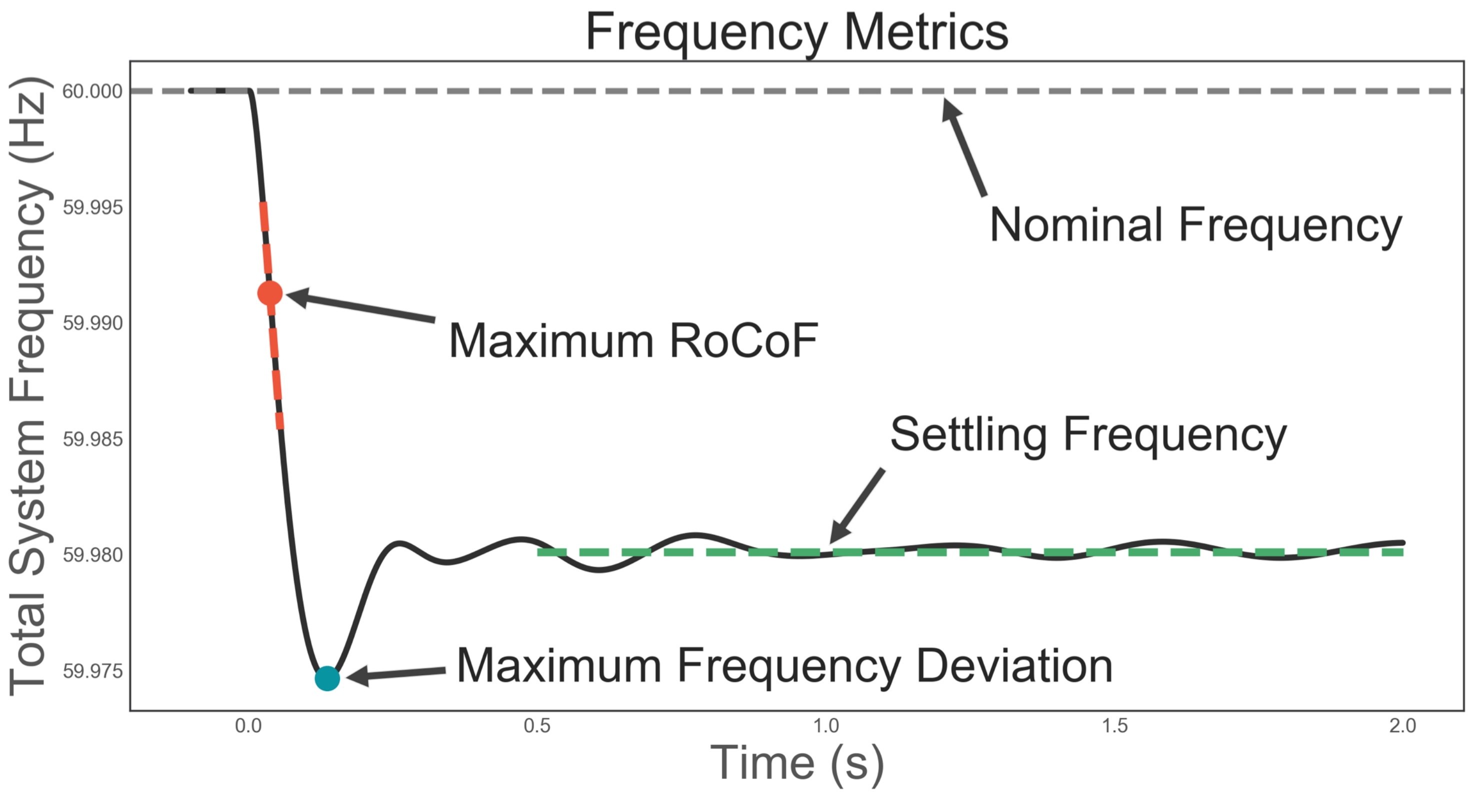
Cascading Failures - Model

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

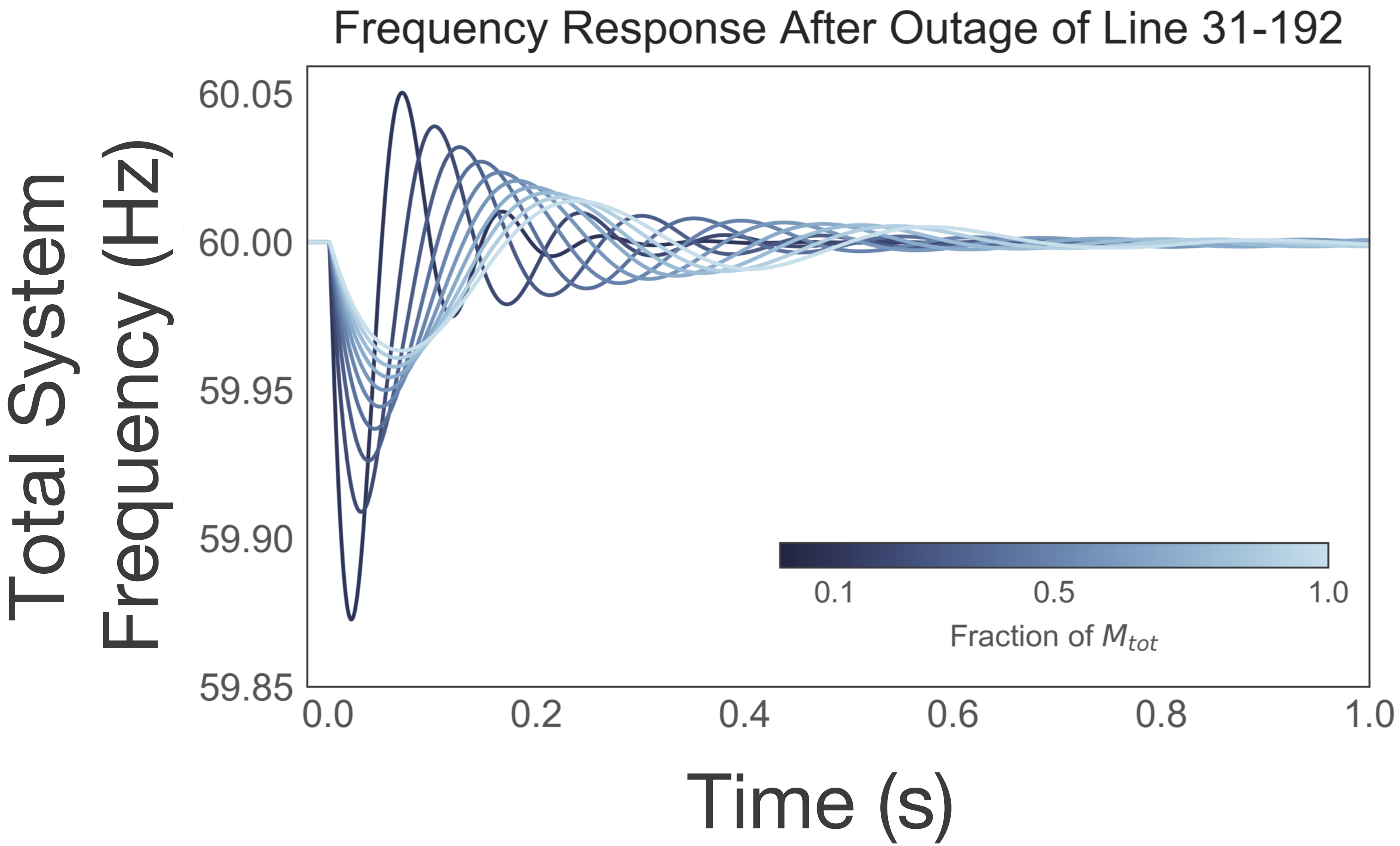
Frequency Stability

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



Outline

Category (I) – Illinois



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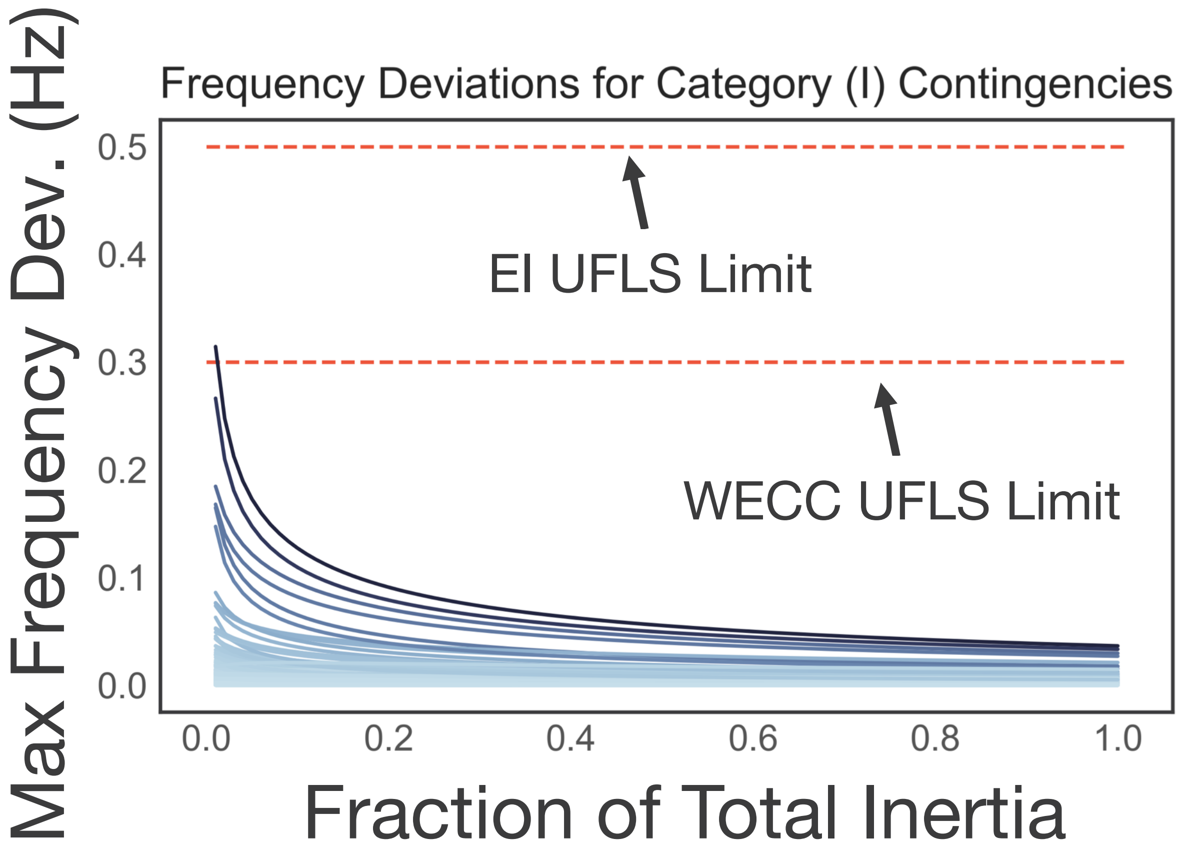

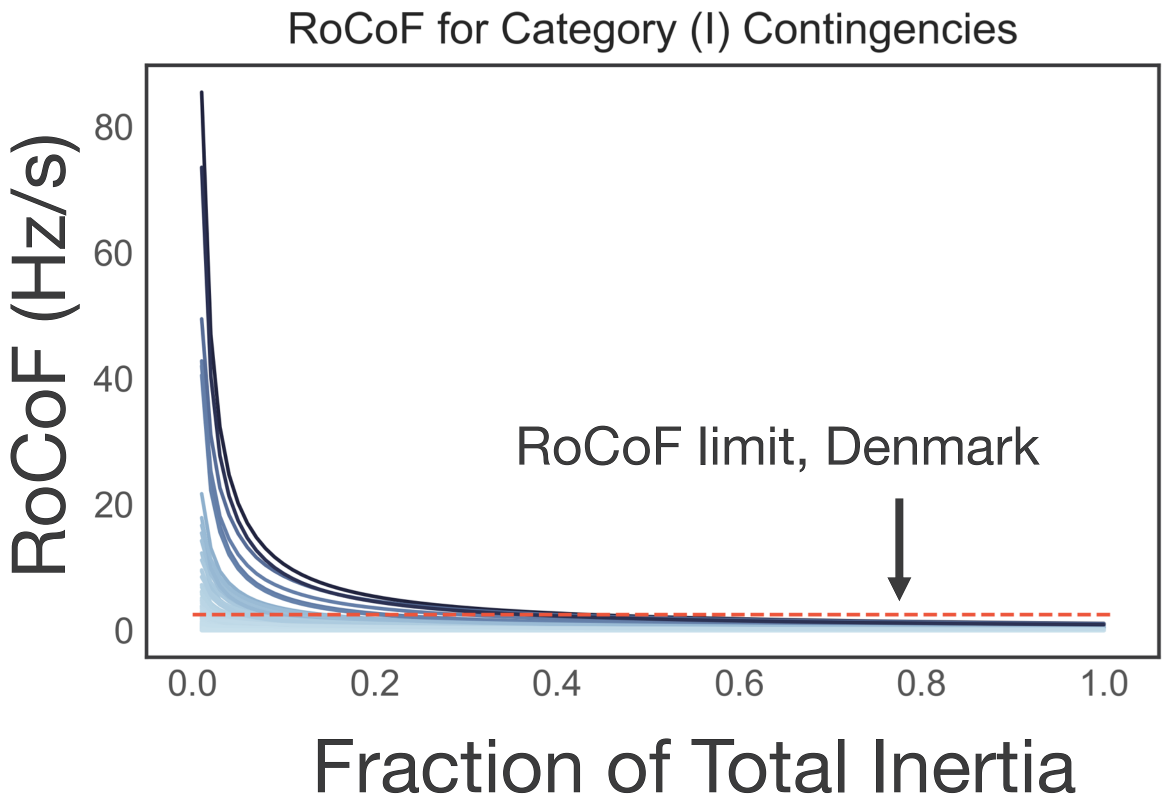

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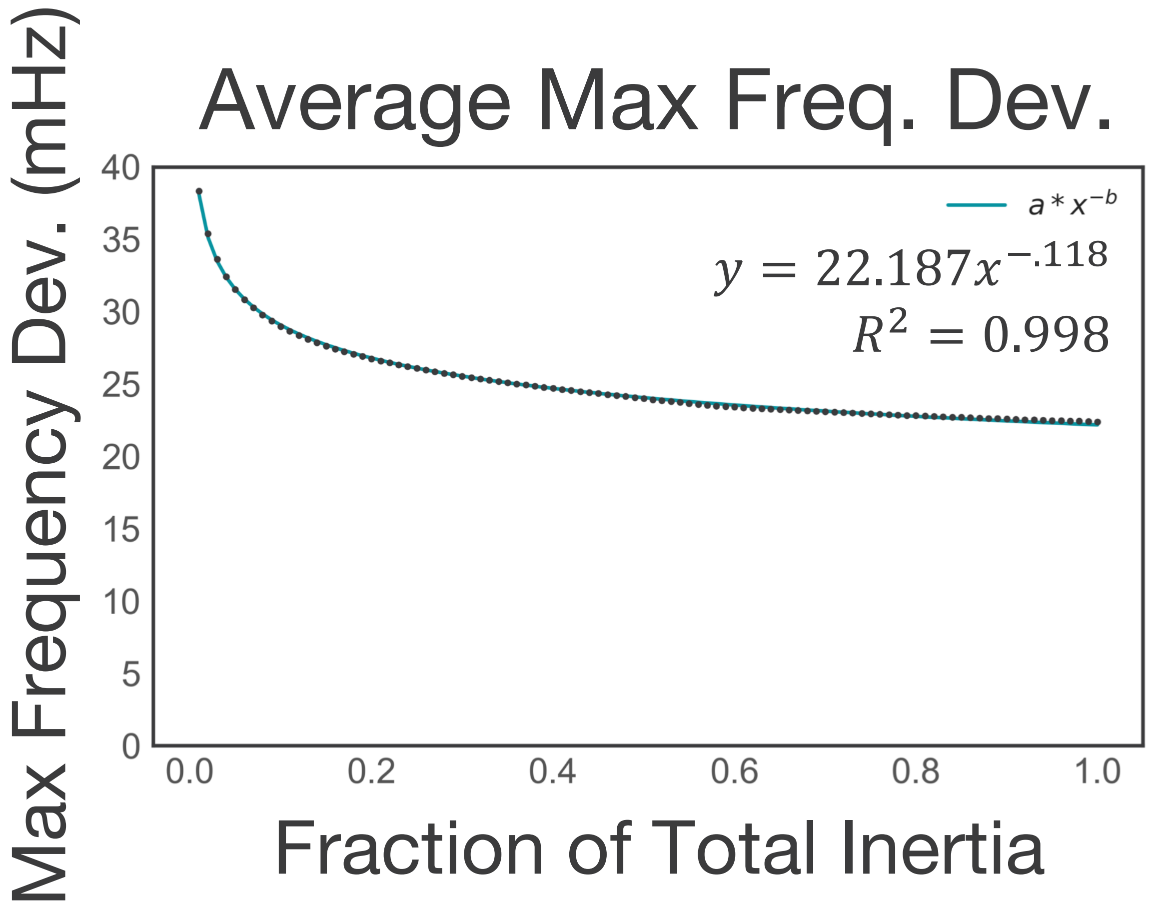
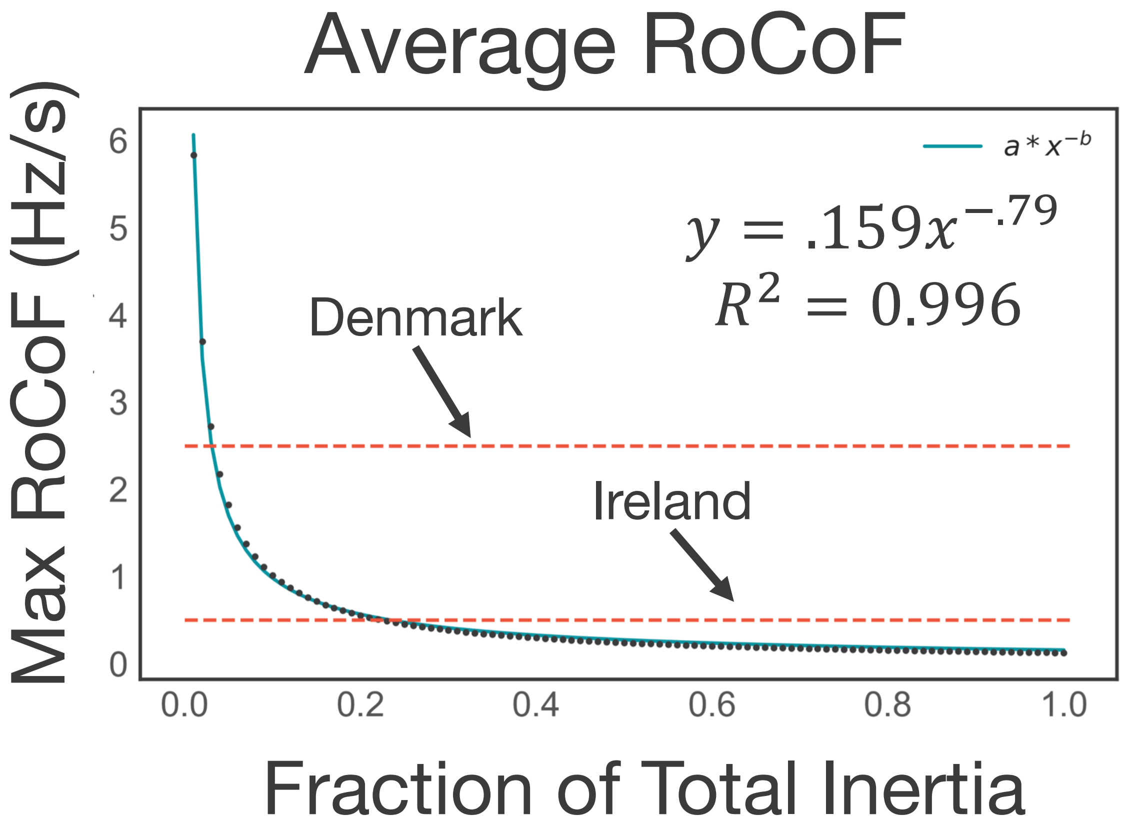
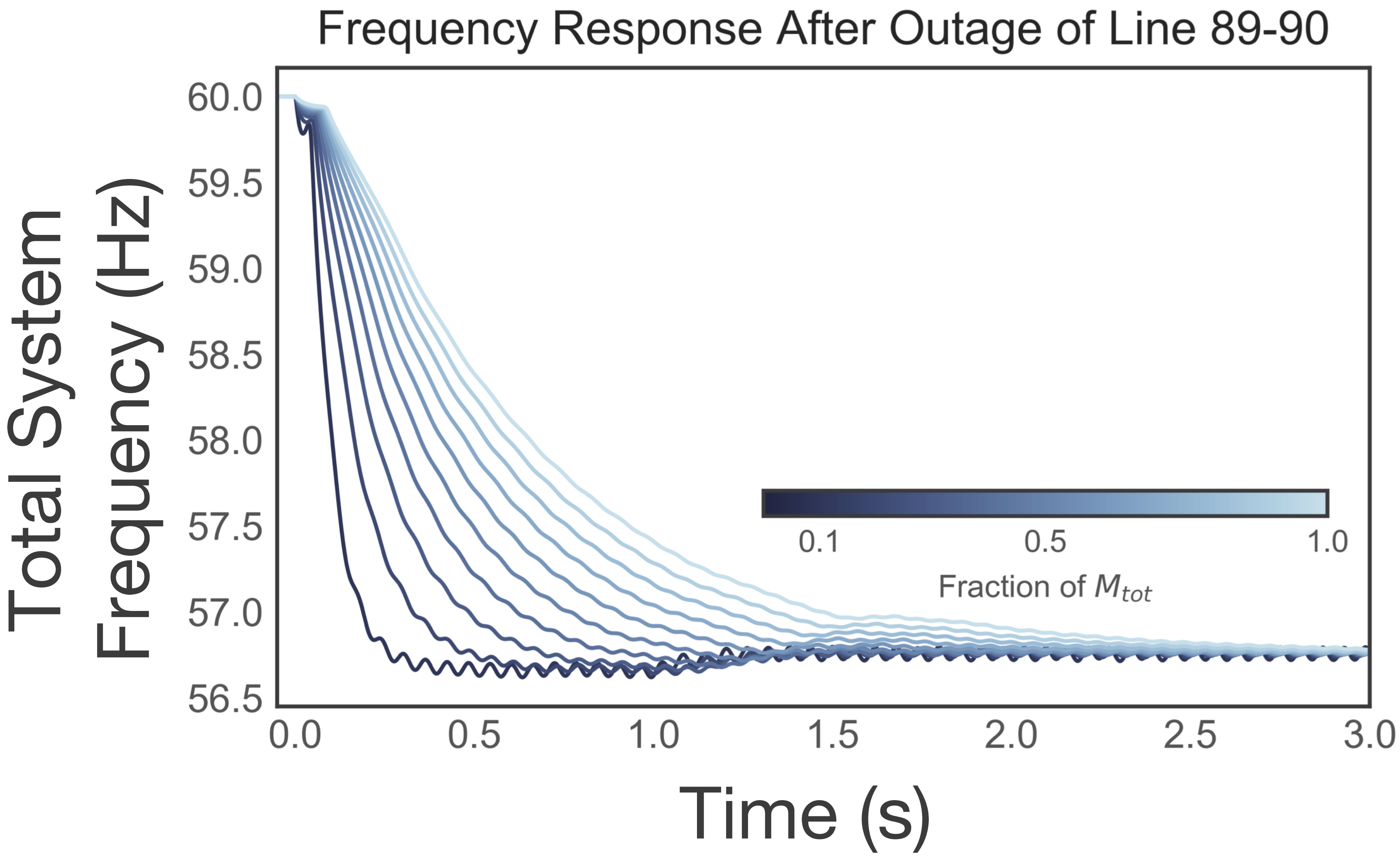
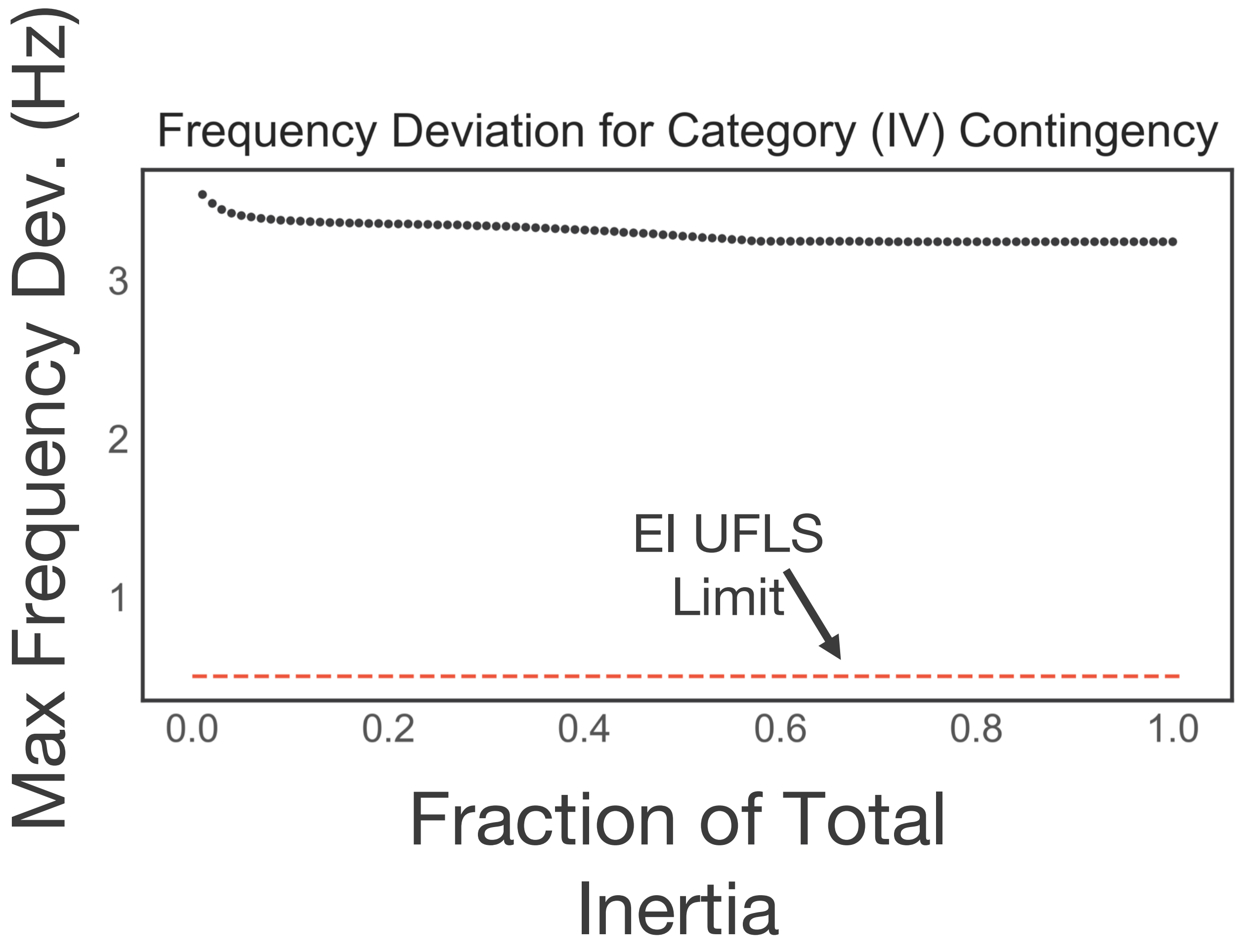


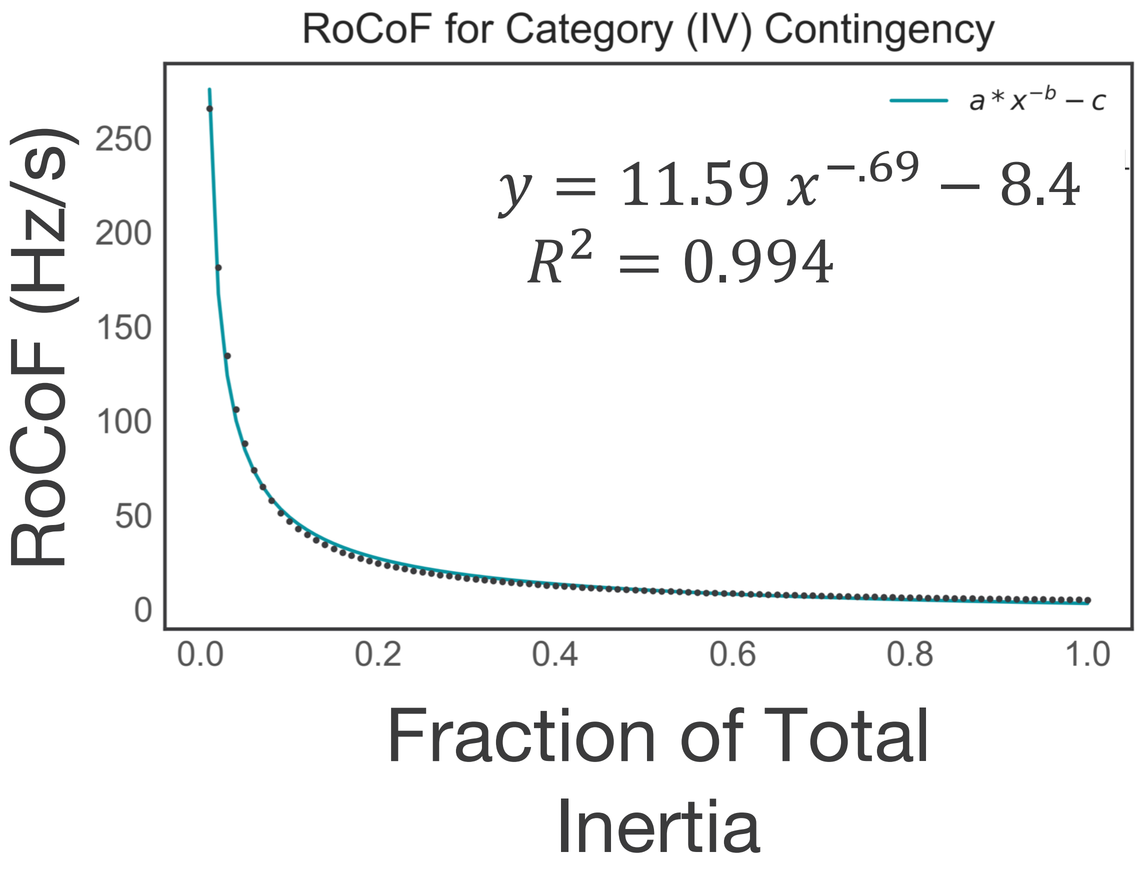


Category (IV)—Illinois

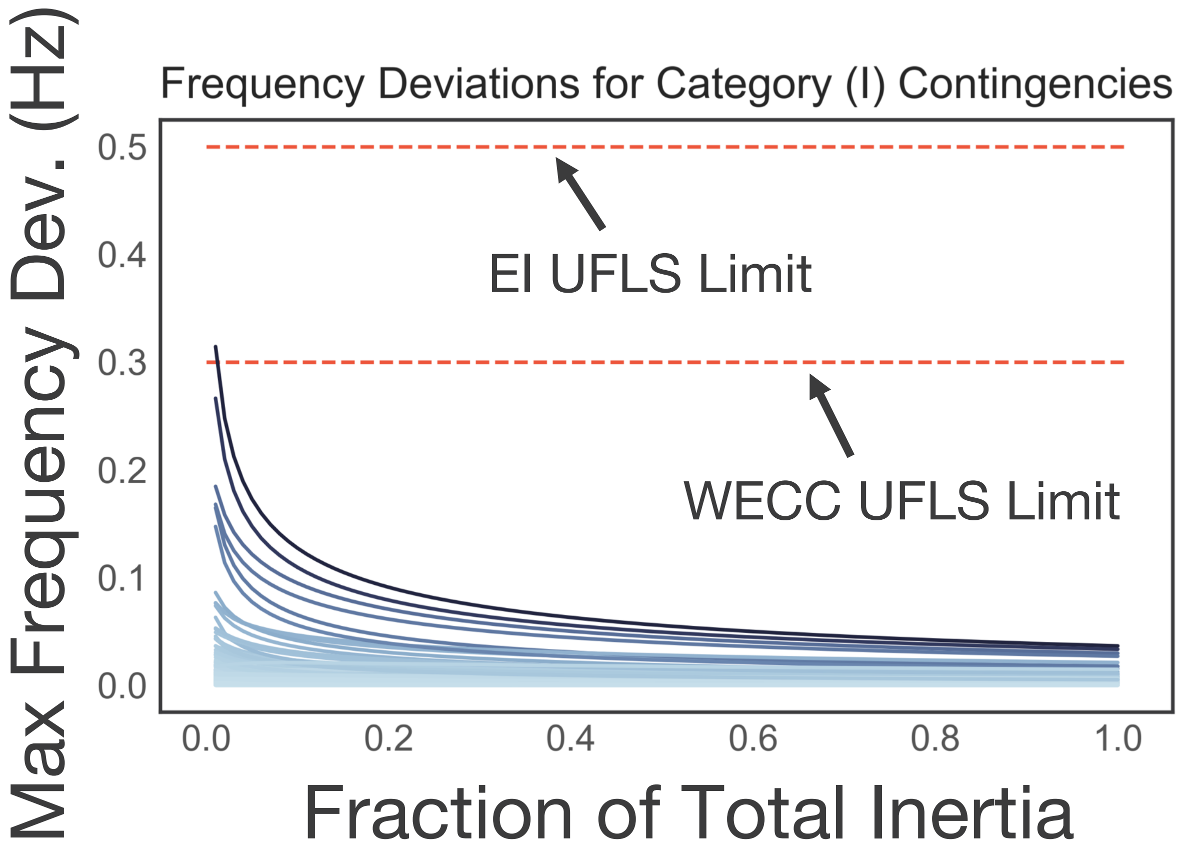


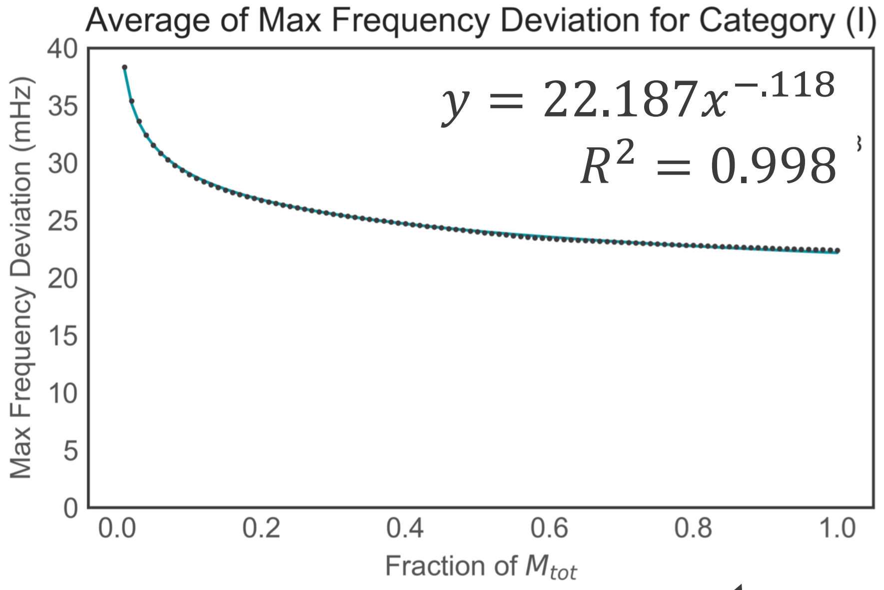
Category (IV)—Illinois





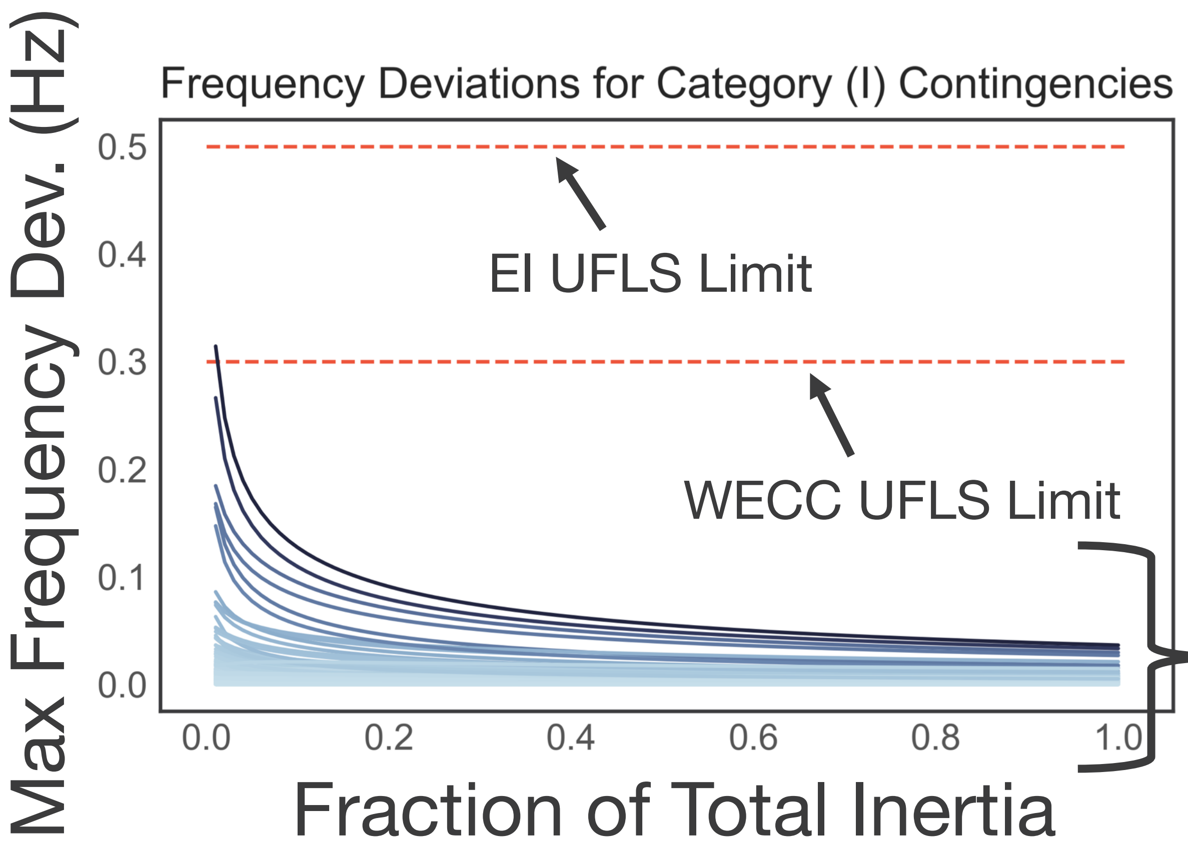
How metrics change

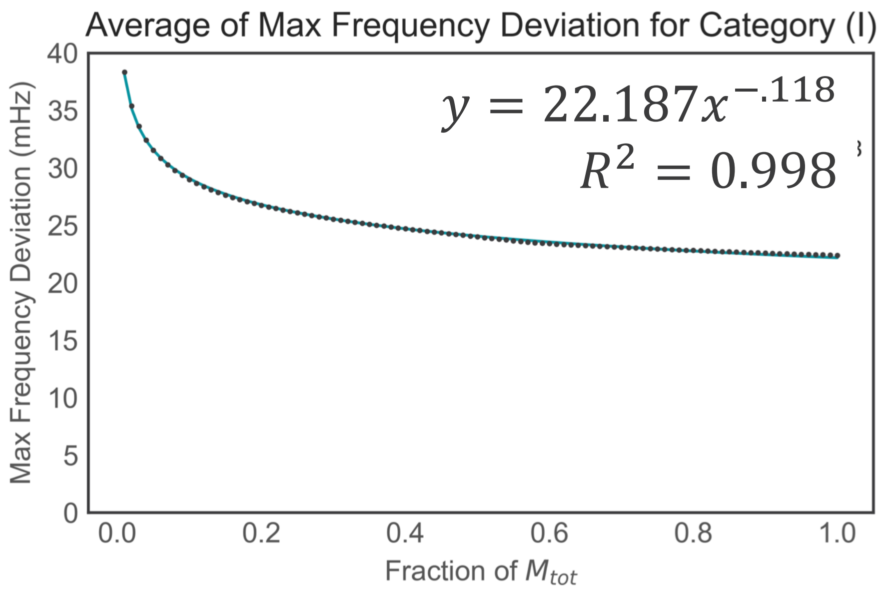




Frequency metrics as a function of total system inertia

Why Contingencies Differ





Why do some contingencies cause larger deviations than others?

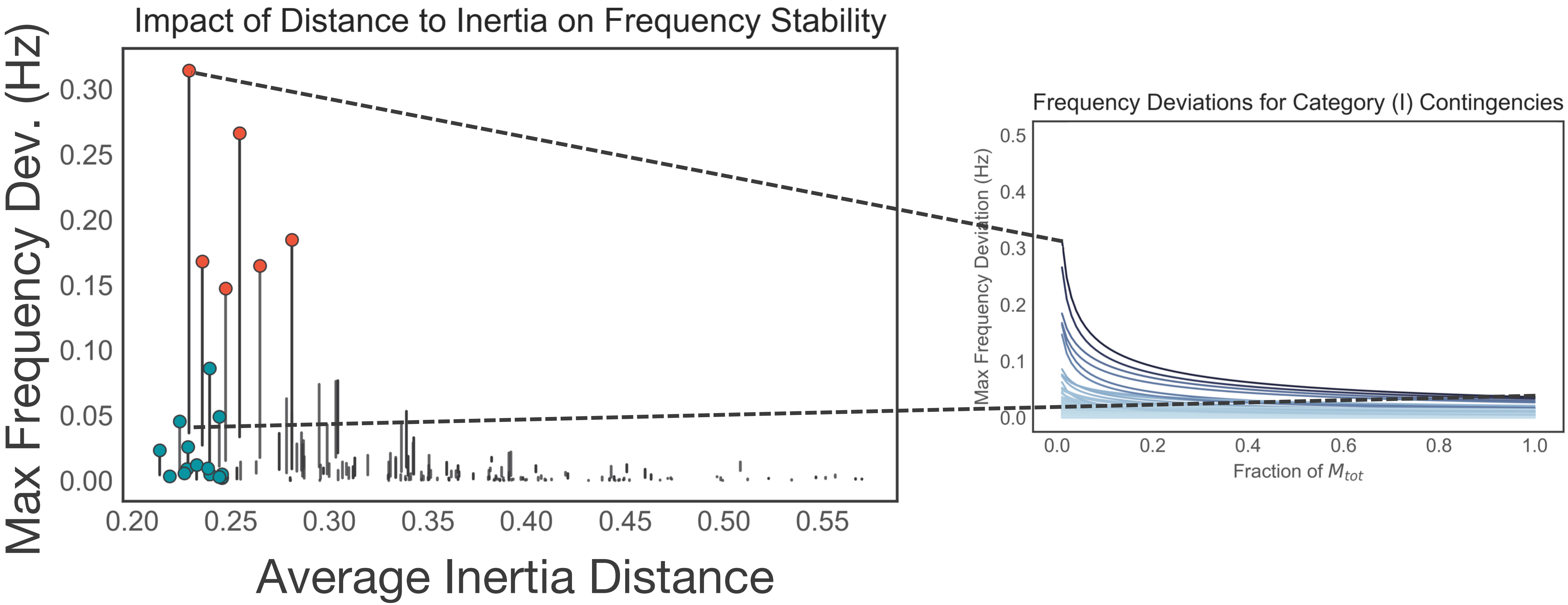
Average Inertia Distance

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

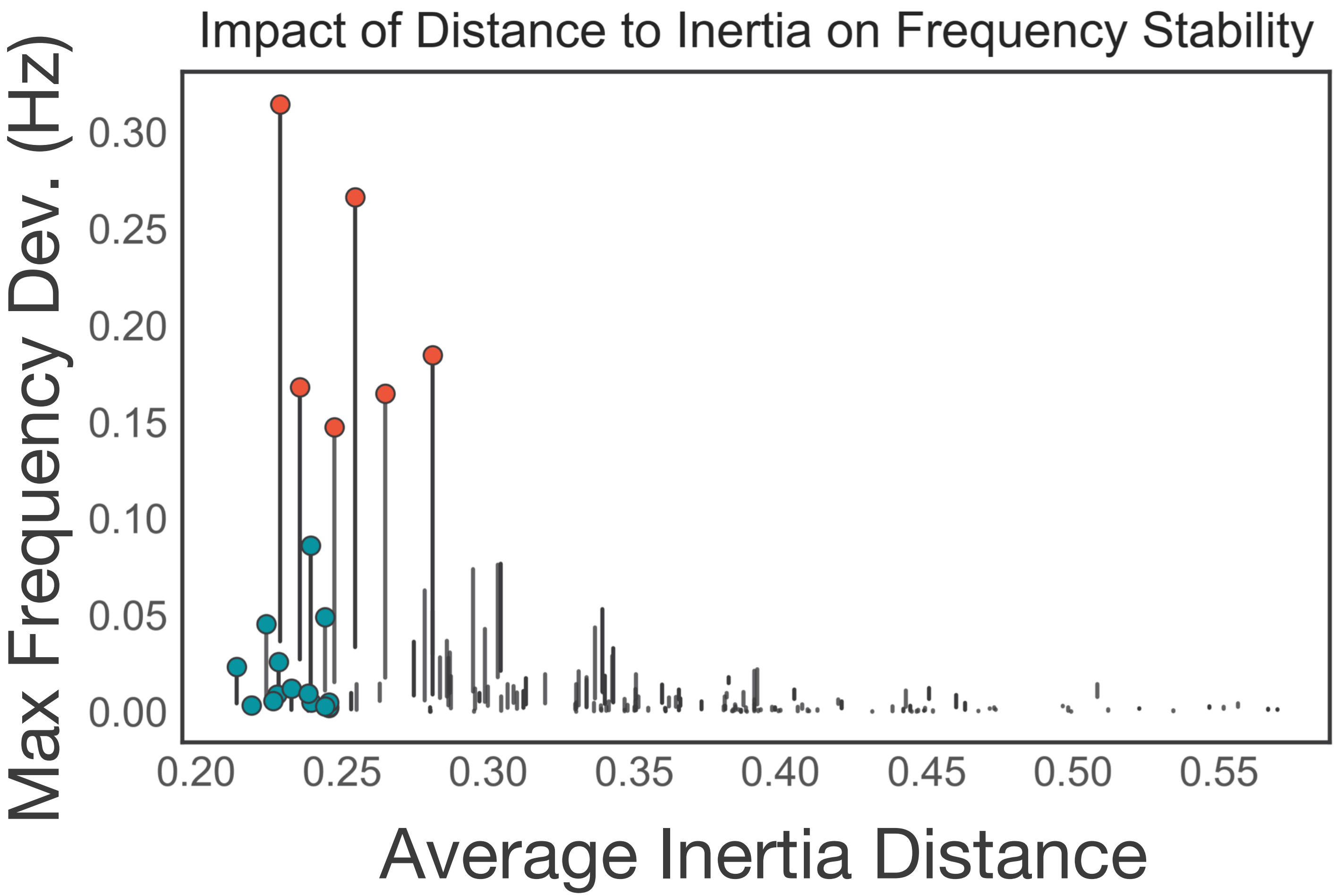
Shortest distance to generator

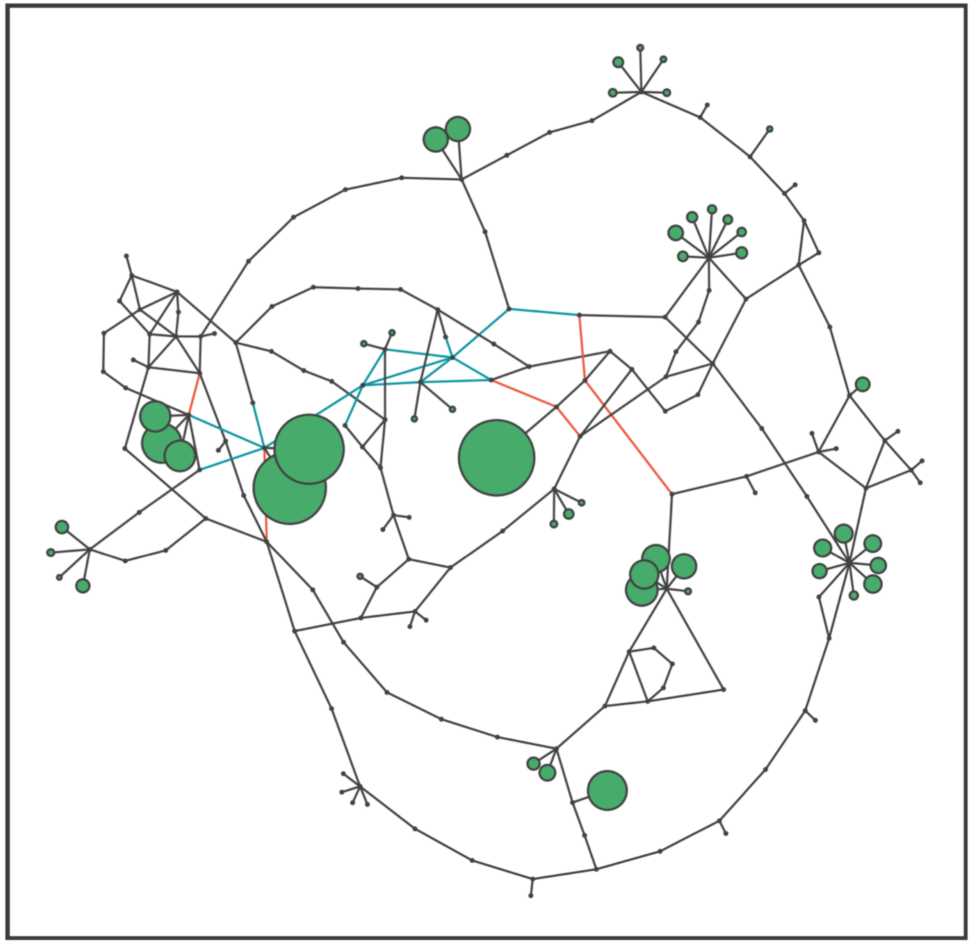
Diameter of network

Average Inertia Distance—Illinois

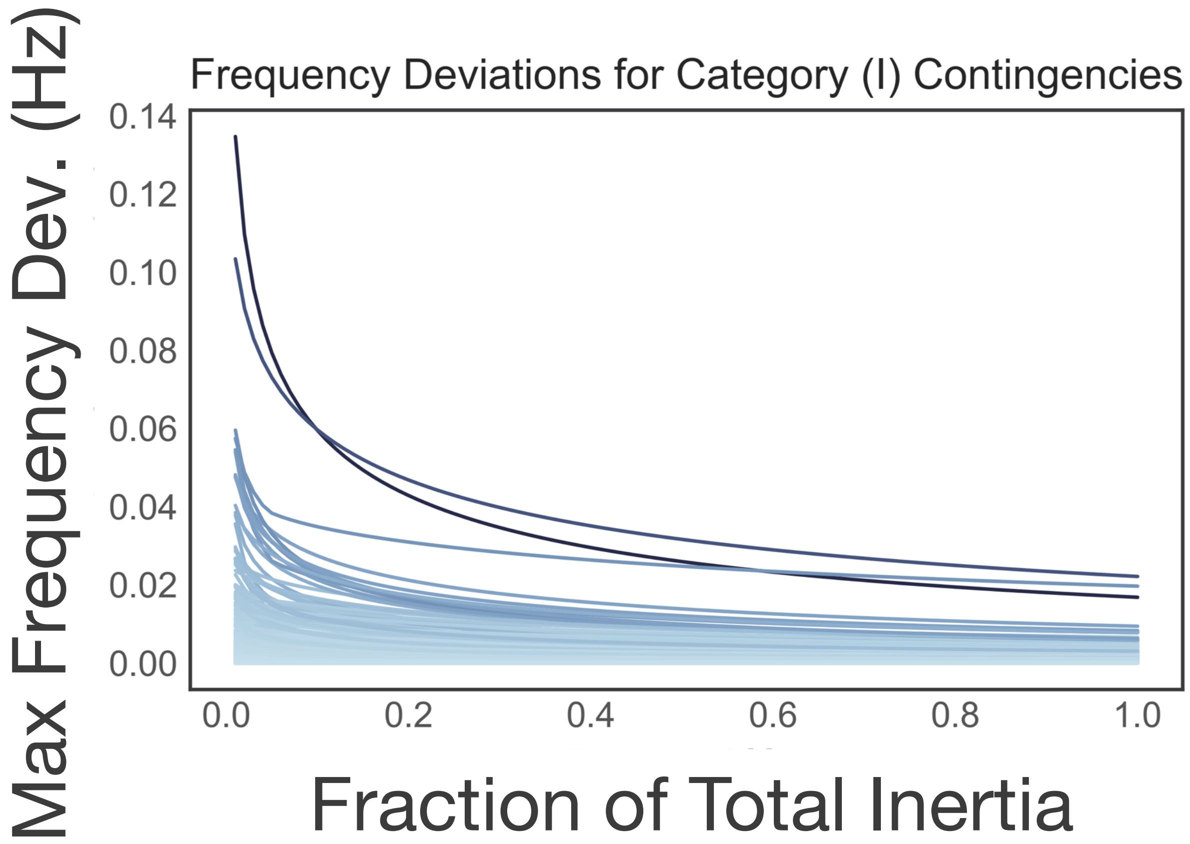


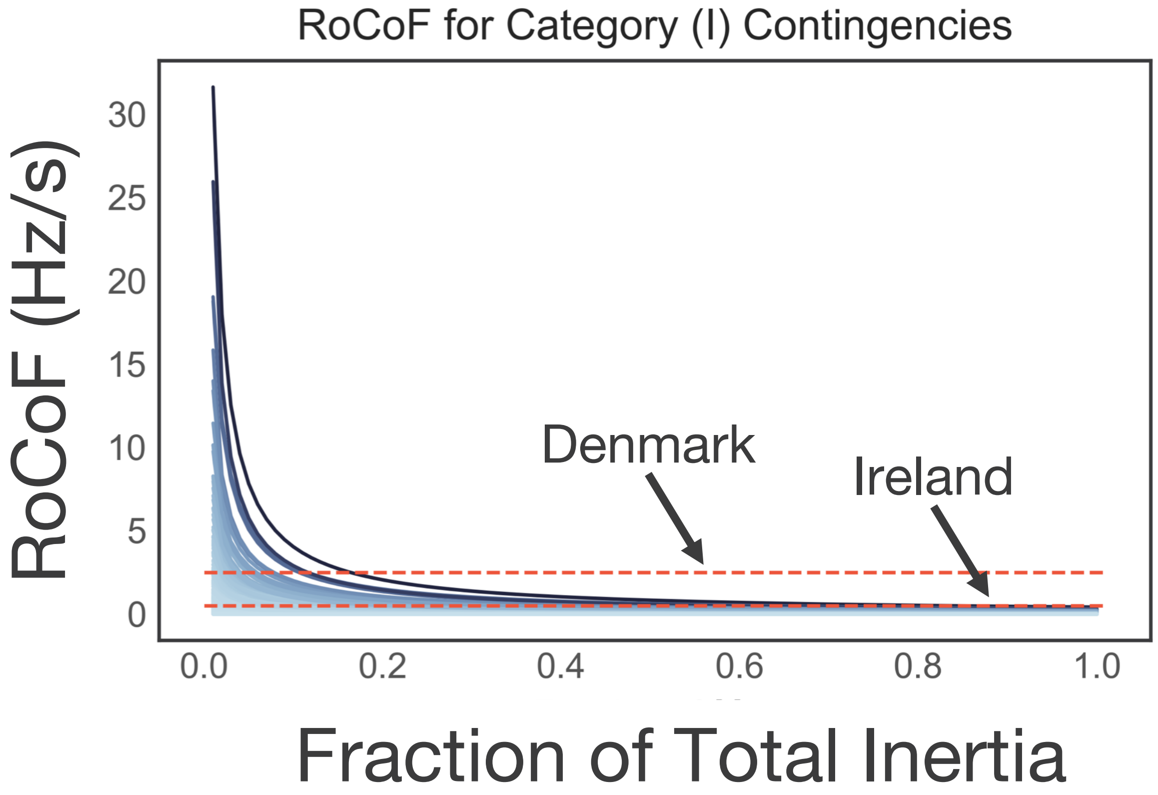
Average Inertia Distance—Illinois





Category (I) – South Carolina





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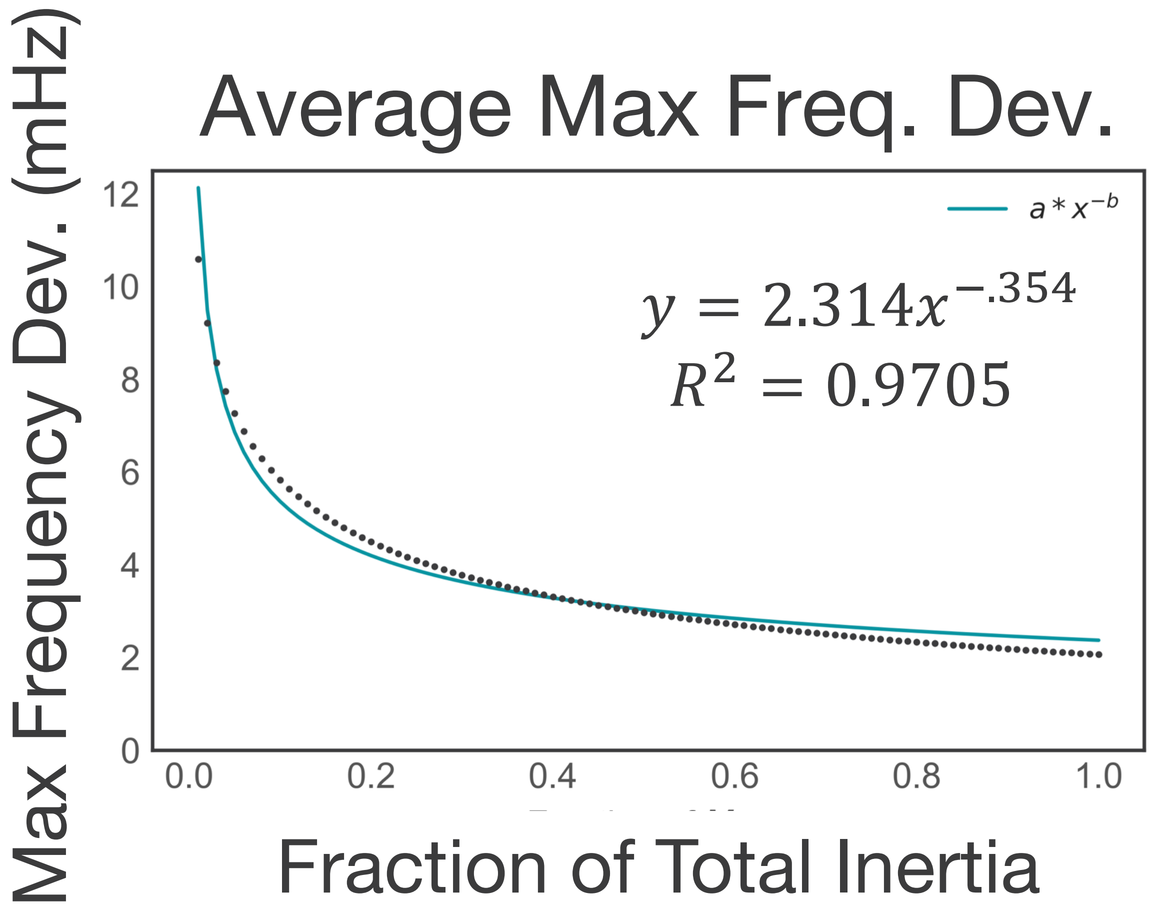
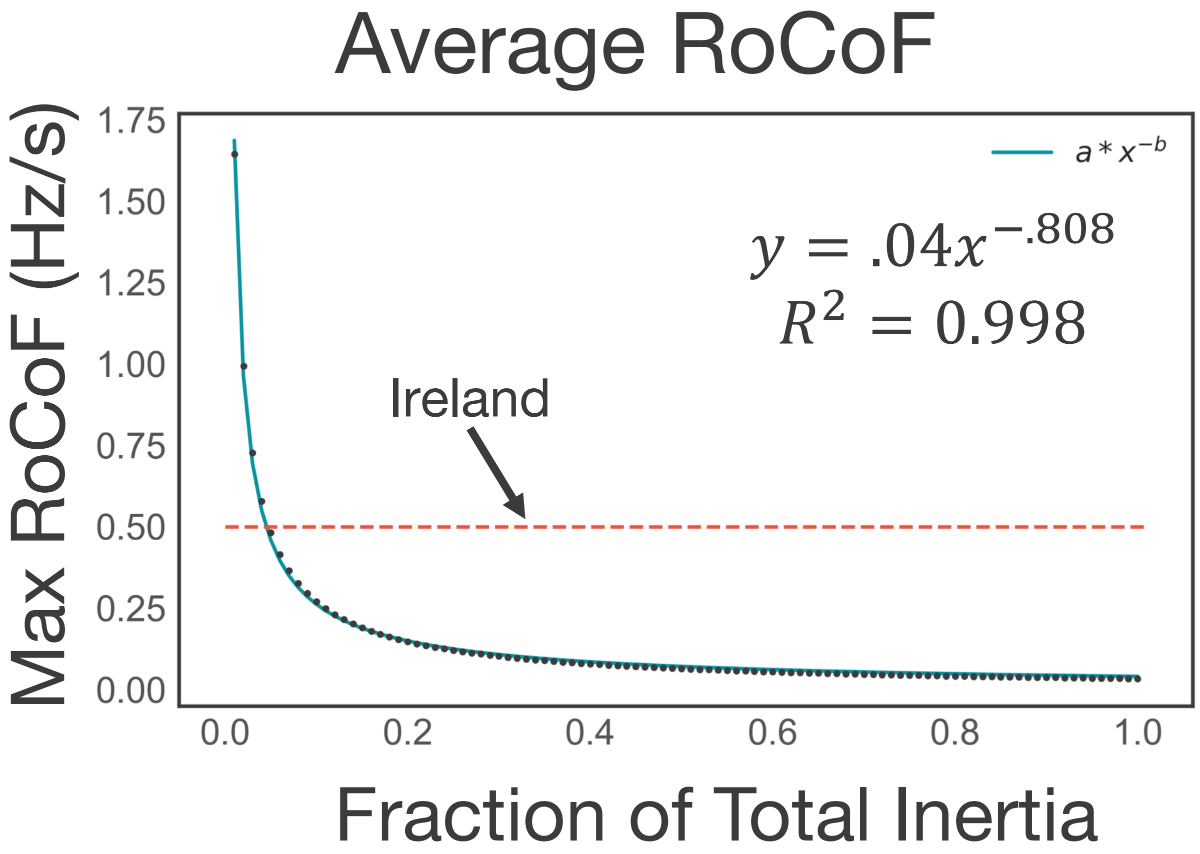
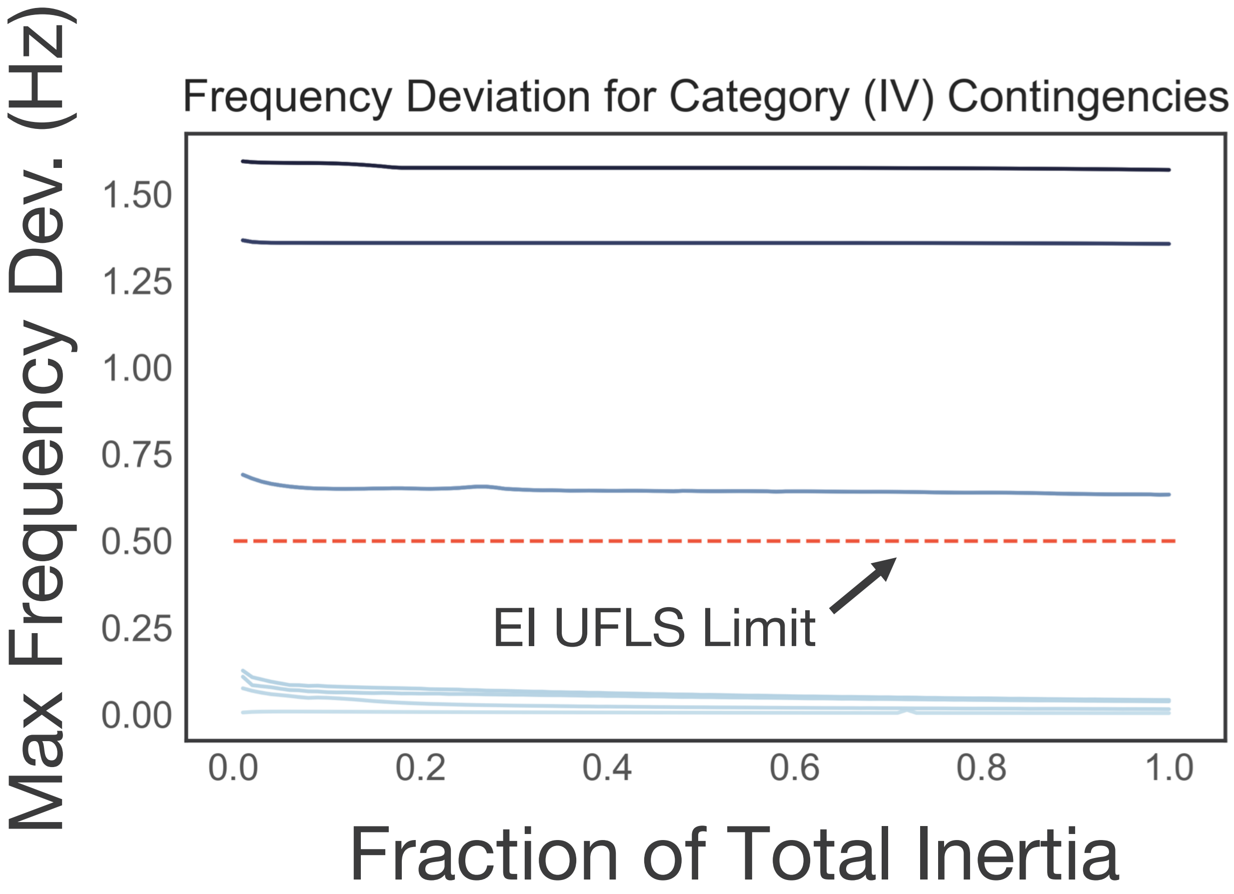
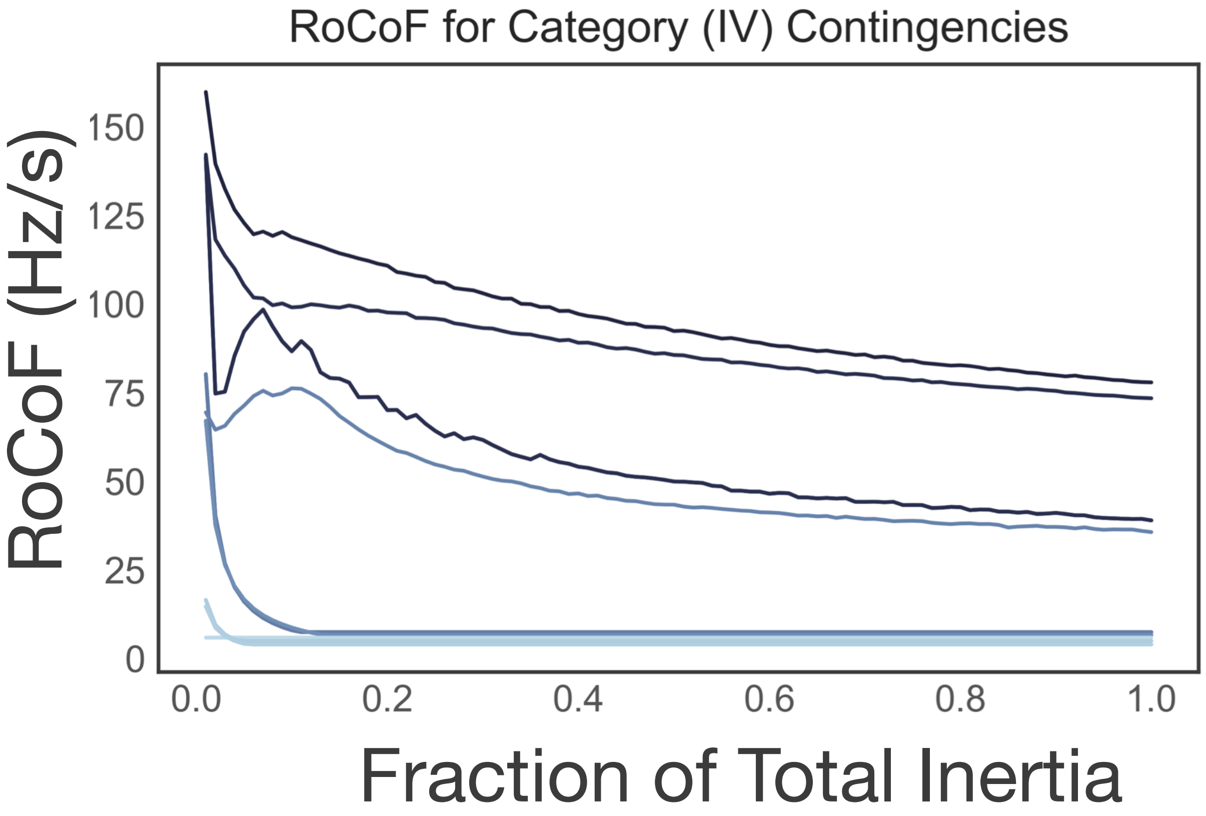


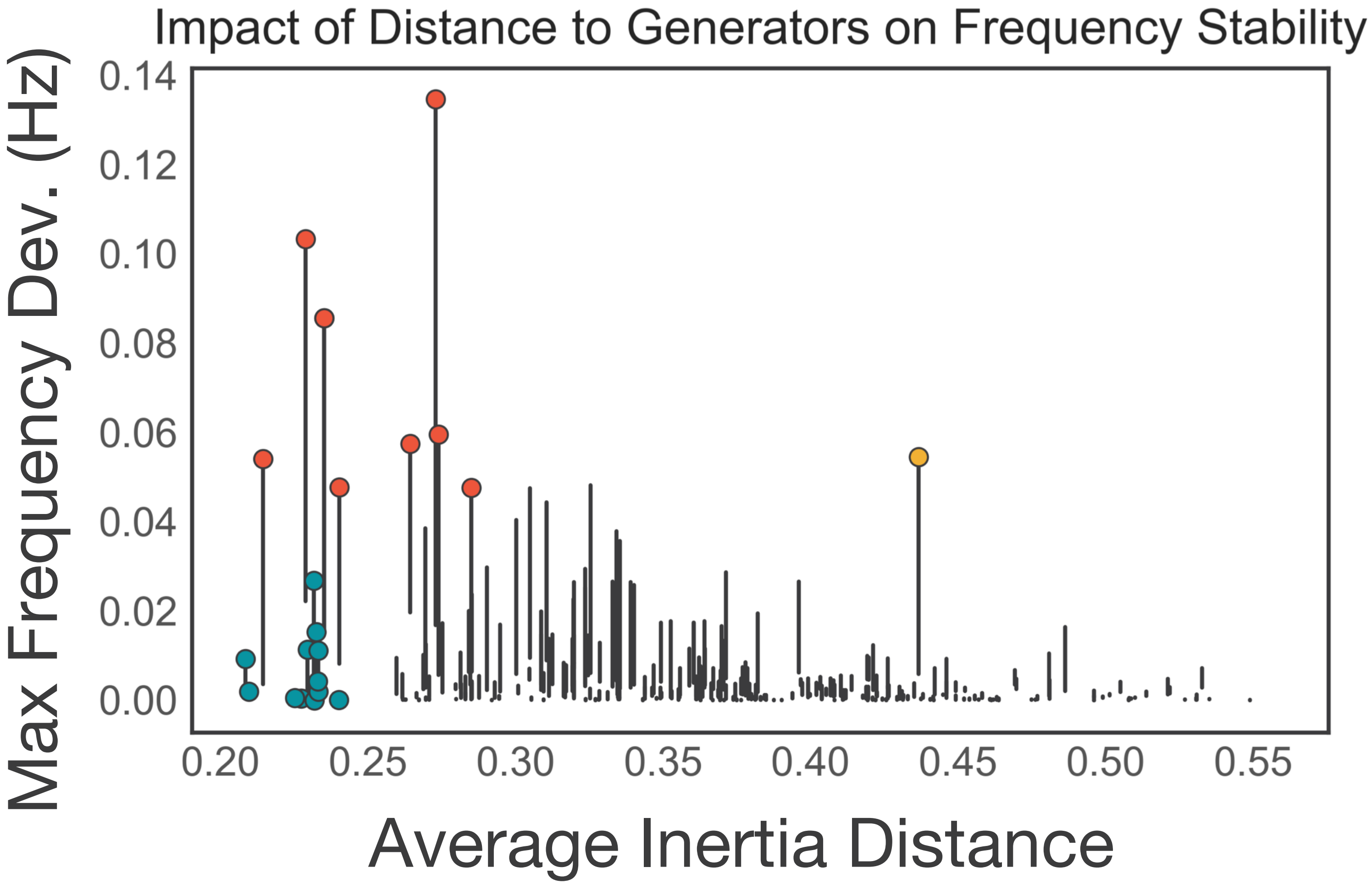


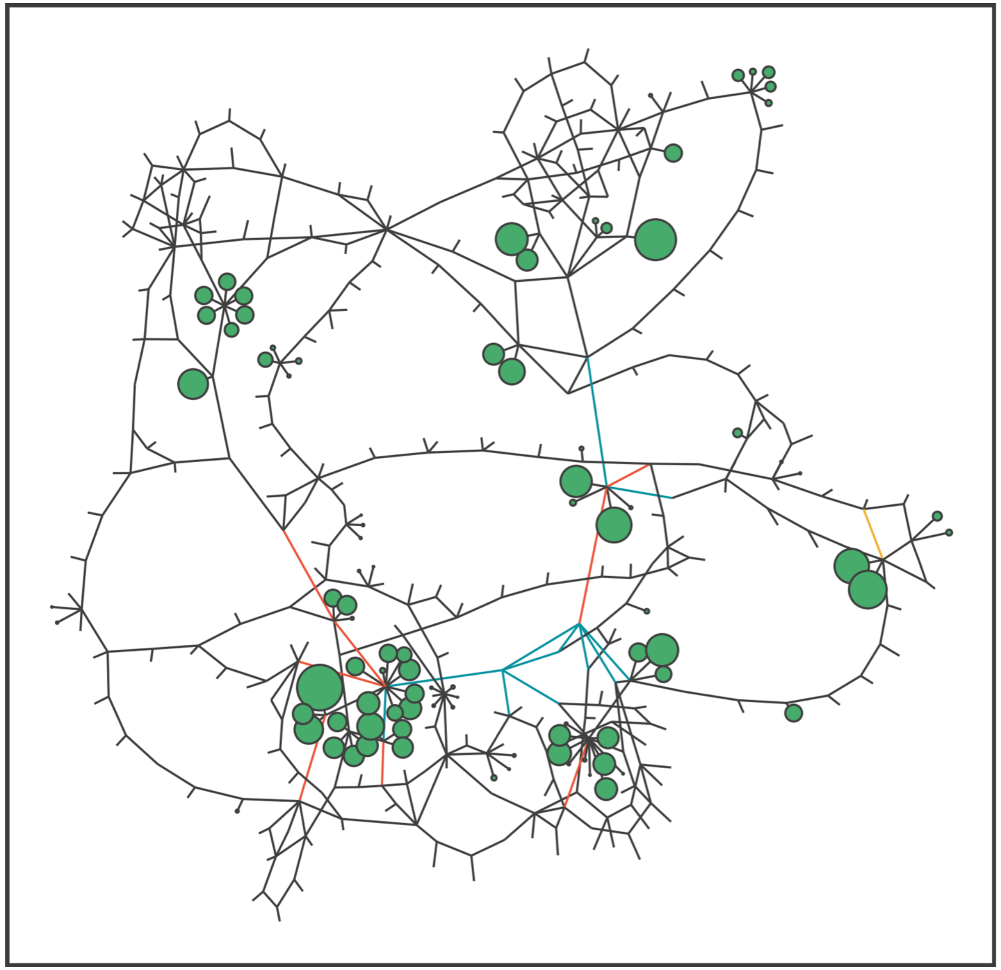
Category (IV)—South Carolina



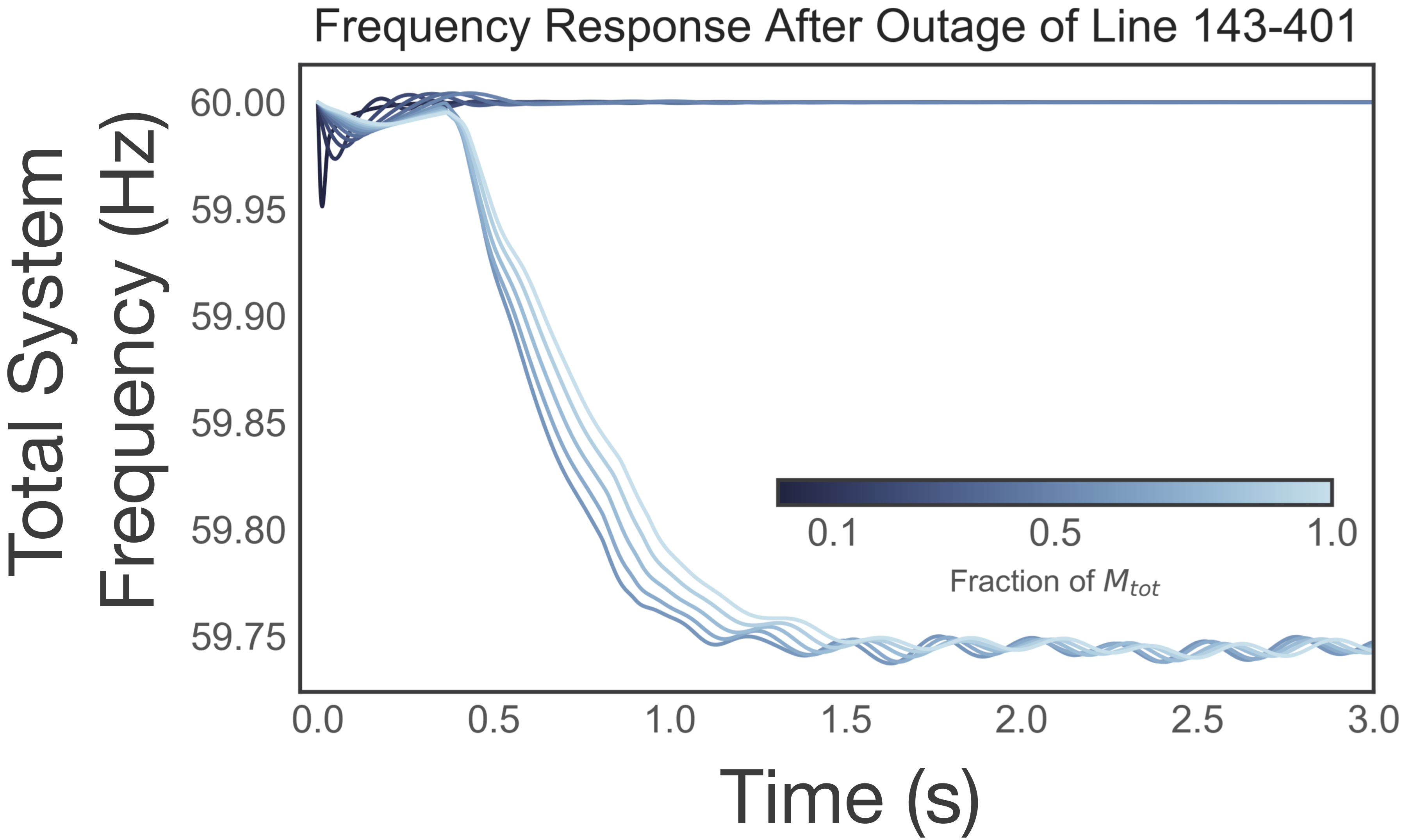


Average Inertia Distance—South Carolina

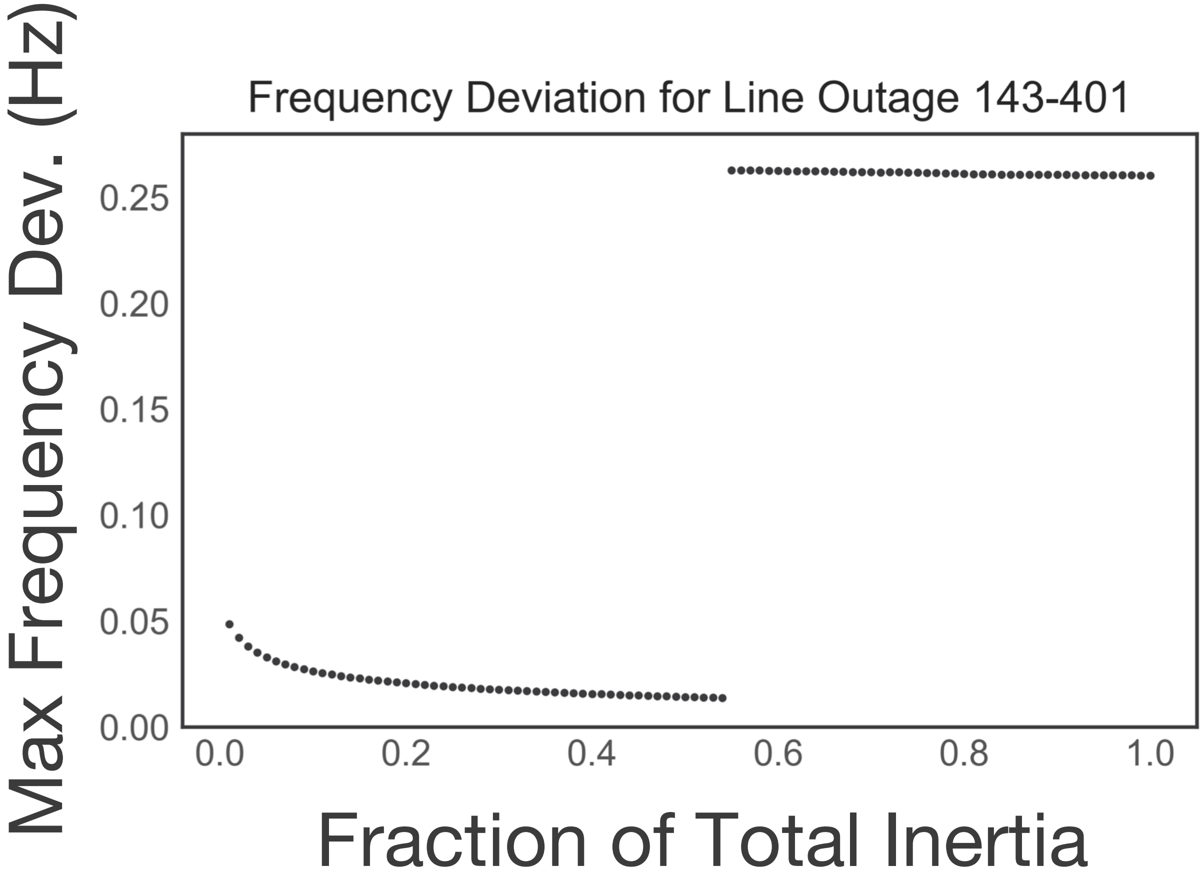


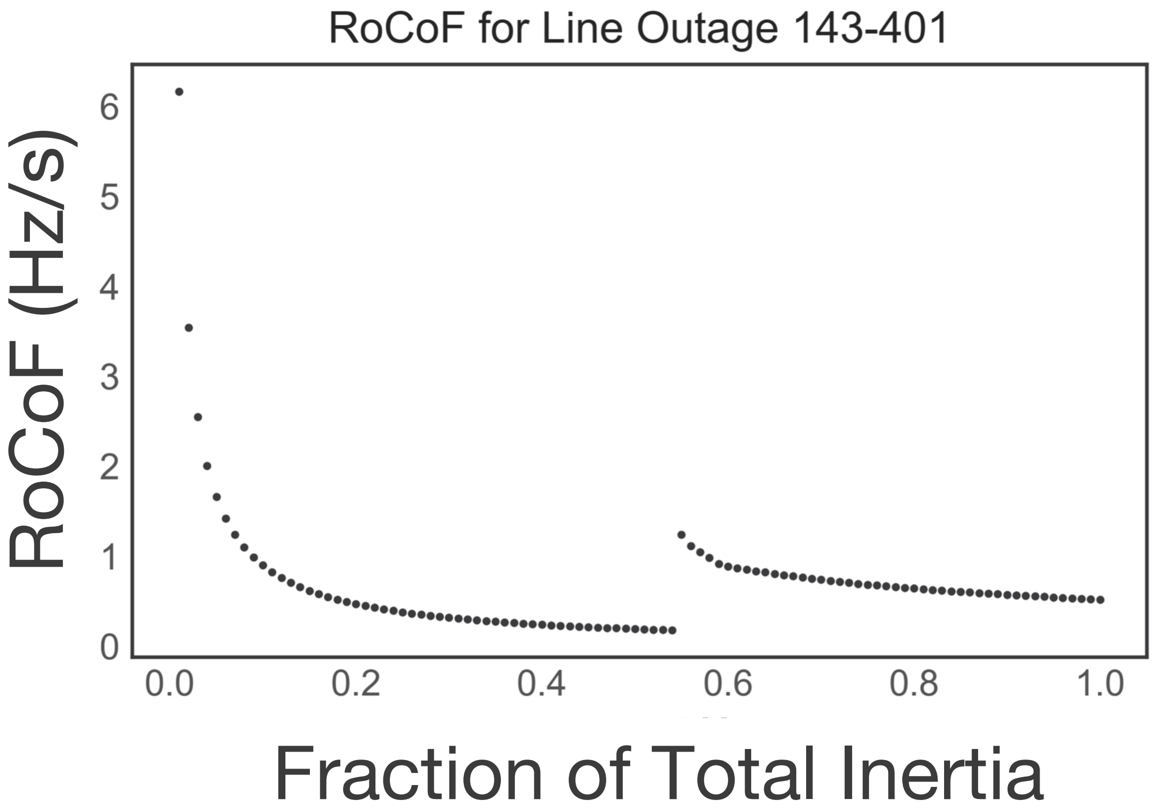


South Carolina—Bifurcations?



South Carolina—Bifurcations?





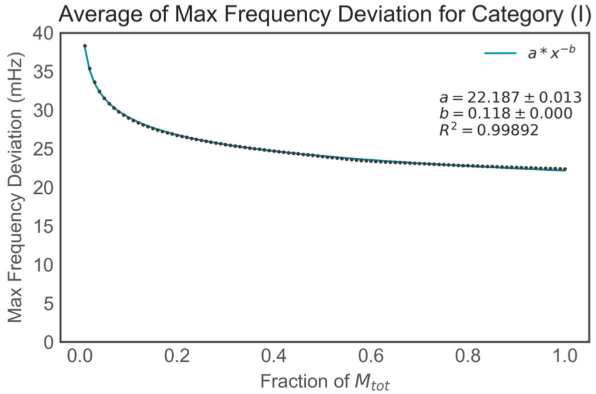
Outline

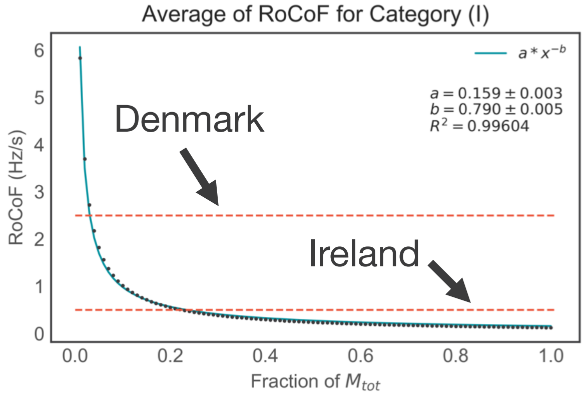
1. Motivating example
2. Traditional vs. Renewable Generation
3. Previous Work
4. Contributions
5. Experimental Setup
6. Preliminary Results
7. Conclusions, Future Work, Timeline

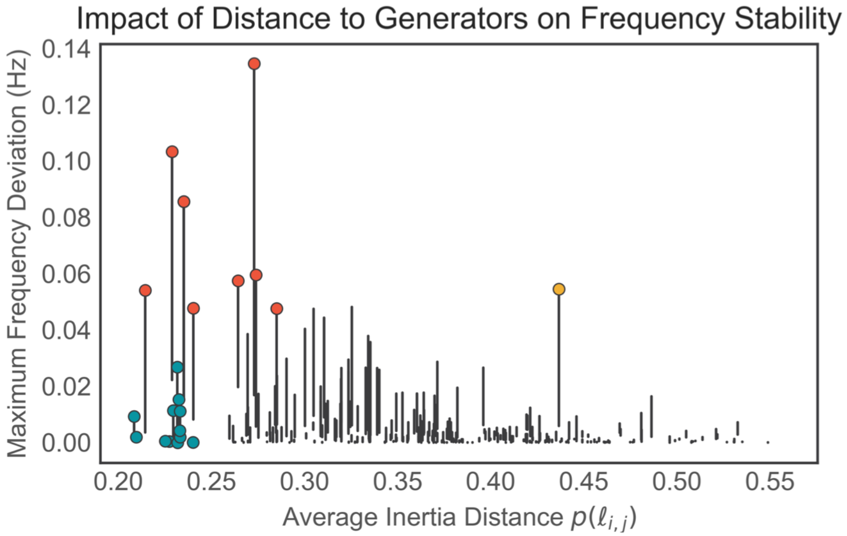
Conclusions—Total System Inertia

How does inertia impact power system stability?

- Established a functional relationship between frequency stability and total system inertia
$$y = a * x^{-b}$$
- Described the relationship between frequency stability and distance to inertia

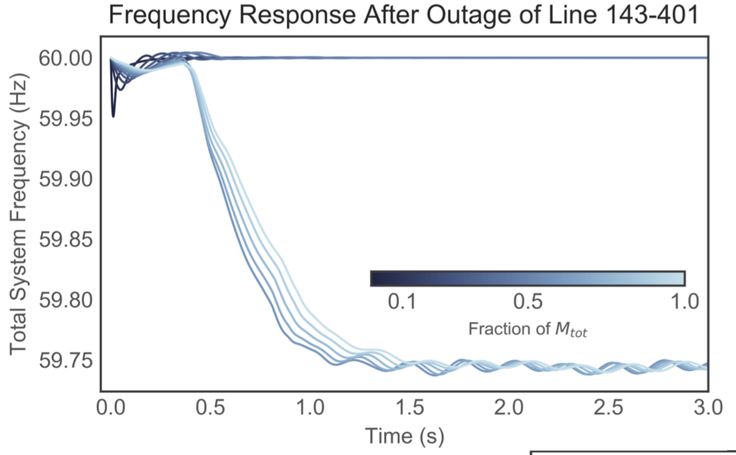




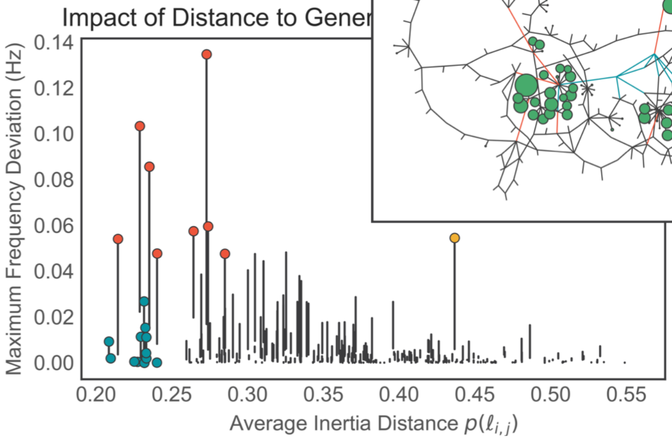


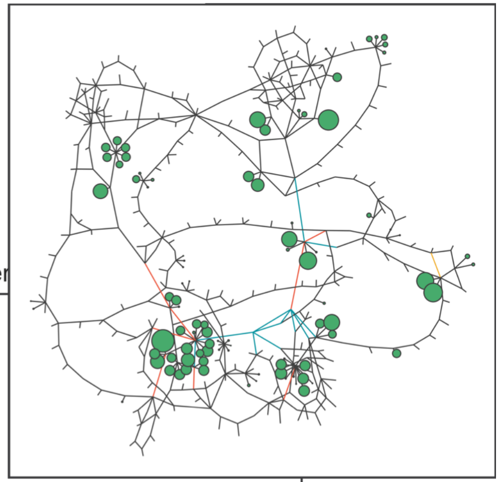
Future Work—Structural Distribution

How does inertia impact power system stability?



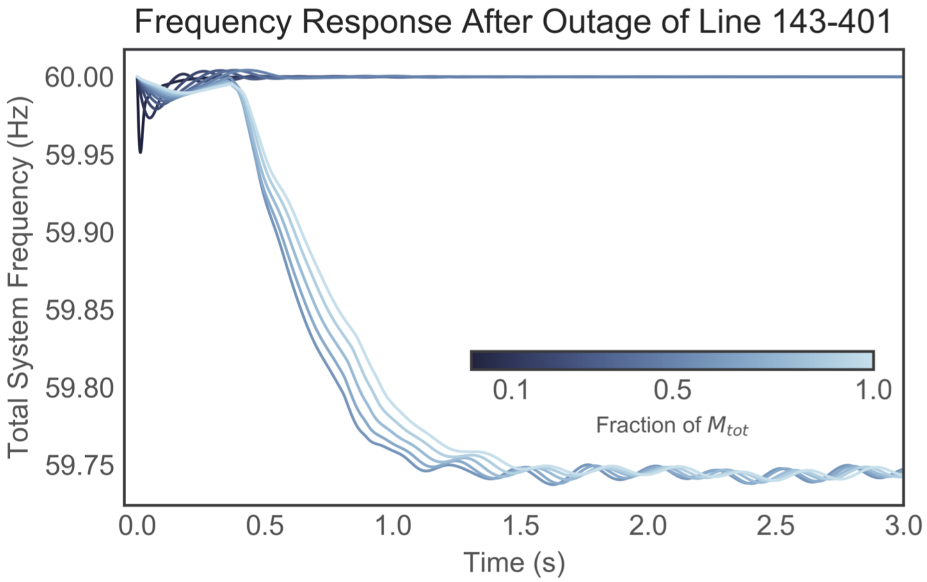
- Investigate inertia as a bifurcation parameter
  - Use time series of all nodes
- Investigate the *structural distribution of inertia*
  - Influence on bifurcations
  - For each distribution explore change in basin stability
  - Explore relationship to network motifs

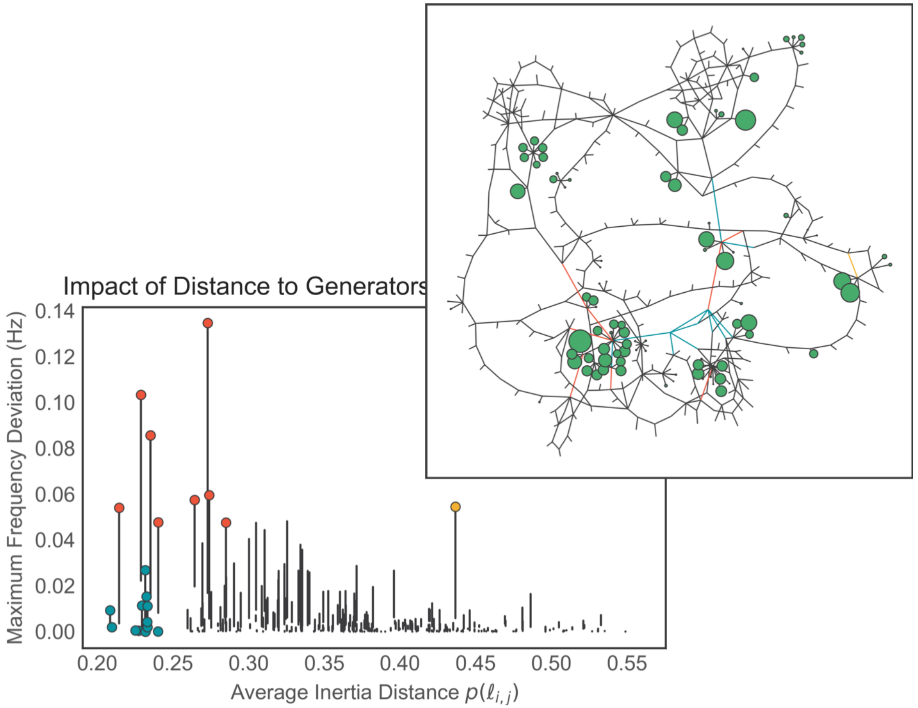




Timeline

- March - May 2019
  - Finalize total system inertia results
  - Prepare results for journal submission
- June – July 2019
  - Define inertia distribution test cases
  - Run cascading failure simulations
- August – December 2019
  - Analyze results of structural distribution experiment
- December 2019 – March 2019
  - Prepare and submit results for publication
- Planned graduation: December 2020



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Questions?

Wait...a wind generator spins!

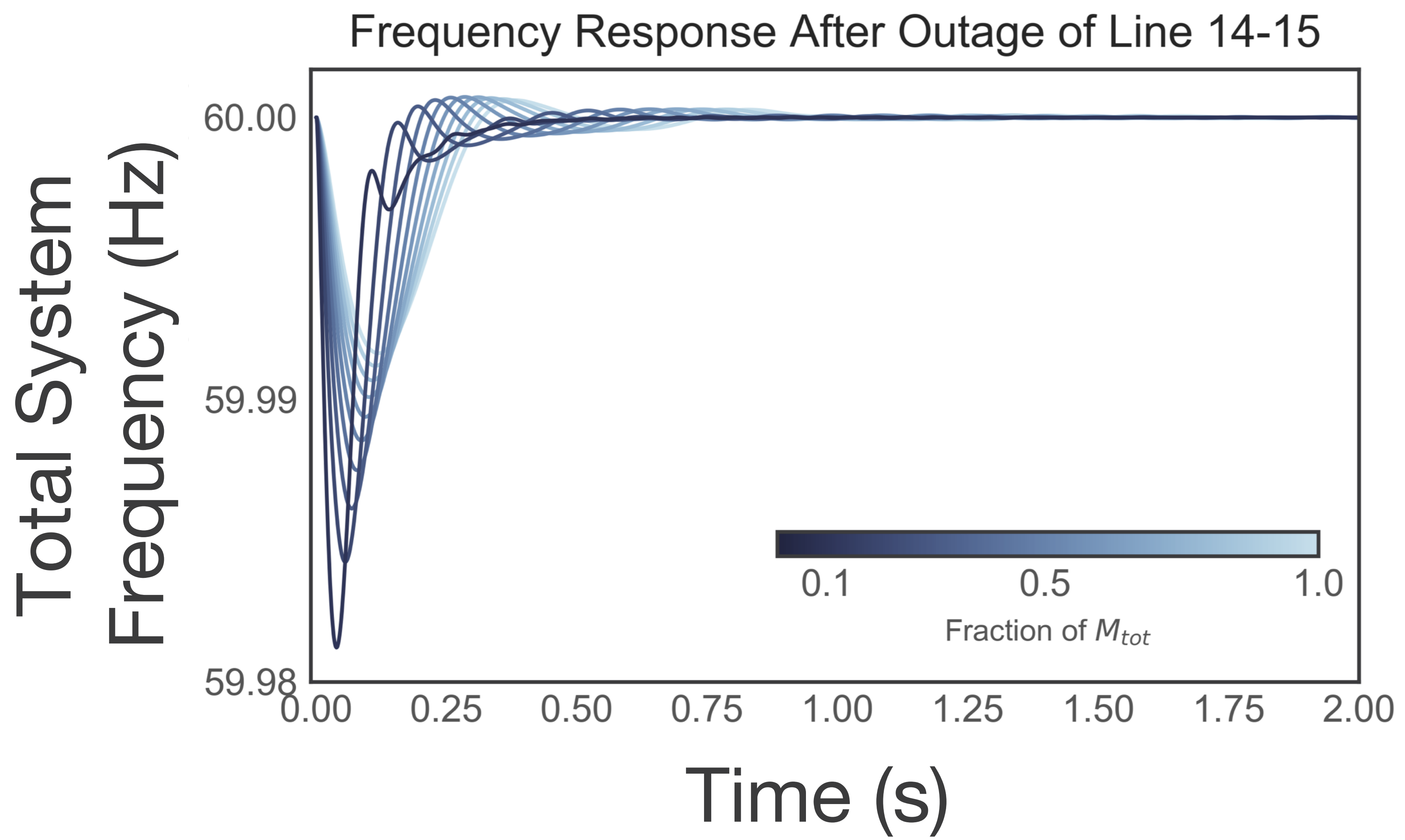
- 4 Types of wind turbines
  - Types 1 and 2 are *fixed speed*
    - Turbines always spin at same speed, but might not produce optimal amount of power given a particular wind speed
  - Types 3 and 4 are *variable speed*
    - Turbine speed changes based on wind speed to produce maximum amount of power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

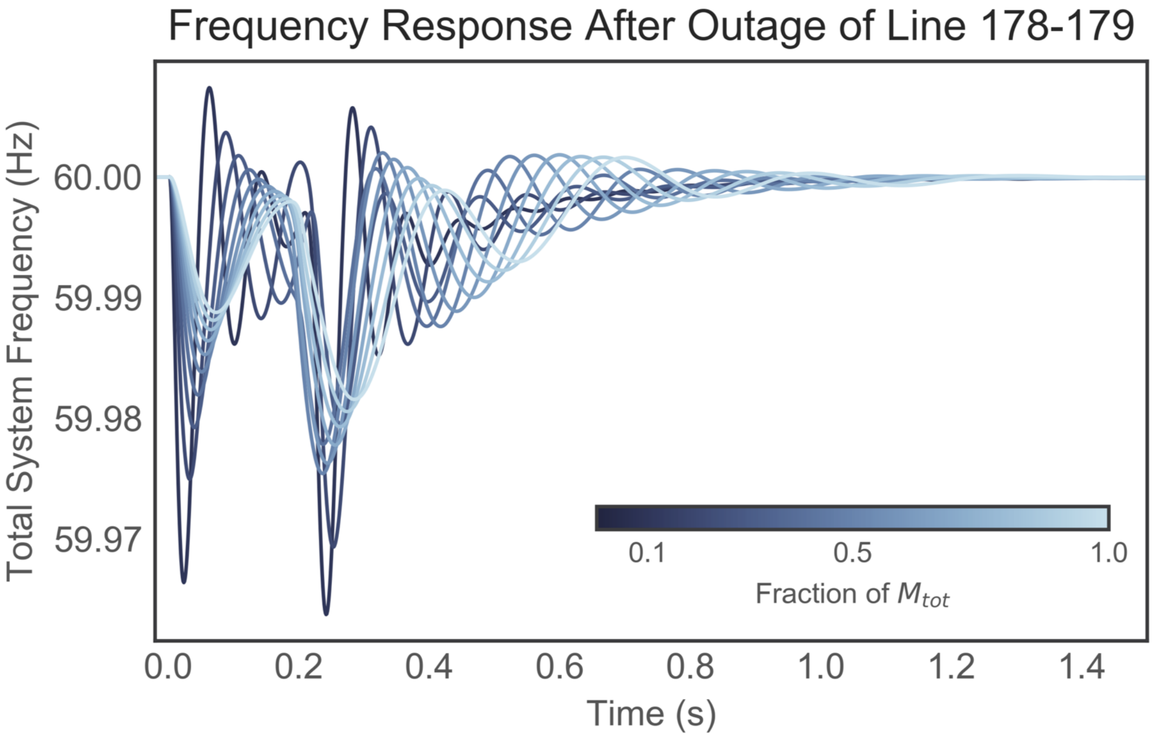
Birchfield, Adam B., et al. "Statistical considerations in the creation of realistic synthetic power grids for geomagnetic disturbance studies." *IEEE Transactions on Power Systems*32.2 (2017): 1502-1510.

Category (I) – South Carolina

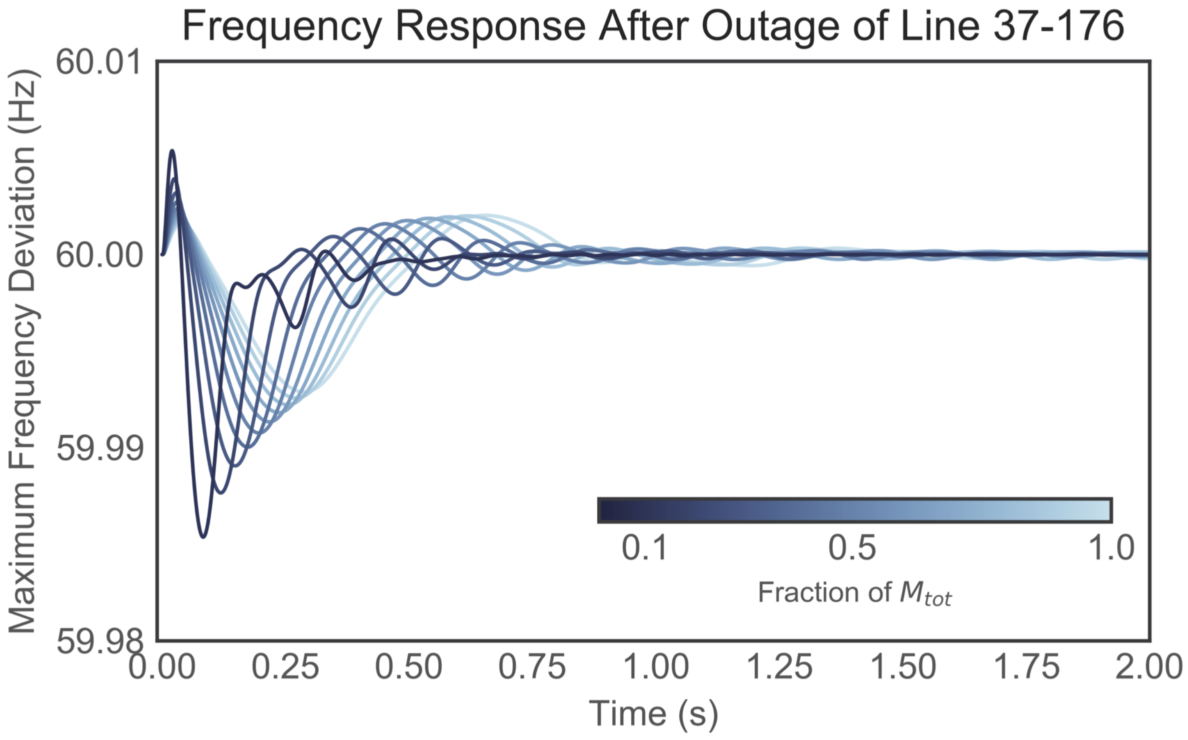


Category (III) – Cascade no disconnect

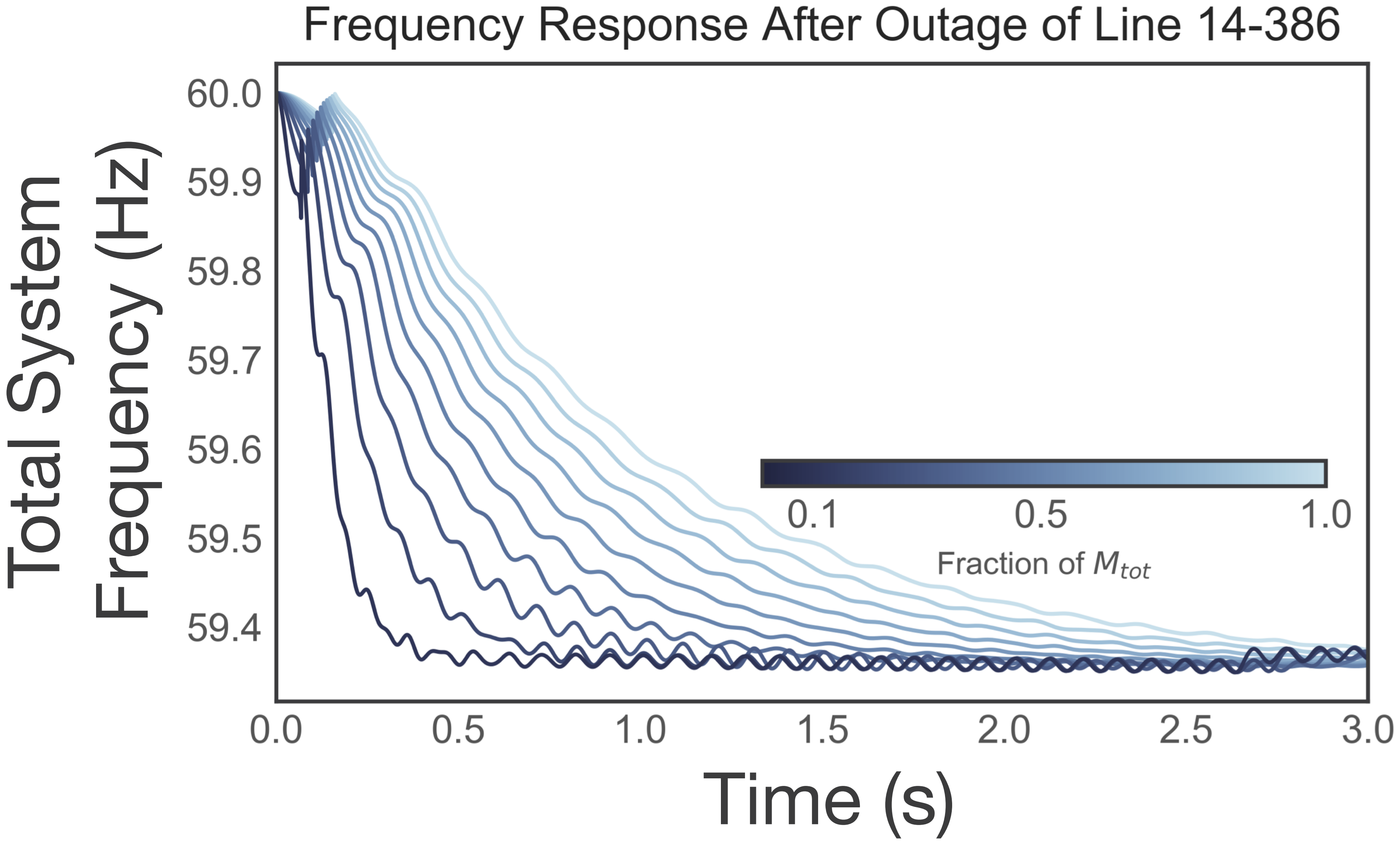
Central Illinois



South Carolina

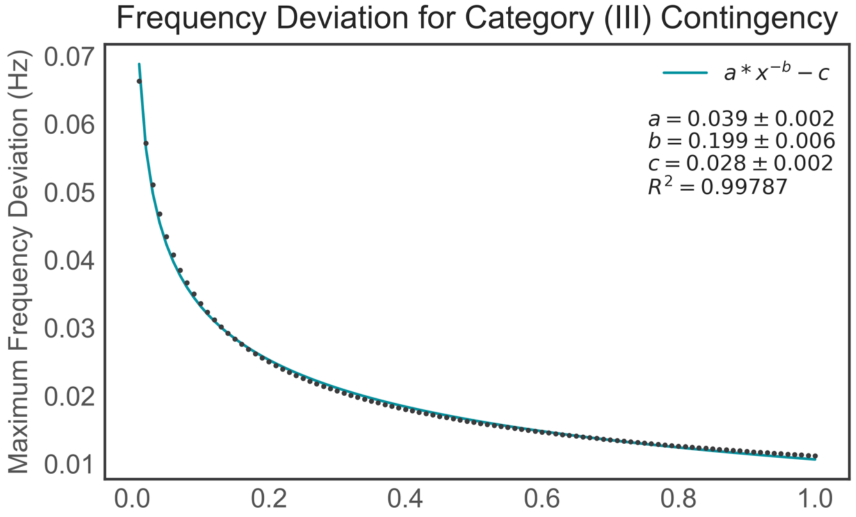


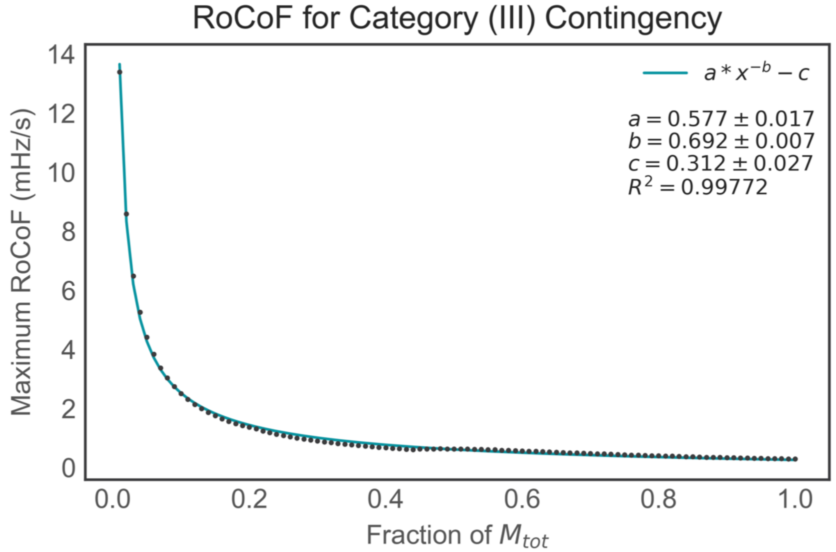
Category (IV)—South Carolina



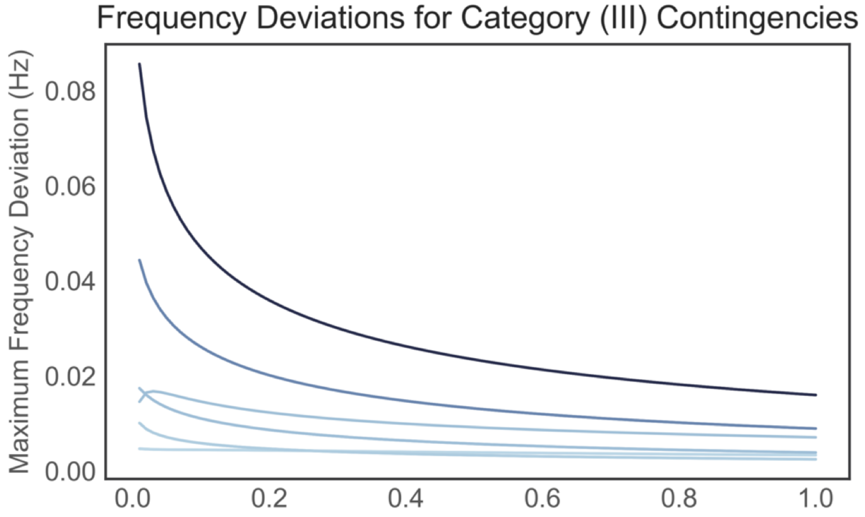
Category (III) – Cascade no disconnect

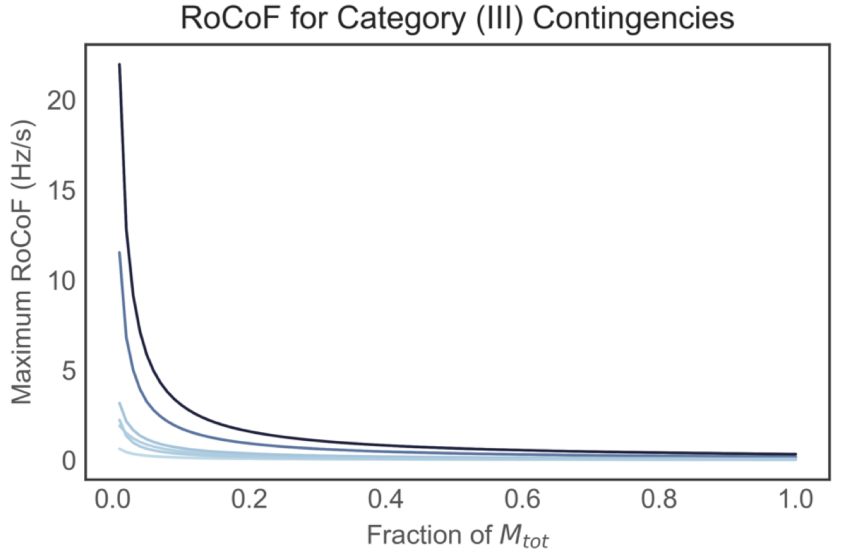
Central Illinois





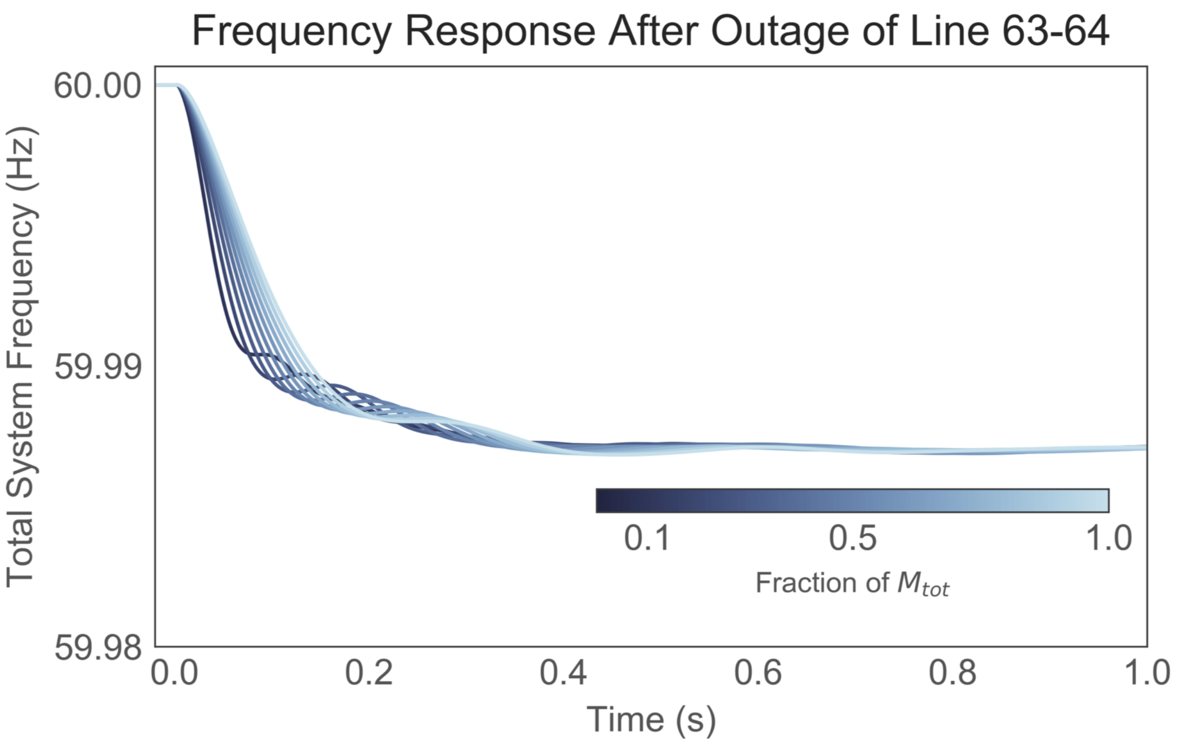
South Carolina





Category (II) – Disconnect

Central Illinois



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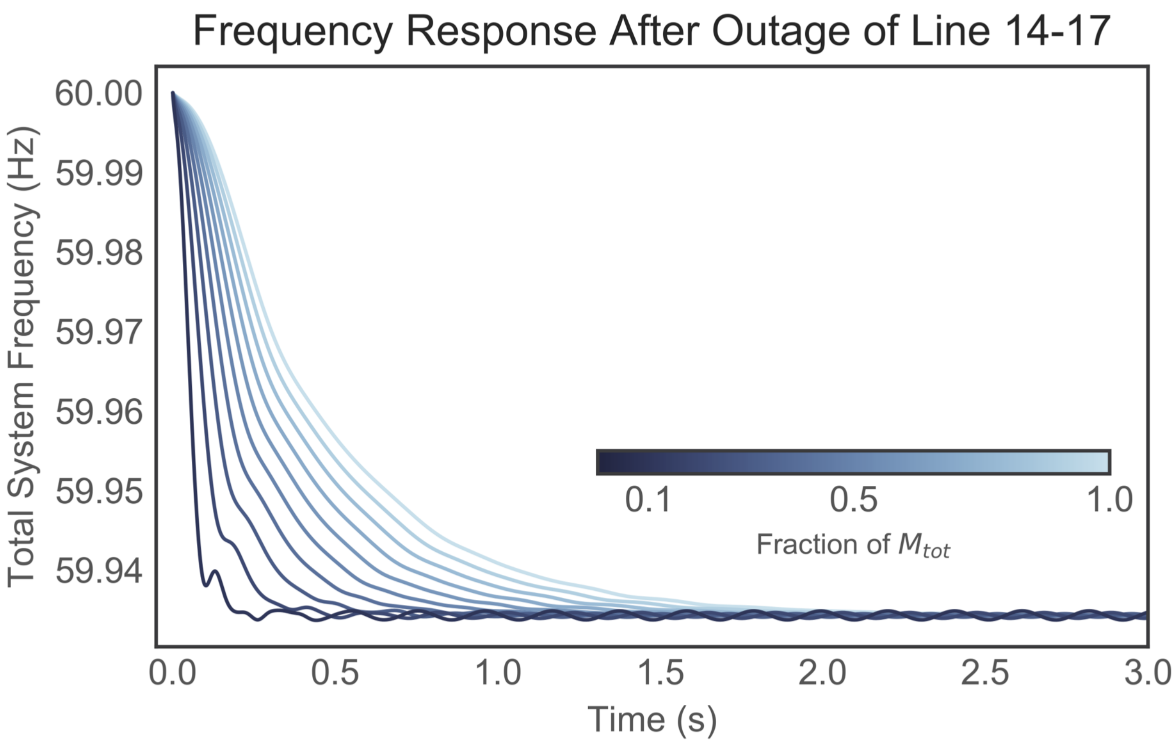

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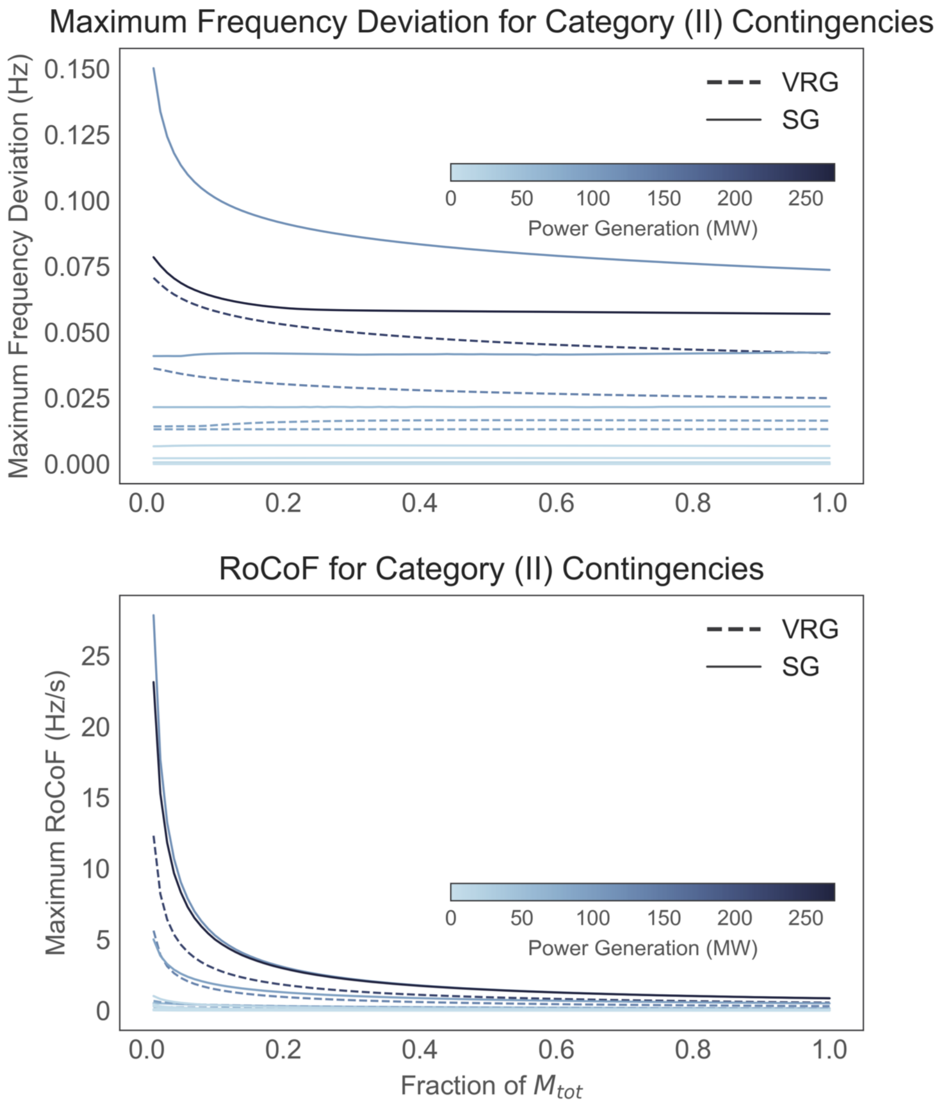

South Carolina