Queen Mary
University of London
Science and Engineering

MITIGATING FAILURES IN POWER GRIDS USING BATTERY ENERGY STORAGE SYSTEMS

Phase 1: DISTRIBUTIONS OF CASCADE SIZES IN POWER SYSTEM EMERGENCY RESPONSES

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1. Power Disturbances

- We attempt to model a network with high penetration of distributed generation;
- At $t = 0^-$, power system is in equilibrium;
- *Power disturbances* - u_i: Random change in power injection at each generator due for *e.g*. errors in renewable generation forecast due to weather events.

$$\chi_i = \chi_{0,i} + u_i$$

- Power disturbances create transients in frequency dynamics for times $t > 0$
- Frequency dynamics evaluated using the Third Order Model plus models for governors at each the generator.

GENERATOR MODEL

$$\begin{cases} M_i\ddot{\delta}_i + D_i\dot{\delta}_i = \alpha_i \left(\chi_i - \nu_i \sum_{j=1}^{N+1} B_{ij}\nu_j \sin(\delta_i - \delta_j) \right), \\ S_i\dot{\nu}_i = \alpha_i E_i - \nu_i + L_i \sum_{j=1}^{N+1} B_{ij}\nu_j \cos(\delta_i - \delta_j), \\ \dot{\rho}_i = -A_i\dot{\delta}_i - H_i\rho_i, \end{cases}$$

LOAD MODEL

$$\begin{cases} M_{N+1}\ddot{\delta}_{N+1} + D_{N+1}\dot{\delta}_{N+1} = \quad -(P^0_{N+1} - P^s\Gamma(\Lambda^-)) \\ \quad + \nu_{N+1} \sum_{j=1}^{N+1} B_{N+1j}\nu_j \sin(\delta_{N+1} - \delta_j), \\ S_{N+1}\dot{\nu}_{N+1} = \\ \quad E_{N+1} - \nu_{N+1} + L_{N+1} \sum_{j=1}^{N+1} B_{N+1j}\nu_j \cos(\delta_{N+1} - \delta_j), \end{cases}$$

2. Correlation between u_i

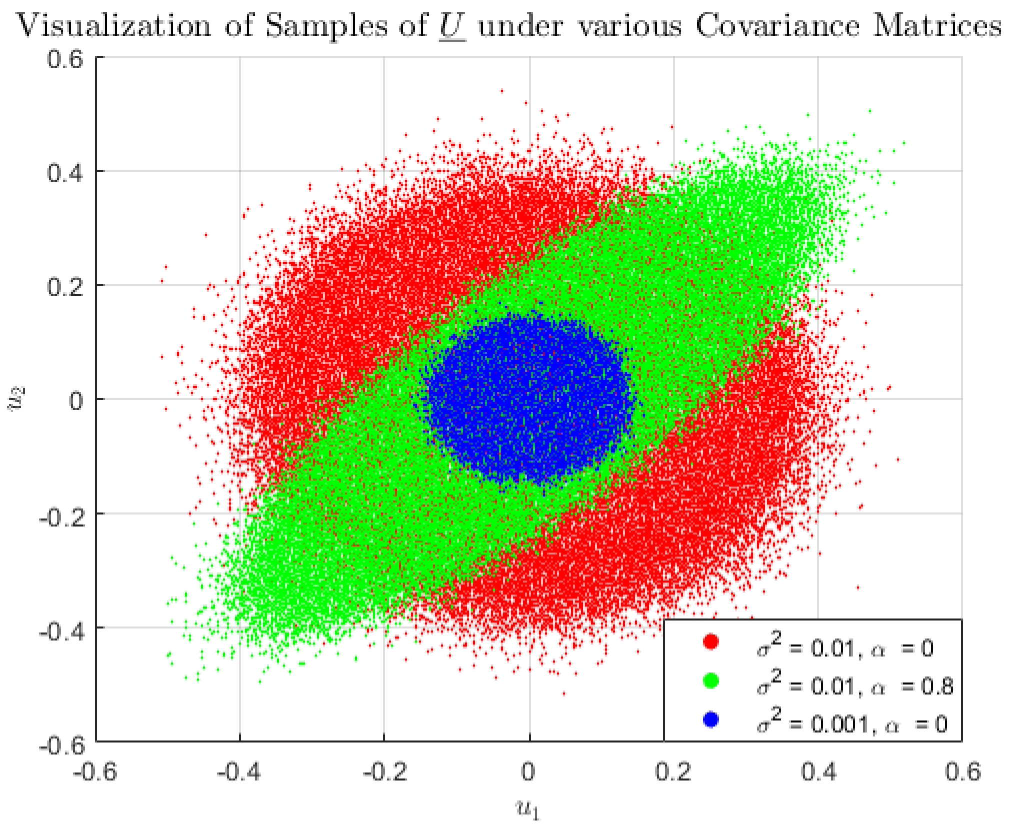
- In power systems with high renewables penetration, large weather phenomena may induce correlated disturbances;

- Disturbances are Gaussian: $\underline{U} \sim N(0, \Sigma)$ with covariance matrices Σ parametrized *by* $\boldsymbol{\sigma}$ and $\boldsymbol{\alpha}$*:*

$$\Sigma_{\text{ij}} = \begin{cases} \sigma^2, & i = j \\ \alpha\sigma^2, & i \neq j \end{cases}$$

- Rareness of large disturbances can be modelled by varying $\boldsymbol{\sigma}^{\mathbf{2}}$ (see figure)

- Correlations between the initial power disturbances $(u_1 \ \ldots u_N)$ modelled by varying $\boldsymbol{\alpha} \in [\mathbf{0},\ \mathbf{1}]$.



3. Network Designs

- The impact of power disturbances depends on network connectivity ;

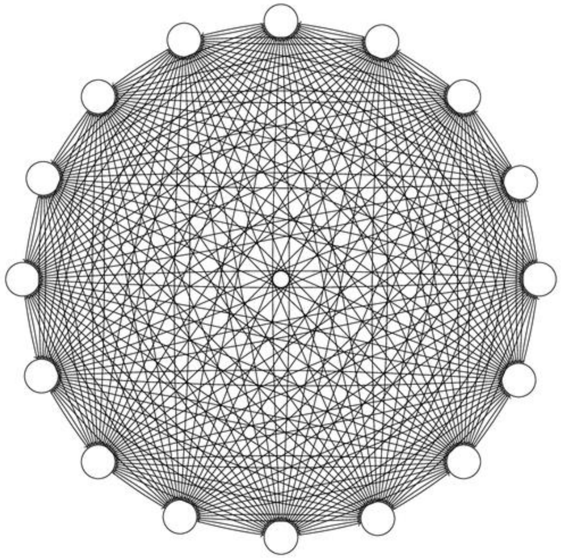
- To understand effect of correlation; our network designs are highly stylized rather than realistic:

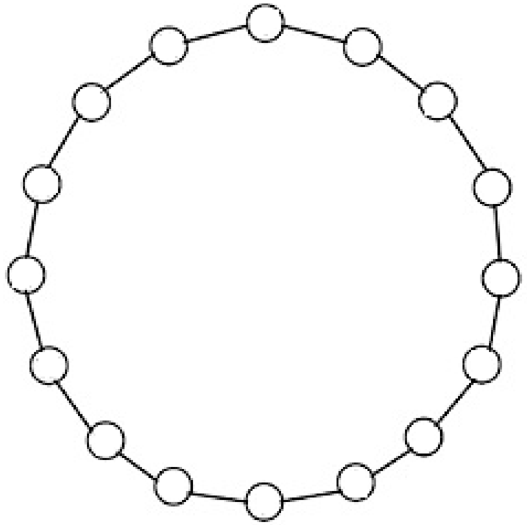
  I. **Fully Connected (Dense) Network**
  II. **Ring (Sparse) Network**

- *N* equivalent generators representing a mixture of conventional generation, distributed generation and loads;

- 1 node modelled as a pure load;

- Symmetric network design: all line parameters equal; net power injections at all generators equal;





4. Cascades of Power System Emergency Responses

- The following *independent* Emergency Response Schemes were modelled to protect generators and equipment:
  - Rate of Change of Frequency Protection
  - Over Frequency Generation Shedding Protection
  - Under Frequency Load Shedding (applied to pure load node)
- *Power System Emergency Response:* The activation of any Emergency Protection Scheme;
- Power disturbances lead to frequency fluctuations and the activation of Power System Emergency Responses, which may propagate in a *cascading fashion.*
- *Cascade Size*: Total number of Power System Emergency Responses following initial power disturbance.

5. Results: Distribution of Cascade Sizes

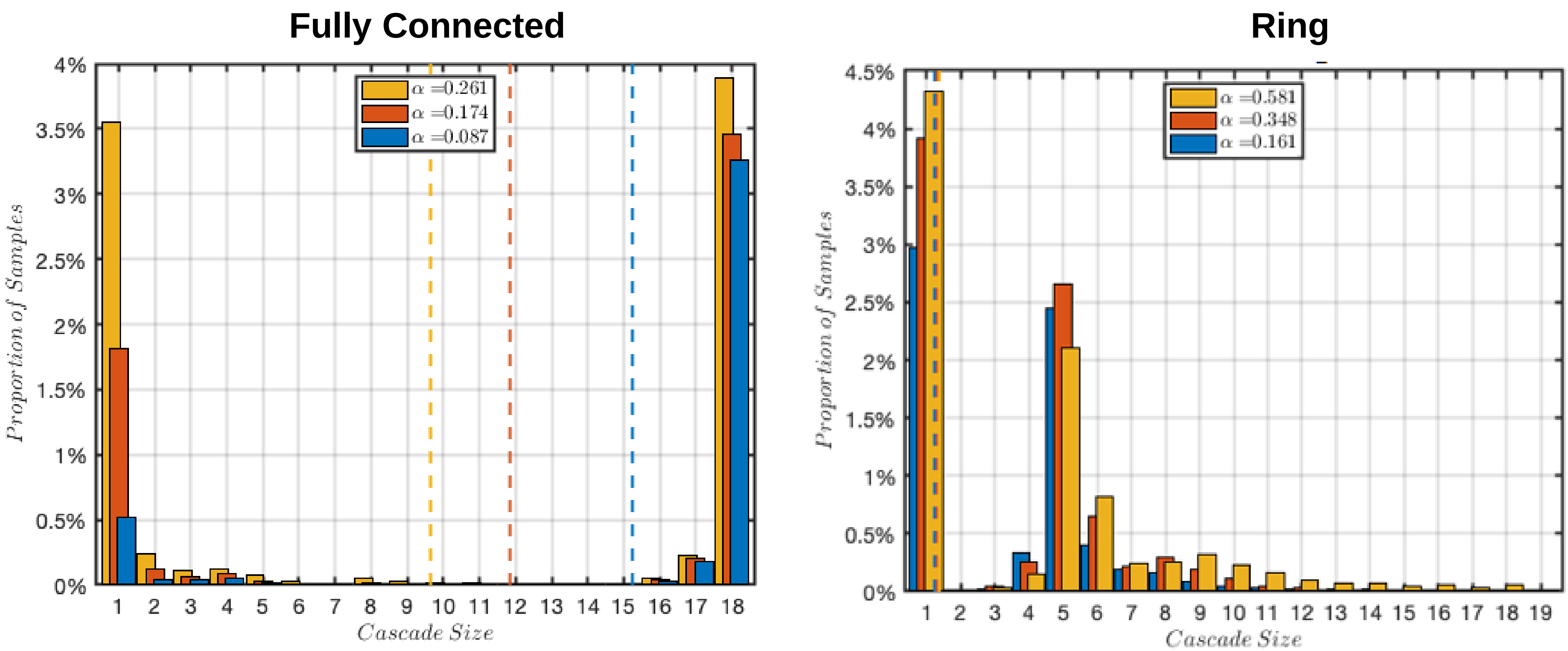


Fig. 1. Histograms of <u>cascade sizes</u> and mean cascade size (dashed vertical lines), as the disturbance correlation varies for Fully-connected network (left) Ring network (right) . note- zero has been omitted for legibility.

- <u>Key Observations:</u>

1. Bimodality in distributions of cascade size for fully connected networks;
2. Increased proportion of single emergency responses as α increases in fully connected networks;

6. Results: Average Cascade Size and Correlation

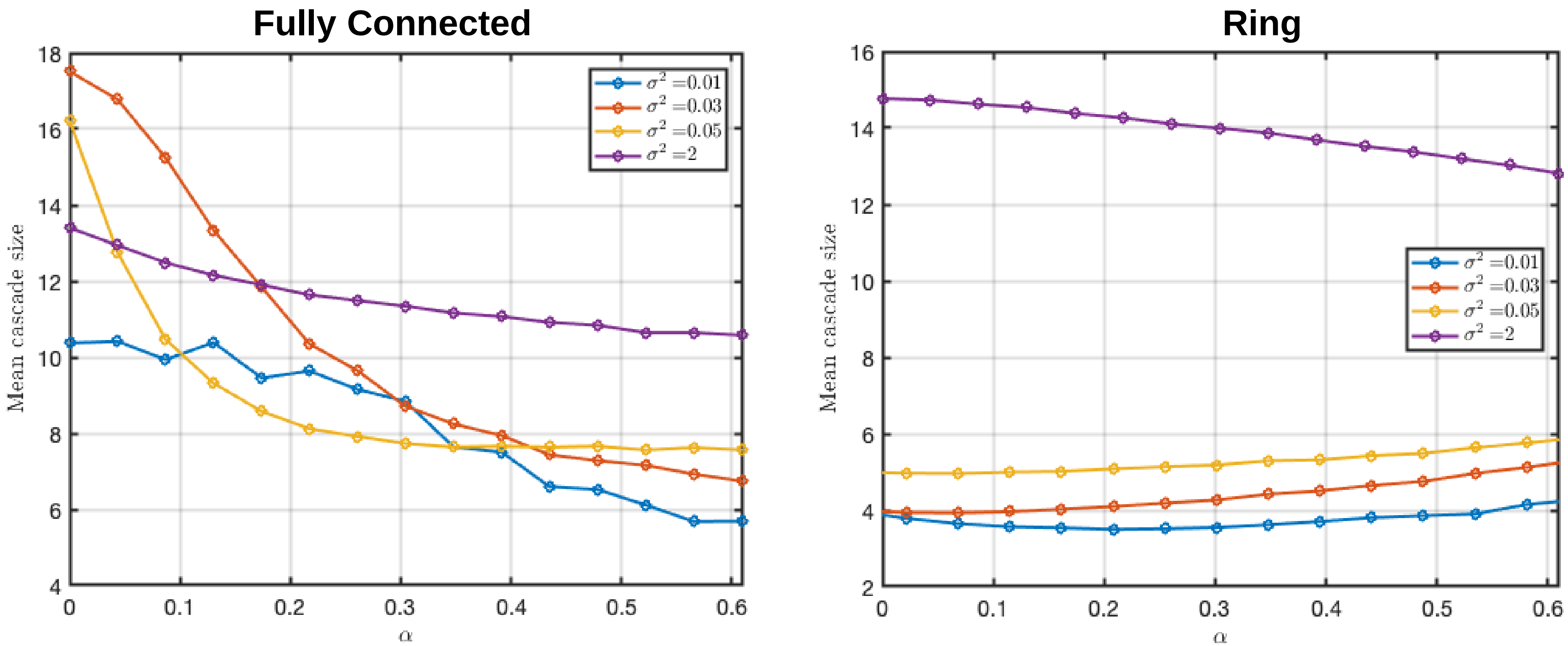


Fig 2. Plot of mean cascade size versus disturbance correlation parameter (α) for the fully-connected network (left) and ring network (right), for different values of σ^2.

<u>Key Observations:</u>

1. Negative relationship between average cascade size and α in fully connected network;
2. Relationship between correlation and cascade size depends on network **connectivity**;
3. Relationship between correlation and cascade size depends on **rareness** of emergency power system responses (Resilience of the network);

7. Discussion

Correlation

- **Why do average cascades decrease with $\boldsymbol{\alpha}$ in fully connected networks?** - as α increases disturbances $\underline{U}$ become more homogenous; thus a single emergency response is more likely to correct the initial power disturbance globally;

Connectivity

- **Why is there little relationship between $\boldsymbol{\alpha}$ and average cascade size?** disturbances and emergency responses in the sparse ring network primarily have local influence; reducing the impact of global correlations between disturbances.

- Fully connected network exhibits greater resilience- it required disturbances with significantly higher σ^2 than those in the ring network to generate the same proportion emergency responses.

Rareness of Emergency Responses

- **Why does the distribution change as $\boldsymbol{\sigma^2}$ changes?** This follows from large deviation theory, which states that the rareness of an event influences the way it occurs. It follows that as the disturbance variance parameter decreases and emergency responses become more rare, so the statistical pattern of the disturbances U causing them may also change.

8. Future Work

- We intend to use the framework to study how grid connected Battery Storage Systems (BSS) can improve a high DG network's resilience to correlated disturbances;

- Given the rareness of large disturbances in power systems and with BSS, we intend to use a more sophisticated methodology for rare event sampling: the Skipping Sampler Family of MCMC algorithms

- We intend to use the framework to propose optimal BSS strategies for low-inertia power grids.

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Questions?

8. References

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