The Roles of Inertia and Stability in Power Systems

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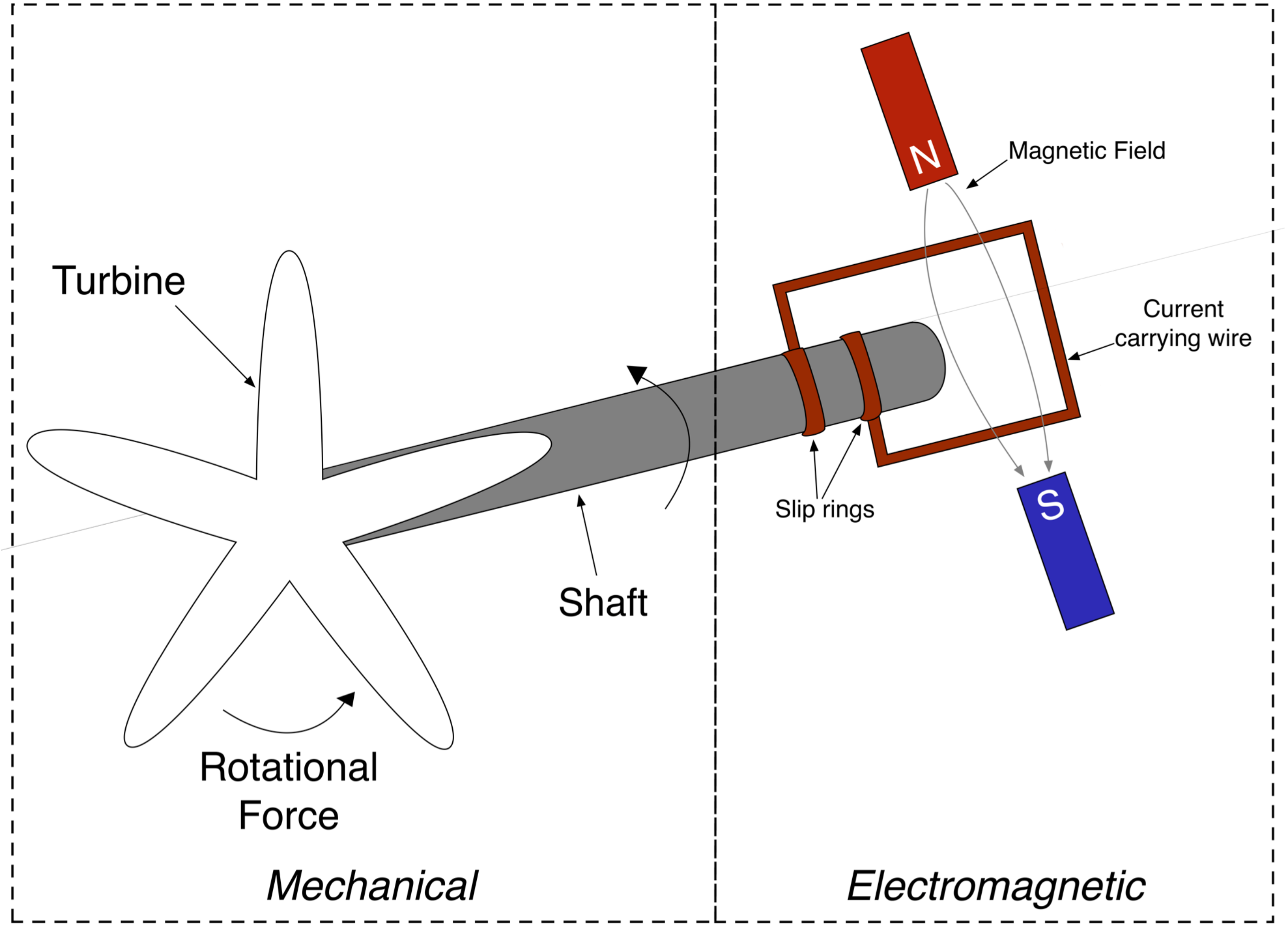
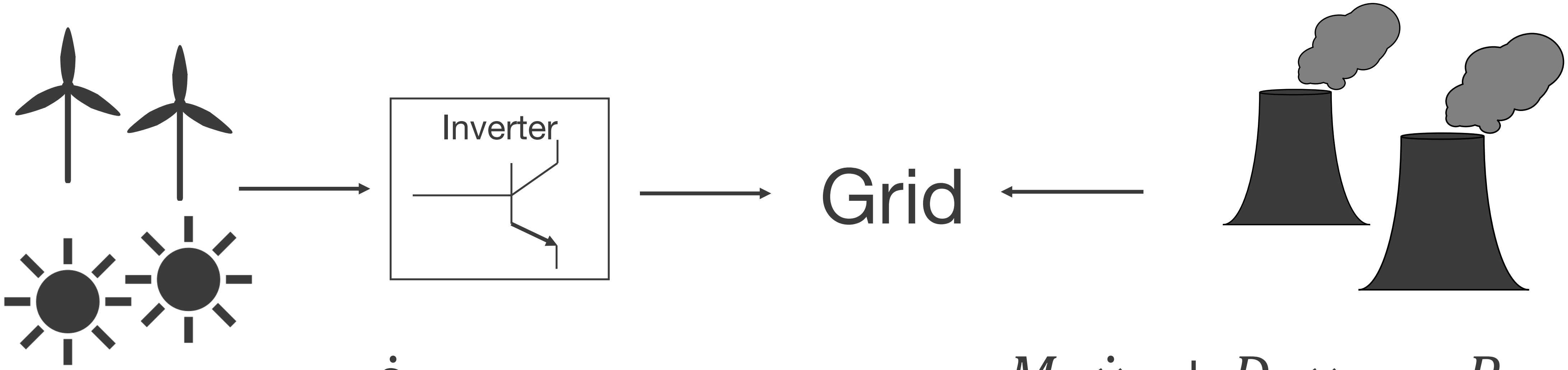
Basics of Power Generation



Traditional Generation

- Coal
- Nuclear
- Natural Gas
- Hydro

Renewable vs. Traditional



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

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

M_g Inertia constant
D_g Damping constant
ω_g Rotational speed
P_g Power generation
P_e Power consumption
δ_g Angle

Renewable vs. Traditional

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

No inertia

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

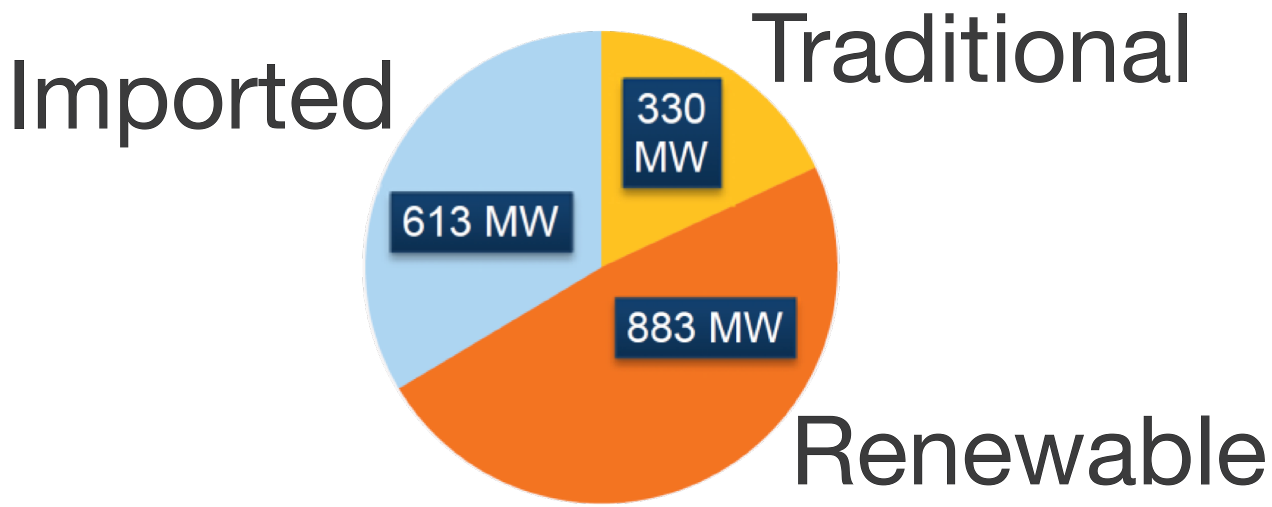
Inertia

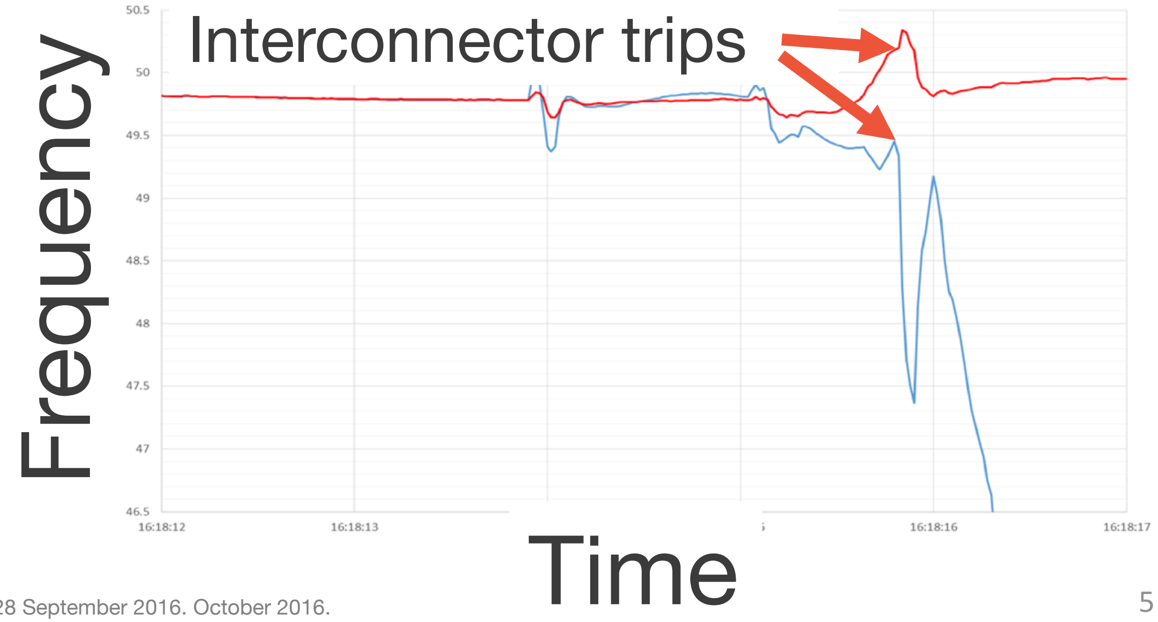
M_g Inertia constant
D_g Damping constant
ω_g Rotational speed
P_g Power generation
P_e Power consumption
δ_g Angle

Inertia – Why does it matter?

ABC News: Tom Fedorowytsch. Accessed 3-6-19

CNN Alison Daye. Accessed 3-6-19





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

Inertia – Why does it matter?

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
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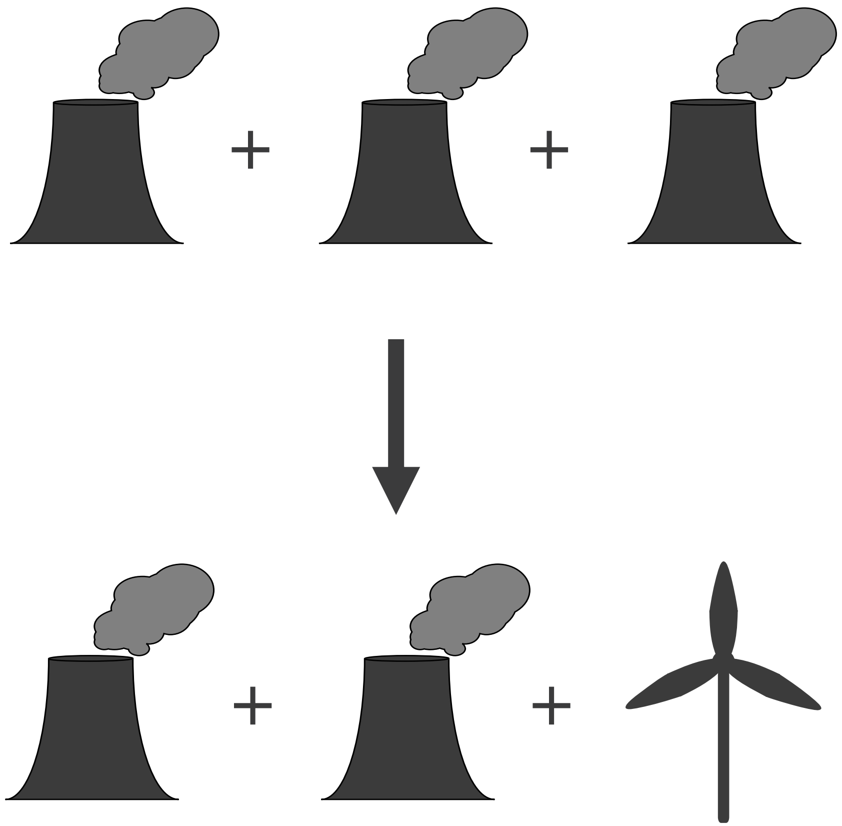
Bension Siebert

Aspects of Inertia – How much?

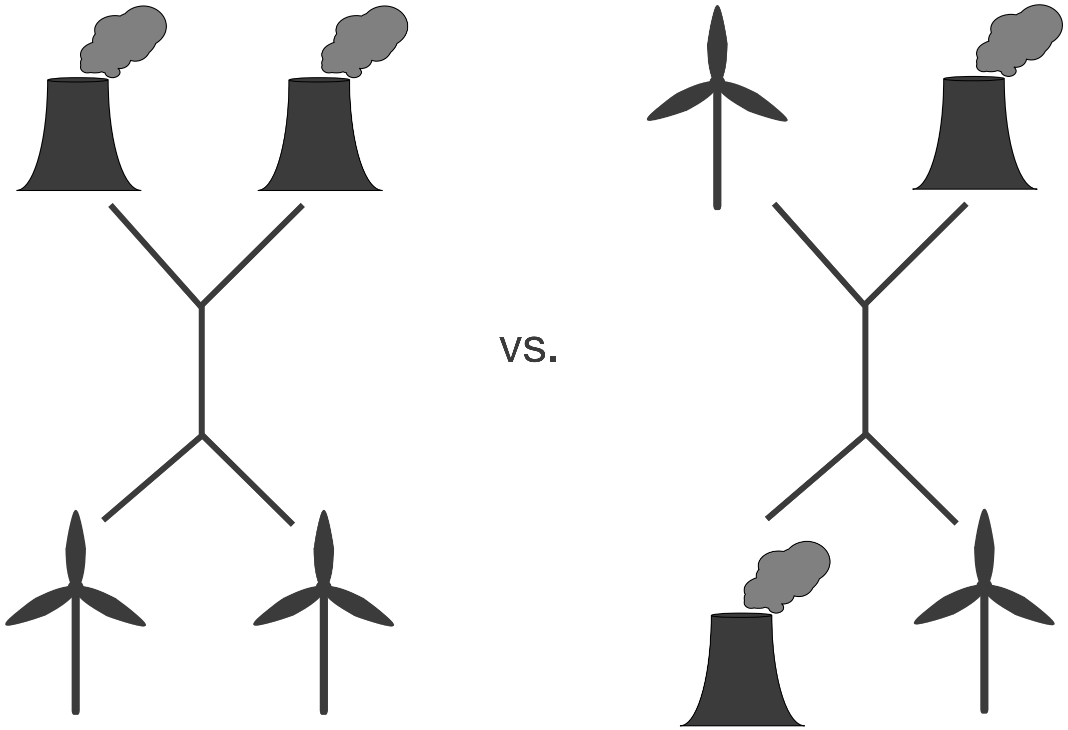


- Study of total system inertia started in 2014[1]
- Regulations are based on the largest single worst-case failure[2]
- That is only one of *many* possible failures
- What about other failures?

1. A. Ulbig, T. S. Borsche, and G. Andersson. Impact of low rotational inertia on power system stability and operation. IFAC Proceedings, 2014.
2. N. W. Miller et al. Western wind and solar integration study phase 3 frequency response and transient stability. Technical report, 2014.

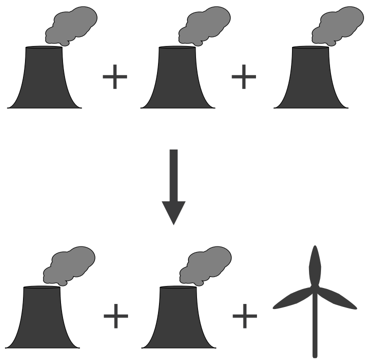
Aspects of Inertia – Where is it?

Structural Distribution



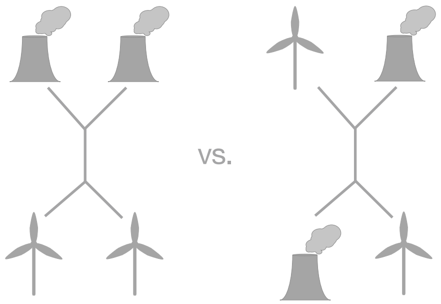
- Total system inertia is an aggregation…
- The structural distribution also plays a role
- Does it matter *where* on the network large inertia generation is located?

Aspects of Inertia – This Talk



Total System Inertia:

- What is the behavior of *all* failures as total inertia decreases?

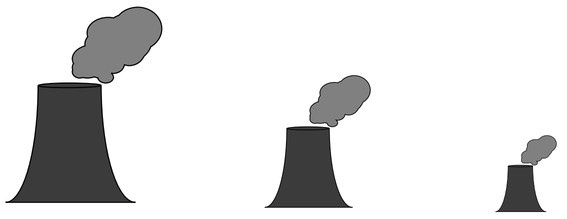


Structural Distribution of Inertia:

- Does it matter *where* on the network large inertia generation is located?

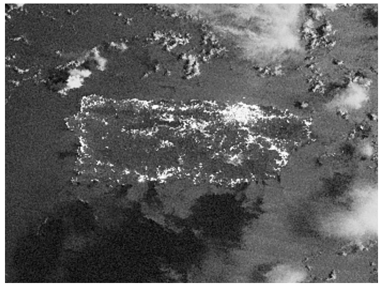
Exploration of Total System Inertia

Set Total System Inertia



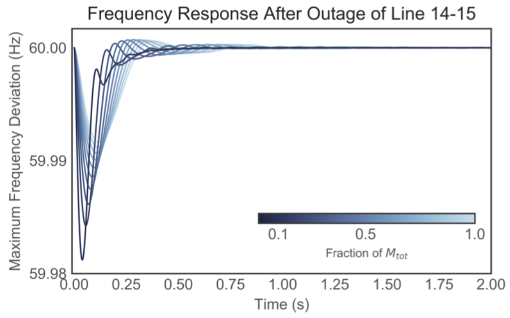
$$M_{tot} = \sum_{g=1}^{n_g} M_g$$

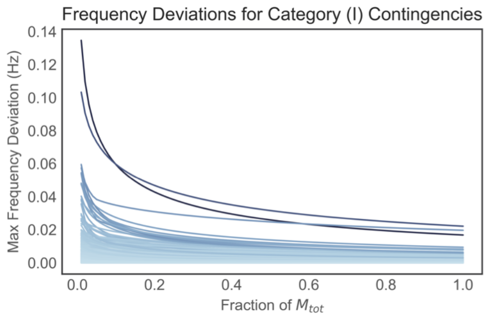
Simulate Failures



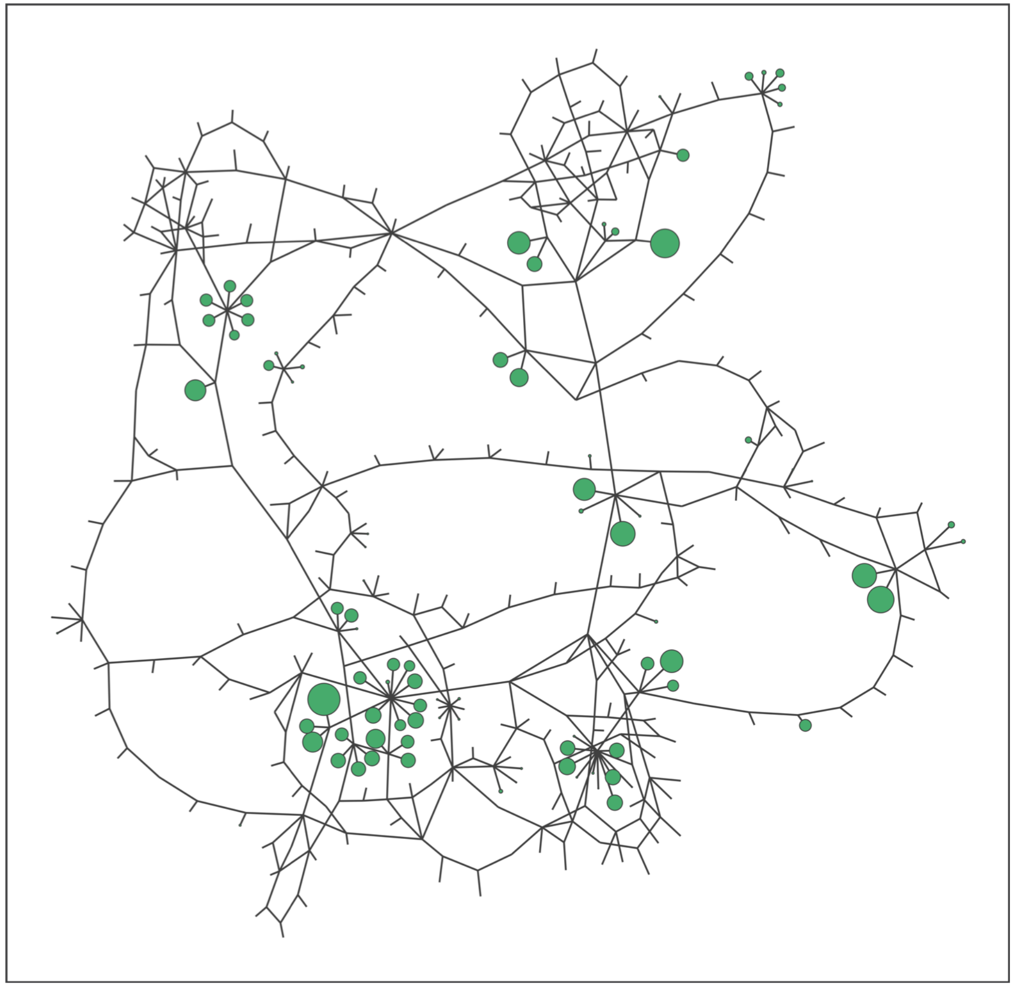
NASA Suomi NPP 2016.

Analyze Stability





Power System Test Case



Nodes → 500

- Generators → 90
- Loads → 200
- Intermediaries → 300

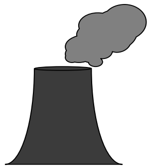
Edges → 597

- Lines

M_{tot} → 139.13 MWs

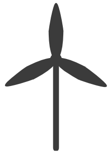
1. T. Xu, A. B Bircheld, K. S Shetye, and T. J Overbye. Creation of synthetic electric grid models for transient stability studies. In IREP Symposium Bulk Power System Dynamics and Control, 2017.
2. T. Xu, A. B. Bircheld, and T. J. Overbye. Modeling, tuning, and validating system dynamics in synthetic electric grids. IEEE Transactions on Power Systems, 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, 2017.

Cascading Failure Model



$$\dot{\omega}_g = -\frac{D_g}{M_g}\omega_g - \frac{1}{M_g}\left(P_g + \sum_{\forall i \notin G} B_{gi}\sin\left(\delta_g - \delta_i\right)\right)$$

$$\dot{\delta}_g = \omega_g - \omega_1$$



$$\dot{\delta}_{RG} = -\frac{1}{D_{RG}}\left(P_{RG} + \sum_{\forall i \notin G} B_{RGi}\sin(\delta_{RG} - \delta_i)\right) - \omega_1$$

Nodes that aren't gens

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

Line status

$$\dot{\eta}_{ij} = 10\left(f\left(\eta_{ij}\right) - \frac{B_{ij}(1-\cos(\delta_i - \delta_j))}{W_{ij}}\right)$$

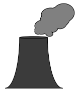
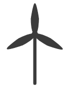
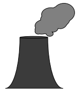
Line energy

Maximum line energy

i, j Nodes
δ Voltage Angle
ω_1 Reference Frequency
$\eta_{i,j}$ Line Status
P_i Power consumption/generation at node i
D_i Damping Constant
M_g Inertia Constant

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

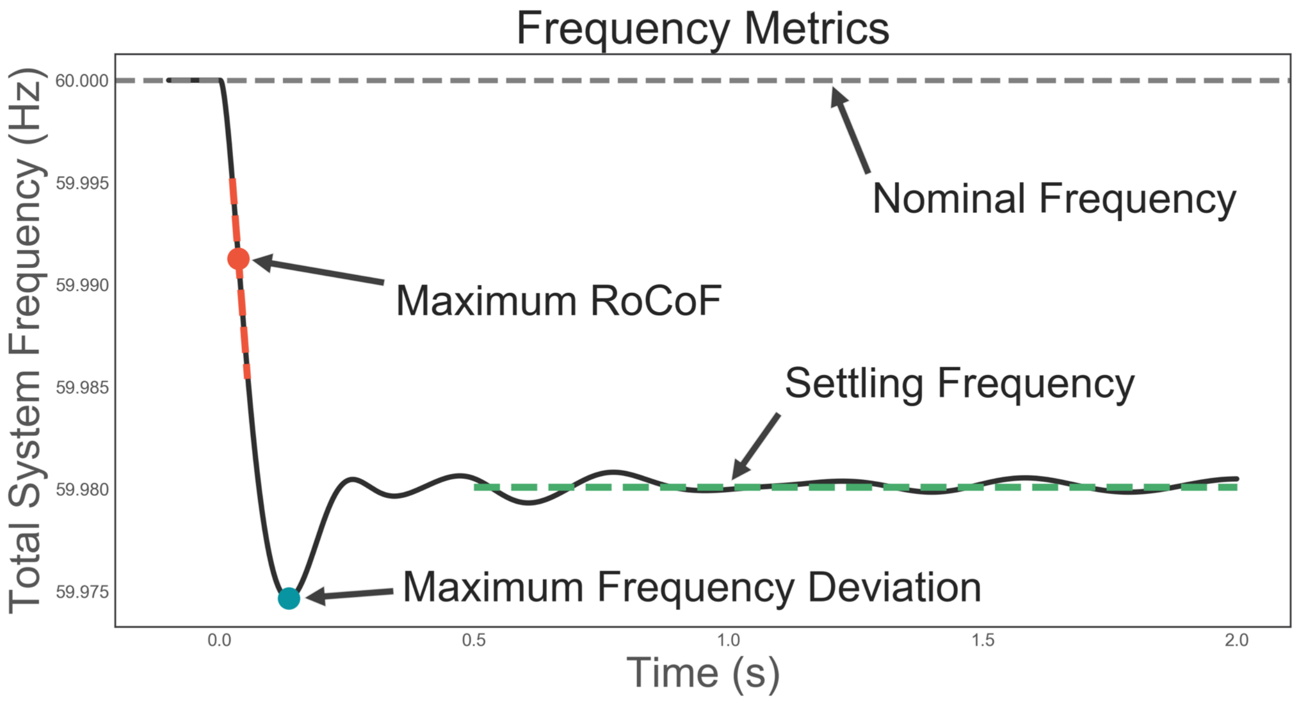
Cascading Failure Model – tl;dr

- State variables:
  - Generator angles  
  - Generator frequencies 
  - Bus angles
  - Status of lines (on or off)
- Relevant Parameters:
  - Induced line failures
  - M_{tot}

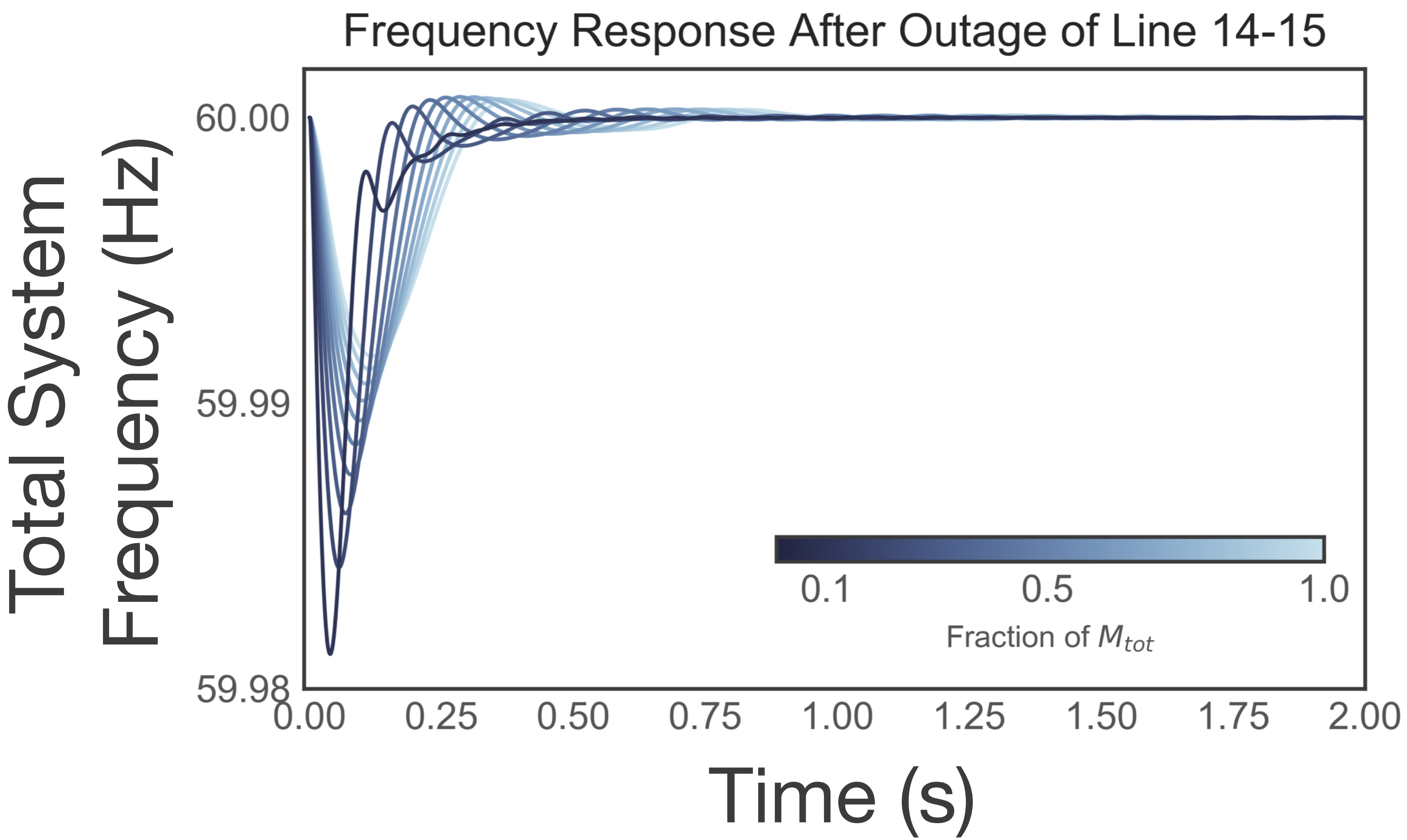
Y. Yang and A. E. Motter. Cascading failures as continuous phase-space transitions. Phys. Rev. Lett., 119 (24), 2017.

Terminology

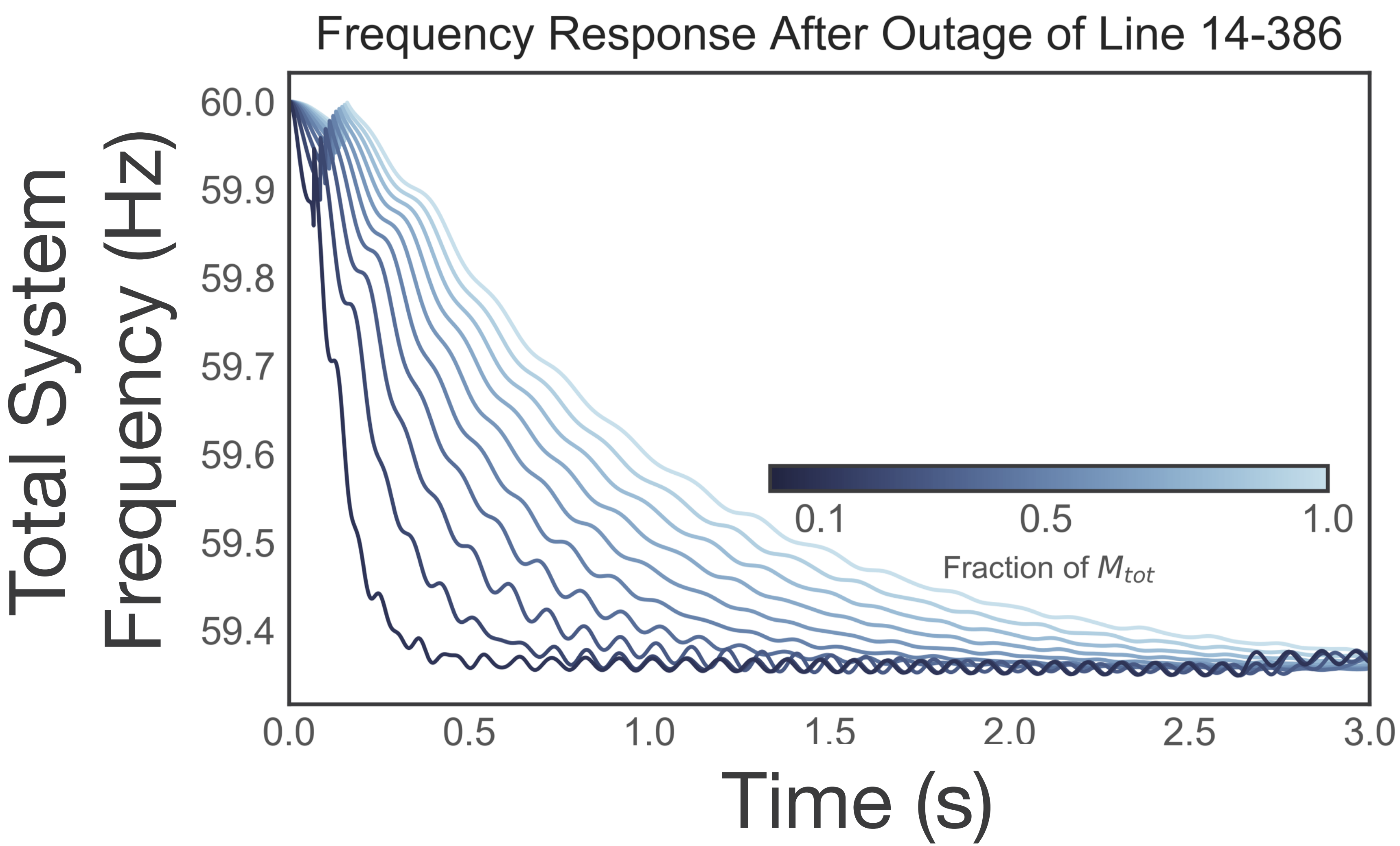
- Contingency = failure of a component (lines, here)
- Metrics defined on total system frequency ($f = \frac{\sum_{g=1}^{n_g} M_g \omega_g}{2\pi \sum_{g=1}^{n_g} M_g}$)
    - (a proxy for the difference between power consumption and generation)

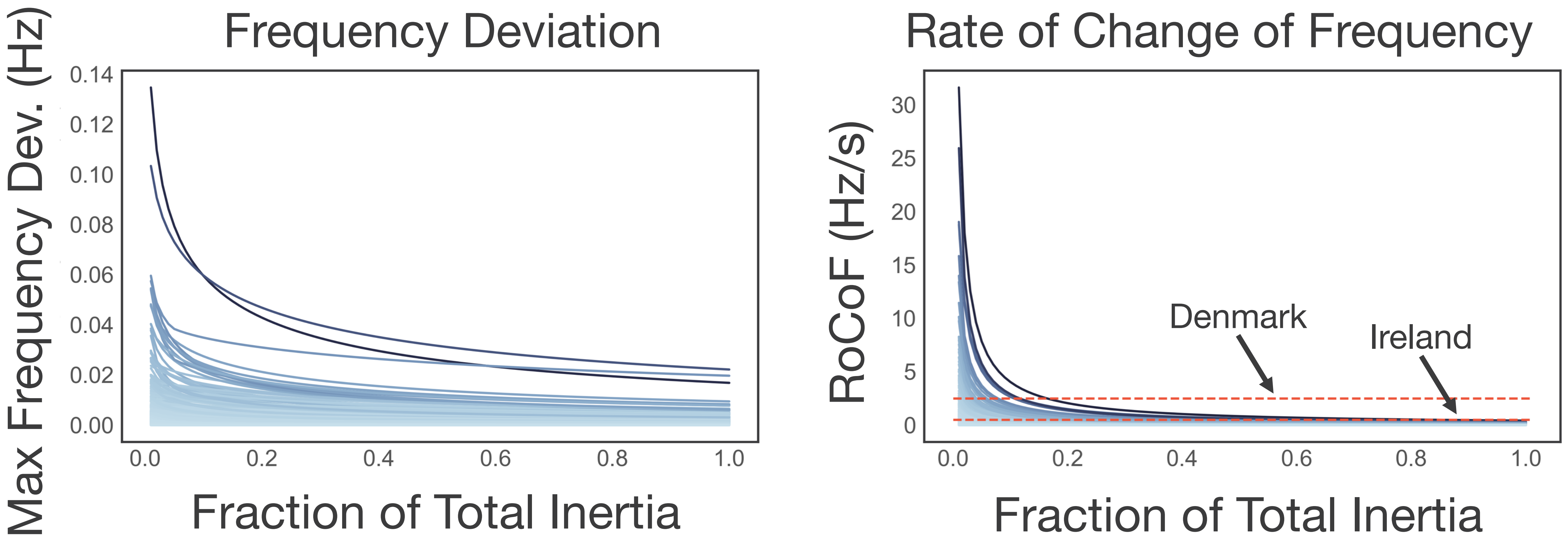


Small Perturbation



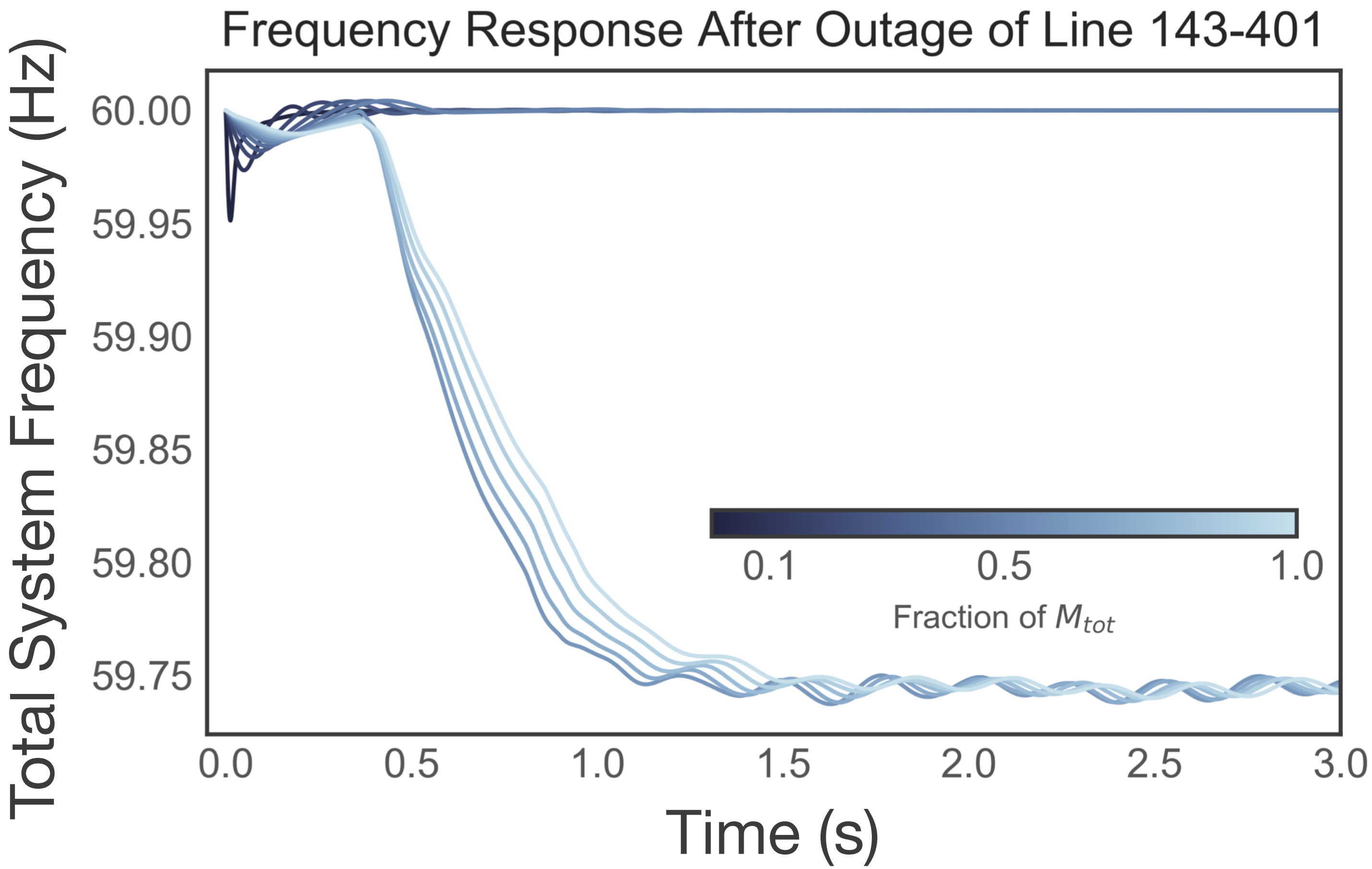
Large Perturbation





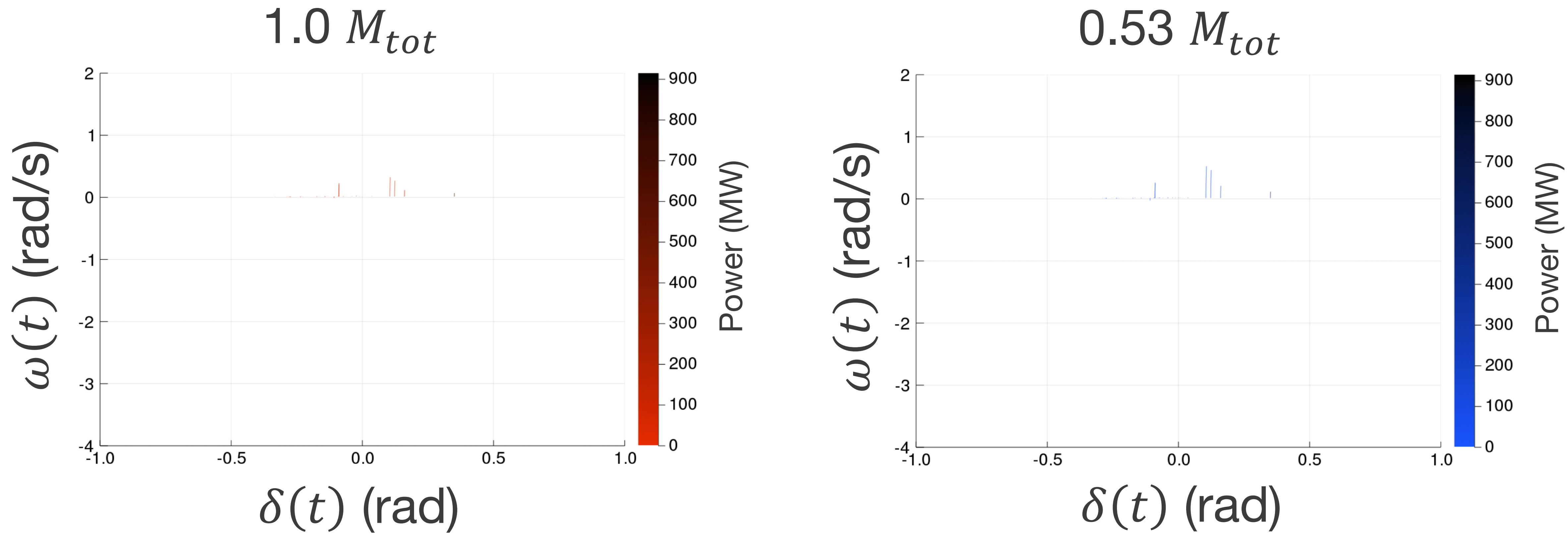
Frequency Deviation
Max Frequency Dev. (Hz)
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0.0
0.2
0.4
0.6
0.8
1.0
Fraction of Total Inertia
Rate of Change of Frequency
RoCoF (Hz/s)
30
25
20
15
10
5
0
Denmark
Ireland
0.0
0.2
0.4
0.6
0.8
1.0
Fraction of Total Inertia

Bifurcation?



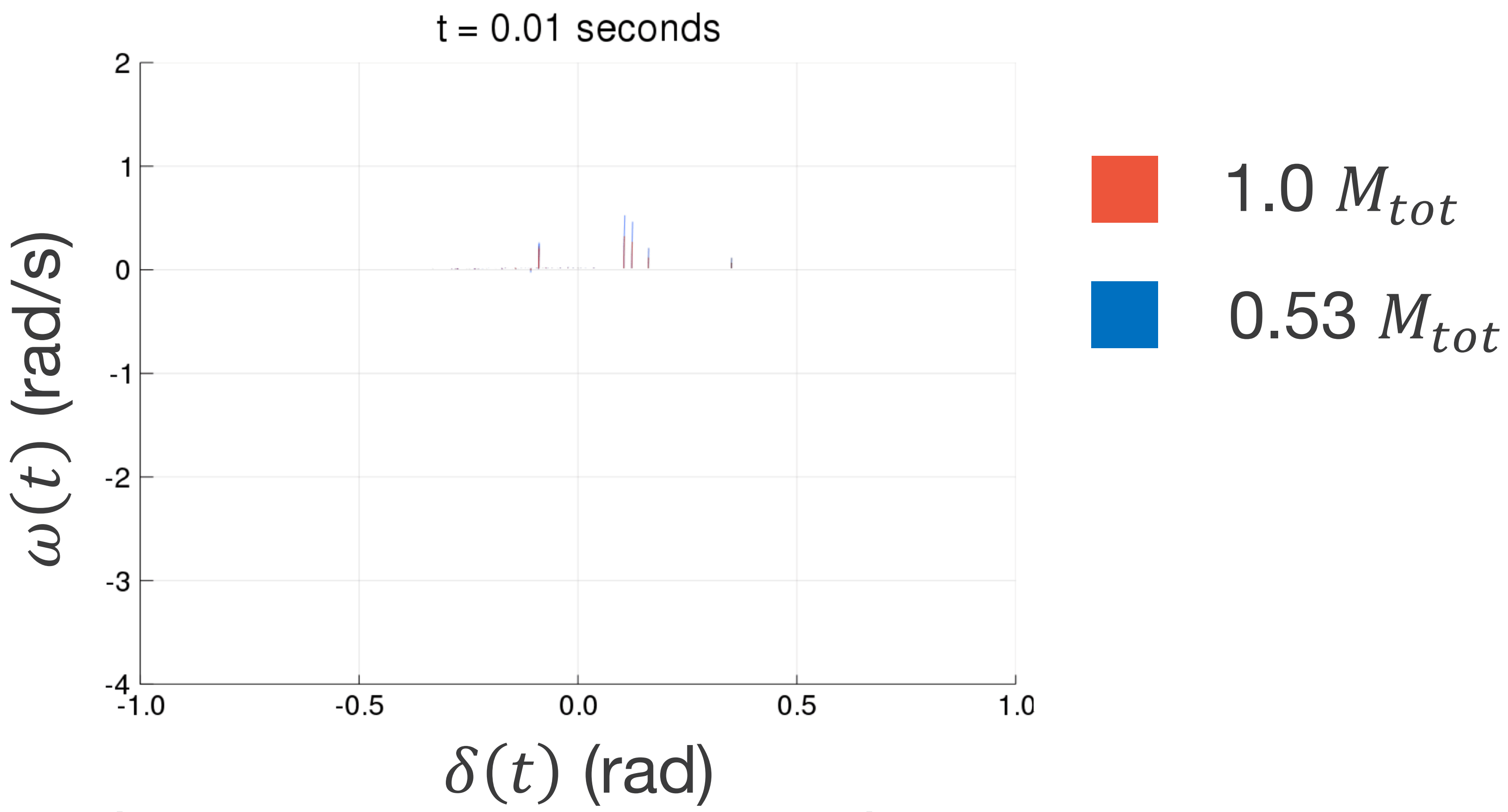
- $\Delta M_{tot} \rightarrow$ Hopf bifurcation (?)

Bifurcation - Generator Dynamics



- Changing M_{tot} changes whether a cascade occurs

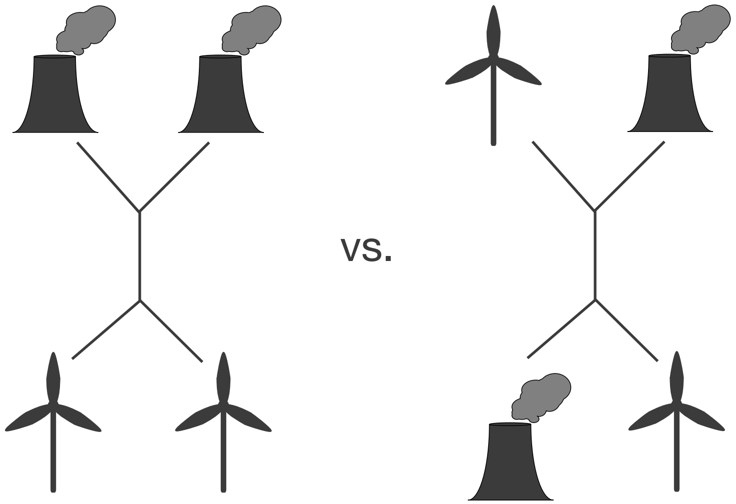
Bifurcation - Generator Dynamics



- Changing M_{tot} changes whether a cascade occurs
- Timing of power flow?

Future Work

- *Why* does lowering total system inertia cause bifurcations?
  - How long does it take a generator to send 1 MW of power to a specific line?

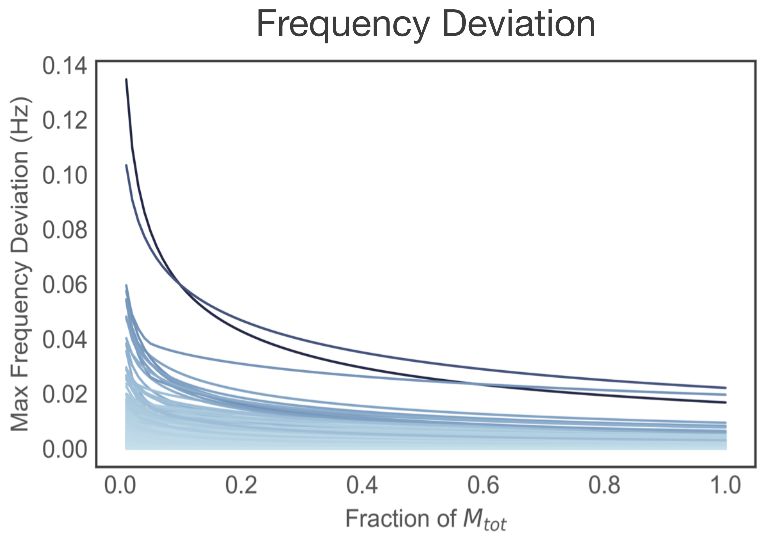


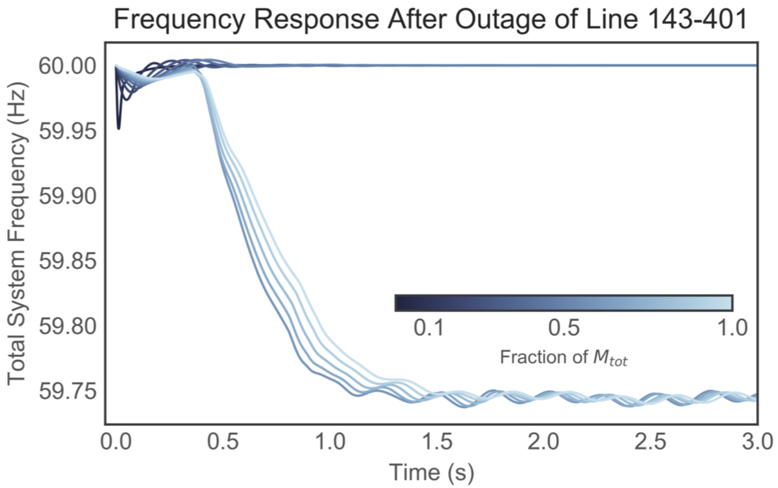
Structural Distribution of Inertia

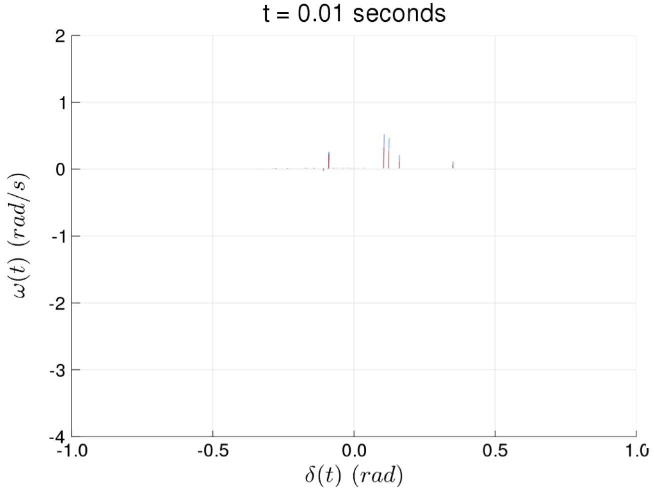
- Does it matter *where* on the network large inertia generation is located?
  - *When* does it matter?

Conclusions

- Important to consider *multiple* contingencies as total system inertia decreases
- The *location* of the contingencies matter
  - Closer to generator = bigger frequency deviations
- Total system inertia can cause bifurcations
  - Possibly due to timing of flows








?
Questions?

…Network structure?

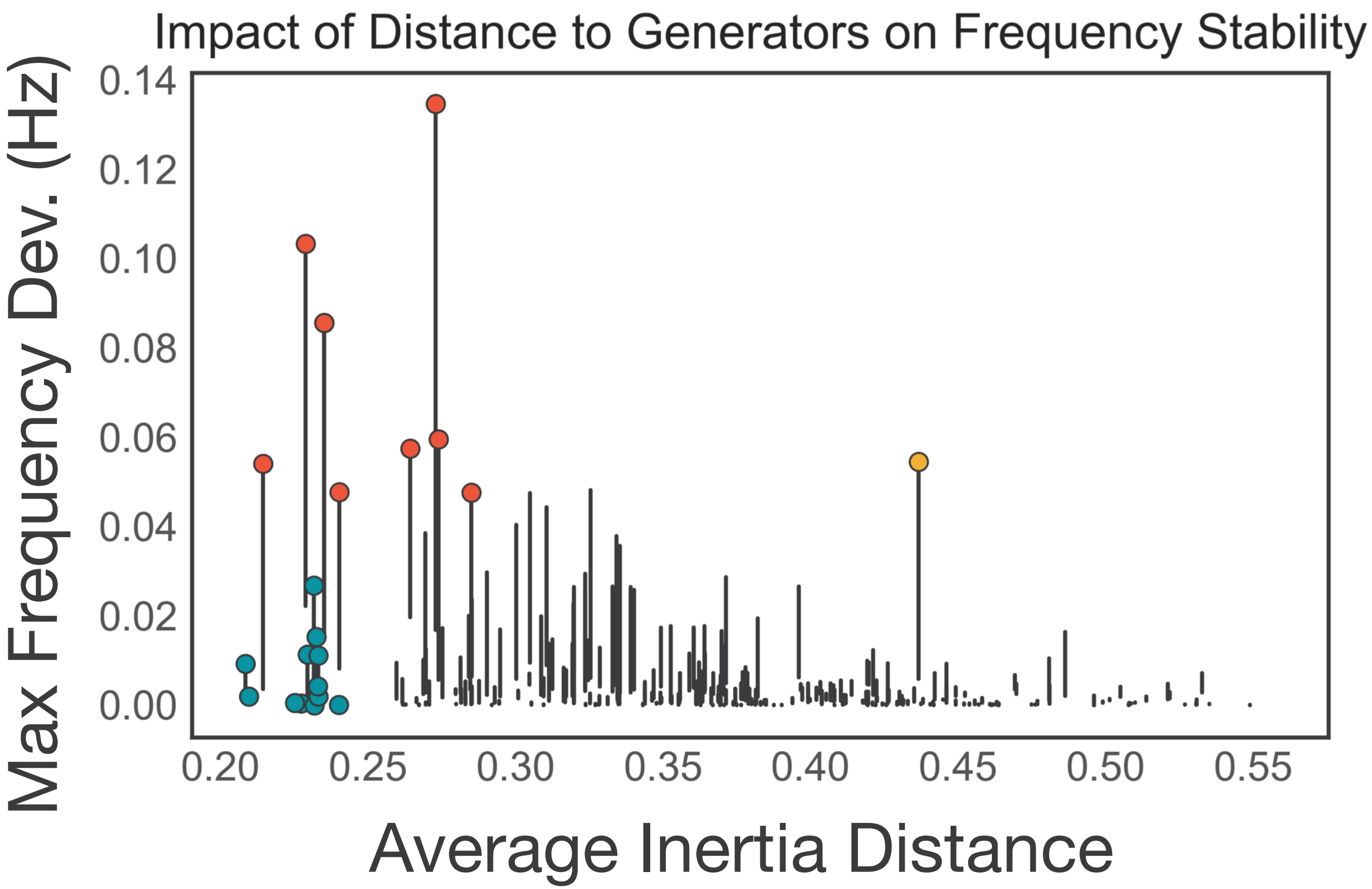
Average Inertia Distance

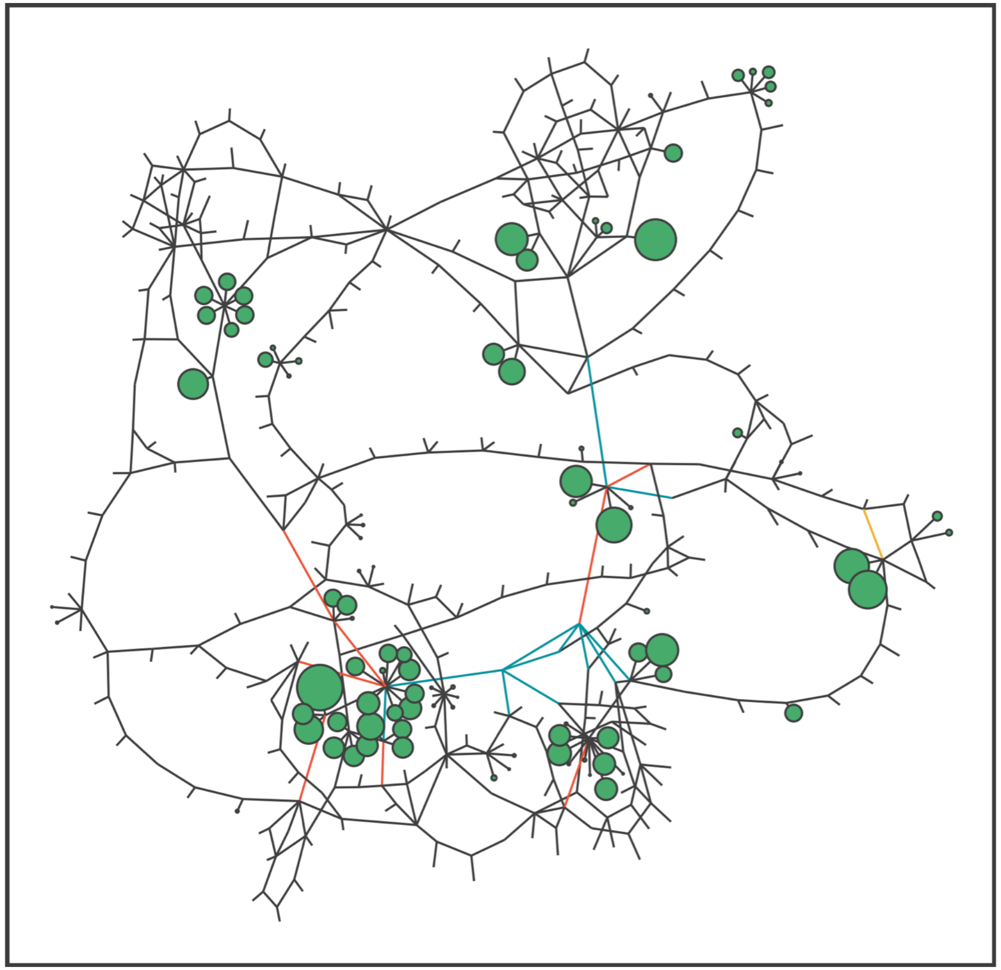
Shortest distance to generator

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

Diameter of Network

Average Inertia Distance





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

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

Other Results