The Role of Inertia in the Cascading-Failure Dynamics of Power Systems

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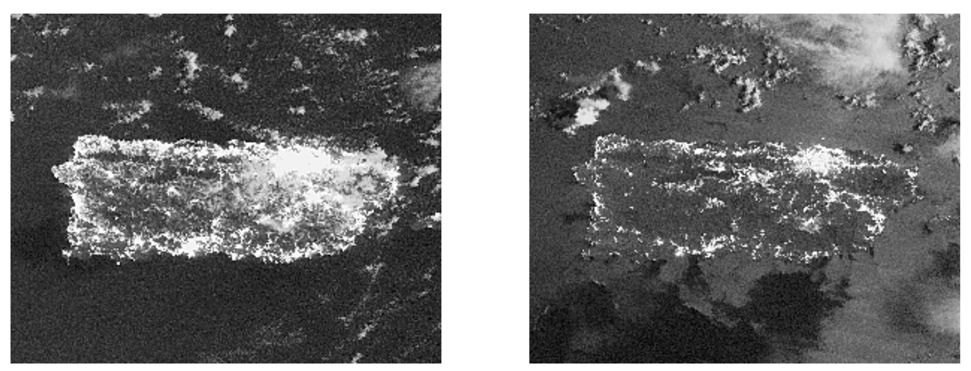
Overview

Power systems today are undergoing extreme changes with the integration of renewable generation sources such as solar and wind. Traditional generation sources, such as coal and natural gas, provide inertial support, which helps maintain system stability when an outage occurs. However, solar and wind generation do not, on their own, provide this support, which potentially makes the system more vulnerable to failures

How does *total* system inertia impact power system stability during cascading failures?

Cascading Failures



September 21, 2016: A fire at Aguirre Power Station in Puerto Rico causes a cascading failure resulting in an island-wide blackout. Image from [1].

Model

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

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

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

Inertia

The *inertia constant* M_g of a generator indicates how much energy it can stores in its rotation. It is a combination of the turbine size and maximum power of the generator

Generation Type	M_g (MW · s)
Nuclear	5344-6530
Coal	863-3158
Solar	0

Total System Inertia

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

Average Inertia Distance

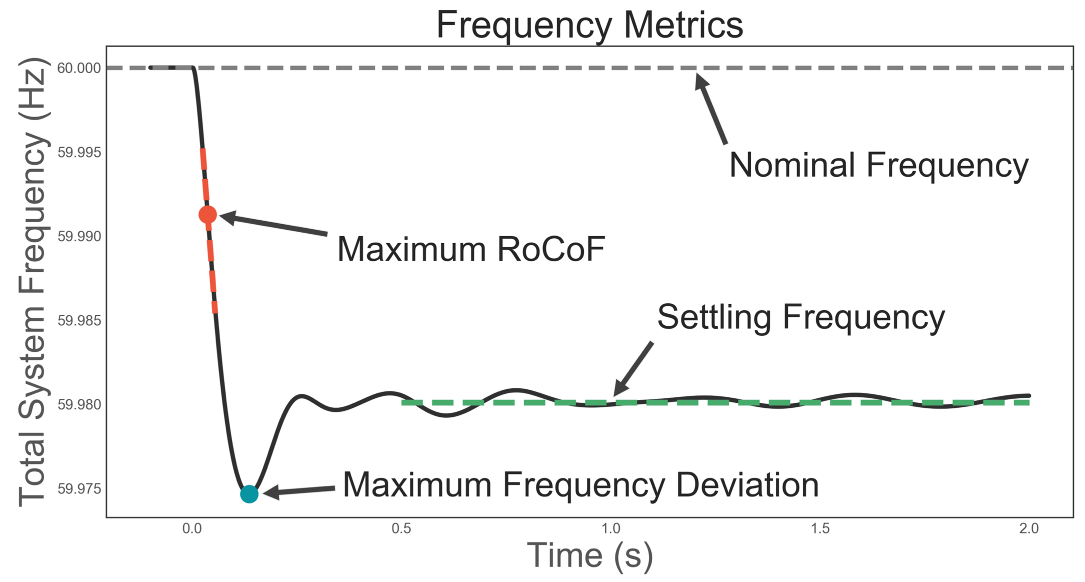
We use the average inertia distance to understand how topology plays a role in frequency stability. Although the

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

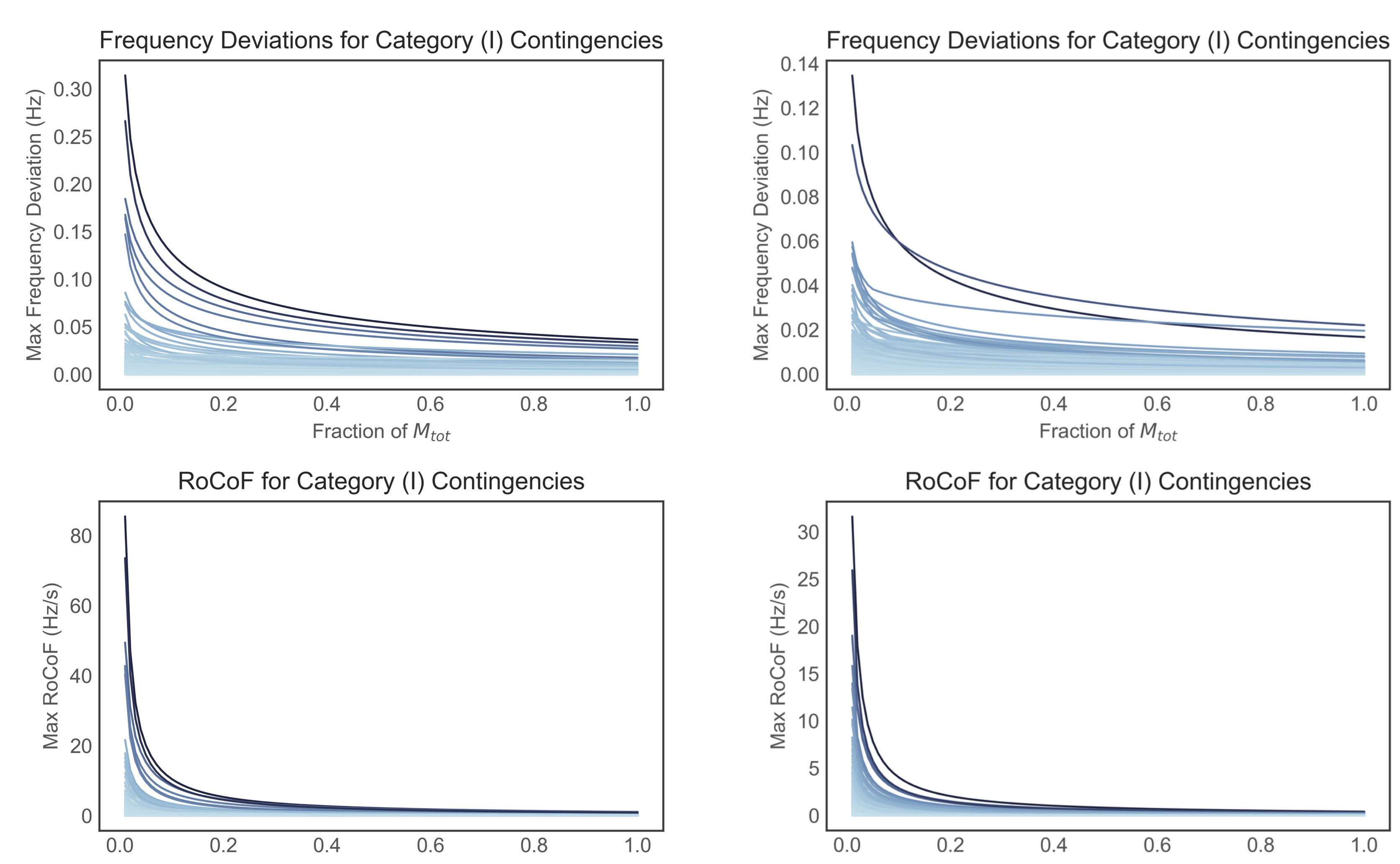
Frequency Stability

We compute the system frequency for each cascading failure simulation to quantify the resulting dynamics. Frequency stability is a growing concern as more renewable generation is added to power systems.

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



As total system inertia decreases, the maximum frequency deviation and the RoCoF increase. Furthermore, the trend is non-linear.



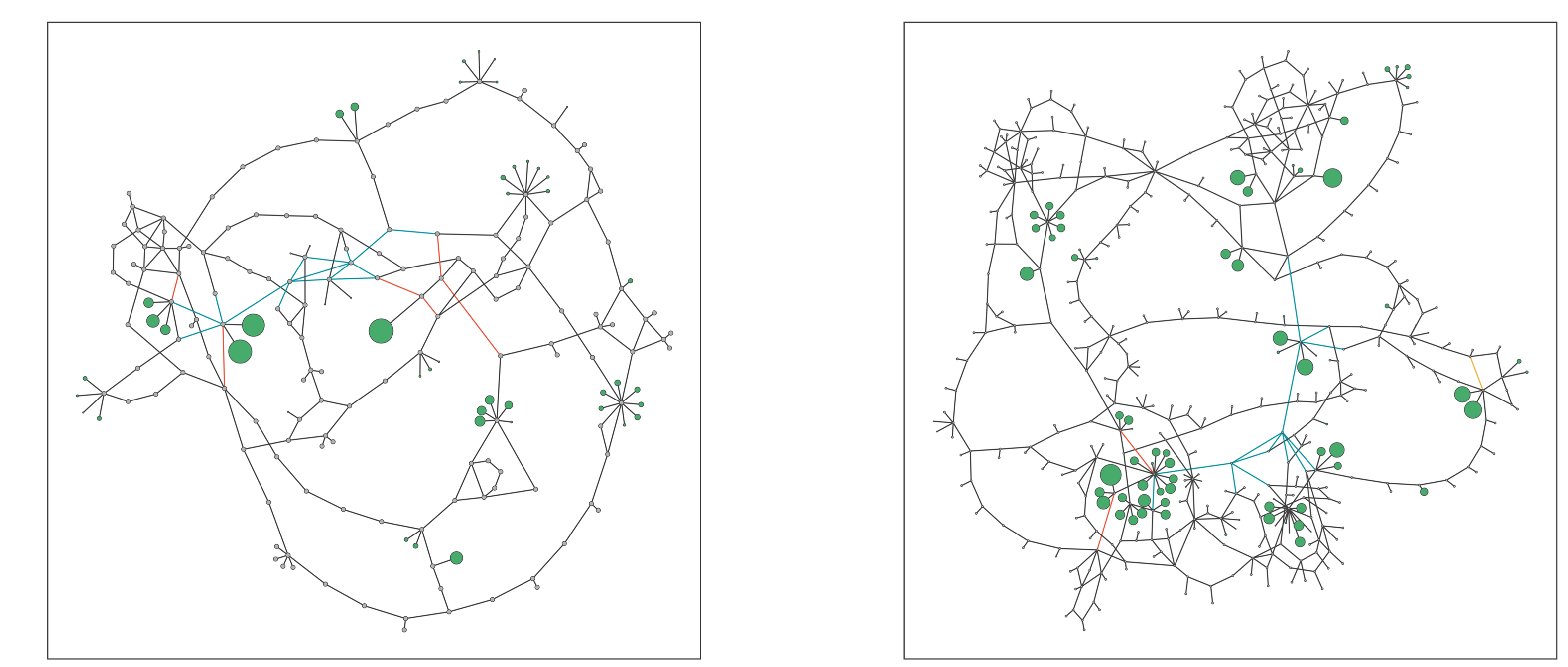
Test Cases

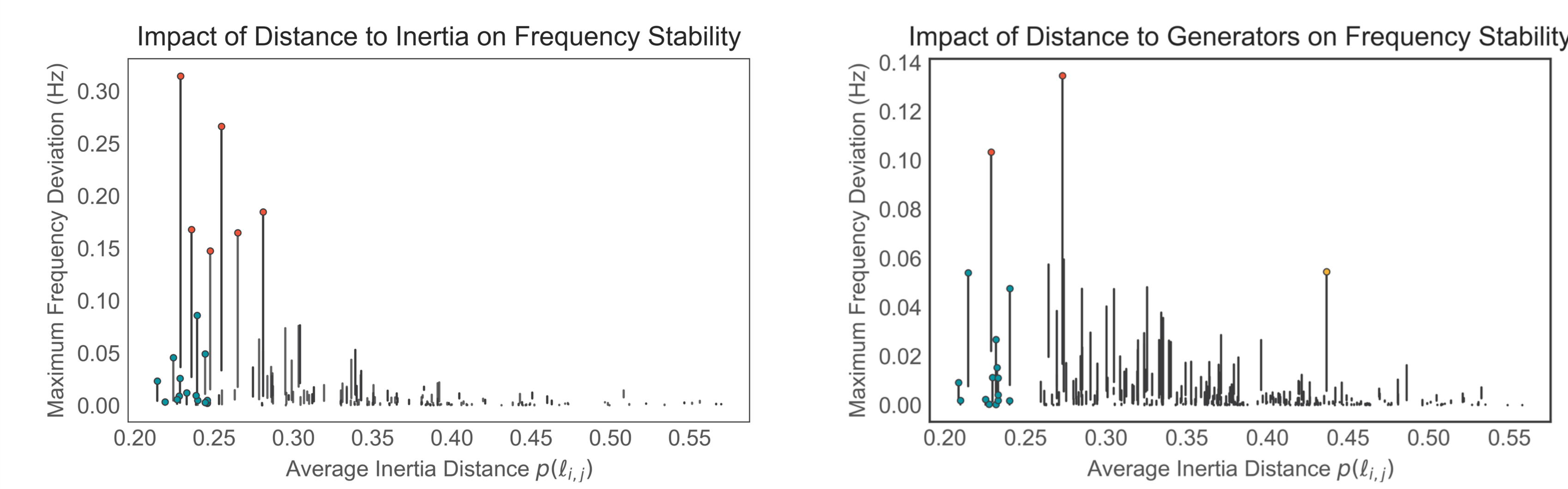
Problem:
- U.S power grids are considered critical infrastructure → Data is not public

Solution:
- Create synthetic networks that *statistically* match real power grid characteristics

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

Illinois | South Carolina





In general, contingencies that are closer to large-inertia generation cause a higher frequency deviation. However, there are some exceptions: denoted by a blue point. This indicates a more complicated relationship with network topology.

Conclusions

As total system inertia decreases power system frequency dynamics will increase non-linearly. Furthermore, these dynamics are dependent on the structure of the network, illustrated by the dependence of the maximum frequency deviation on the average inertia distance. However, the structural dependence is not entirely captured by the average inertia distance which suggests that

References

1. NASA Earth Observatory. *Puerto Rico Goes Dark*. https://earthobservatory.nasa.gov/images/88796/puerto-rico-goes-dark . Accessed: 3-2-2019.