Modeling Cascading-Failures in Power Grid Including Communication and Human Operator Impacts

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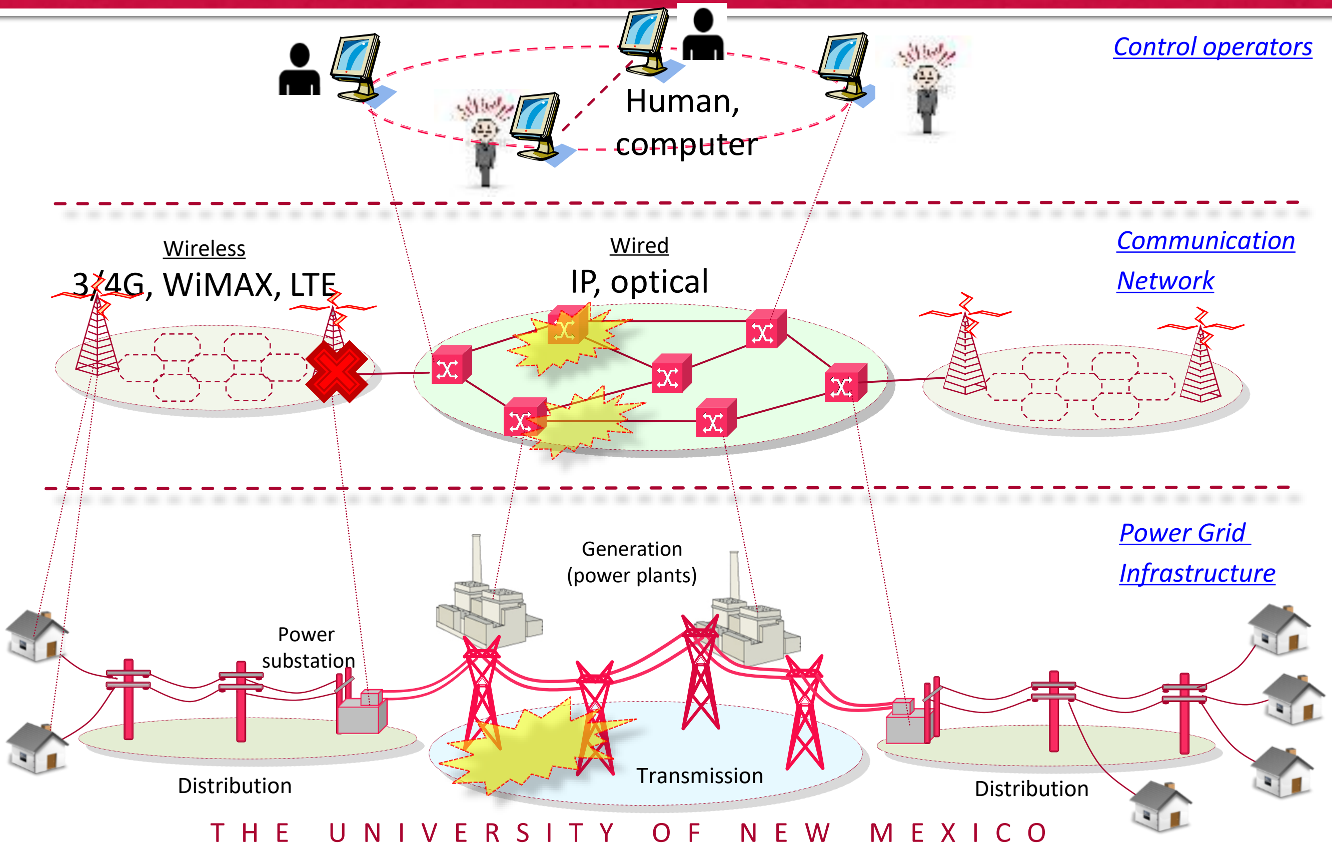
Outline

- *Overview of Cascading Failures in power grid*
- *Discussion on earlier works used in our model*
- *Interdependent three layer Model*
- *Simulation results*
- *Conclusion and Future Works*

Overview of Cascading Failures in Power Grid

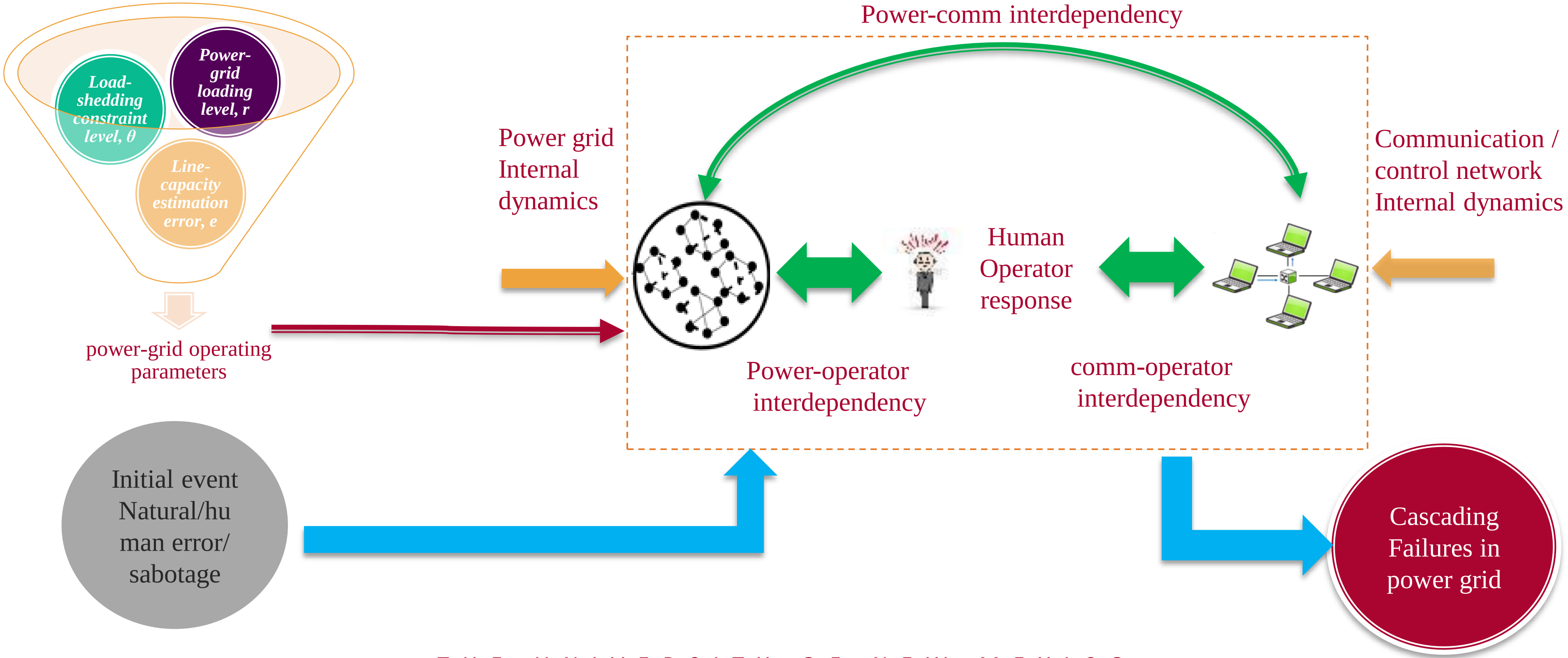
Overview of complex Power grid Infrastructure: Modeling effort requires a multi-layer view



Why do cascading failures and blackouts occur?

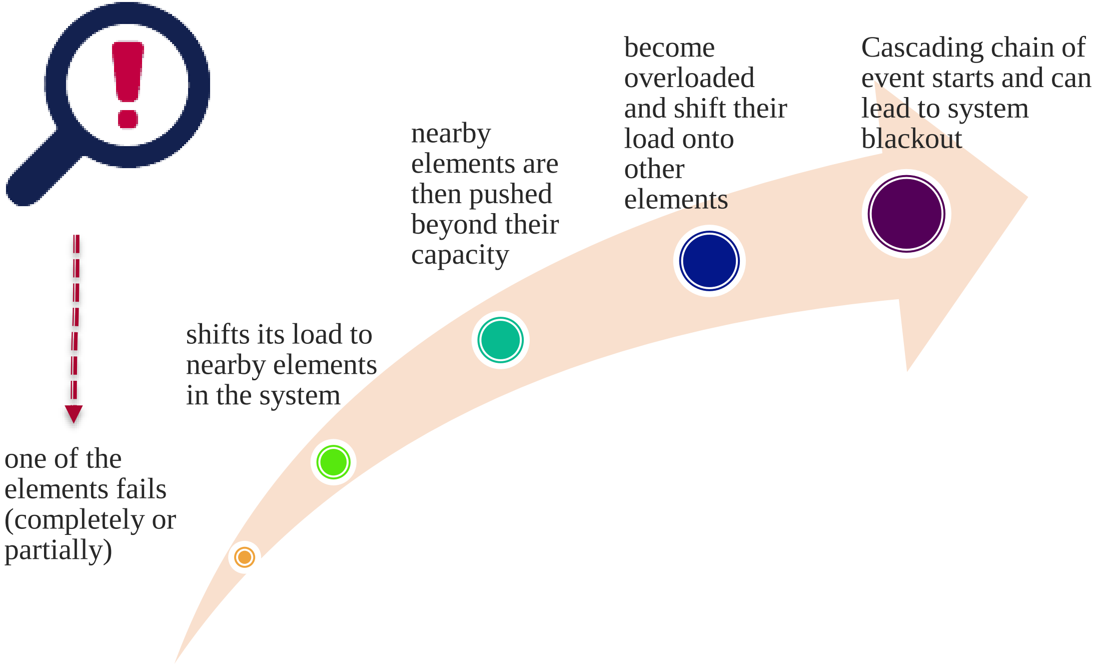
- Large blackouts result from the cascade of component failures in the transmission grid triggered by initial disturbances:
  - Natural disasters and human-related events such as unintentional human faults, sabotage occurrences and WMD attack.
- 2003 Northeast Blackout:
  - Occurred due to a combination of transmission-line failure and communication network failure
  - Alarm software failed leaving the human operators unaware of the transmission-line outage which contributed the cascading failure [1]
- 2003 Italy Blackout:
  - An example of power grid and communication network interdependency
  - An unplanned power shutdown eventually led failures in the communication network, which in turn initiated a series of cascading failures in the power-grid [2].
- 2011 Southwest Blackout:
  - A technician accidentally shut a 500KV transmission line down which led to a blackout
  - 11 million people for over 11 hours with an estimated loss of $12 million to $18 million [3].

Overview of the Cascading Failure dynamics

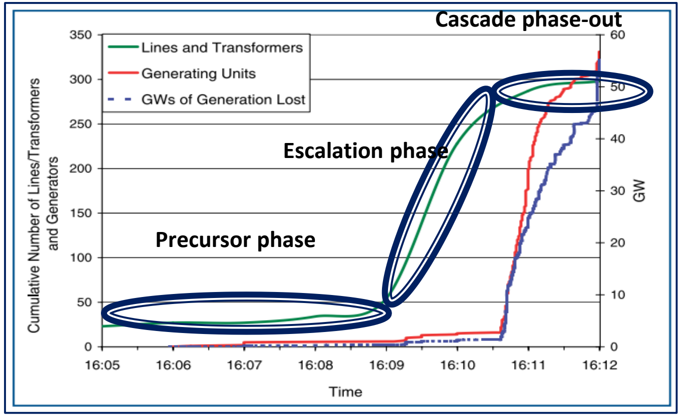


Modeling cascading-failure dynamics : Sequence of events during Cascading Failures

Initial event



Time evolution of failures



Precursor phase: there are a small number of initial and subsequent transmission-line failures

Escalation phase: the number of transmission-line failures increases rapidly

Fade-away phase: when a large number of transmission lines have been failed, the power grid is divided into many islands and the cascading failure starts to phase out

U.S.-Canada Power System Outage Task Force. (2004) Final Report on the August 14, 2003 Blackout in the United States and Canada: Causes and Recommendations. [Online]. Available: http://www.nerc.com.

Key attributes in cascading-failure behavior in the power grid

Base on historical data, nature of power systems, social studies and simulations, the key players include:

Number and capacity of failed transmission lines, F

Capacity of the failed lines, Cmax

Human factor, H

Number of failed communication components, Y

Topological factors in the communication network
- Hop distance of failed nodes from the central node, h
- Maximum of degree of failed nodes, d

Discussion on earlier works used in our model

Earlier work

We used the following three models to define our interdependent three layer model:

- ***Stochastic abstract-state evolution (SASE)*** model [1]:
  - Describes the dynamics of cascading failures based upon Markov chains

- ***Interdependent Markov-chain (IDMC)*** model [2]**:**
  - A minimal MC that encompasses the individual MC for each physical system and their interdependencies

- ***hSASE*** model [3]**:**
  - A MC model captures the coupling between power grid and human operator response.

[1] M. Rahnamay-Naeini *et.al.*"Stochastic analysis of cascading-failure dynamics in power grids," IEEE Transactions on Power Systems, vol. 29, no. 4, pp. 1767–1779, 2014.
[2] IDMC model : M. Rahnamay-Naeini *et. al.* "Cascading failures in interdependent infrastructures: An interdependent markov-chain approach," IEEE Transactions on Smart Grid, vol. 7, no. 4, pp. 1997–2006, 2016.
[3] hSASE model : Z. Wang et al., "Modeling and analyzing impacts of operators behavior on infrastructure reliability during contingencies," in Article can be found on this url http://ece-research.unm.edu/sg/wp-content/uploads/2017/06/hSASE2017.pdf

Review of SASE model

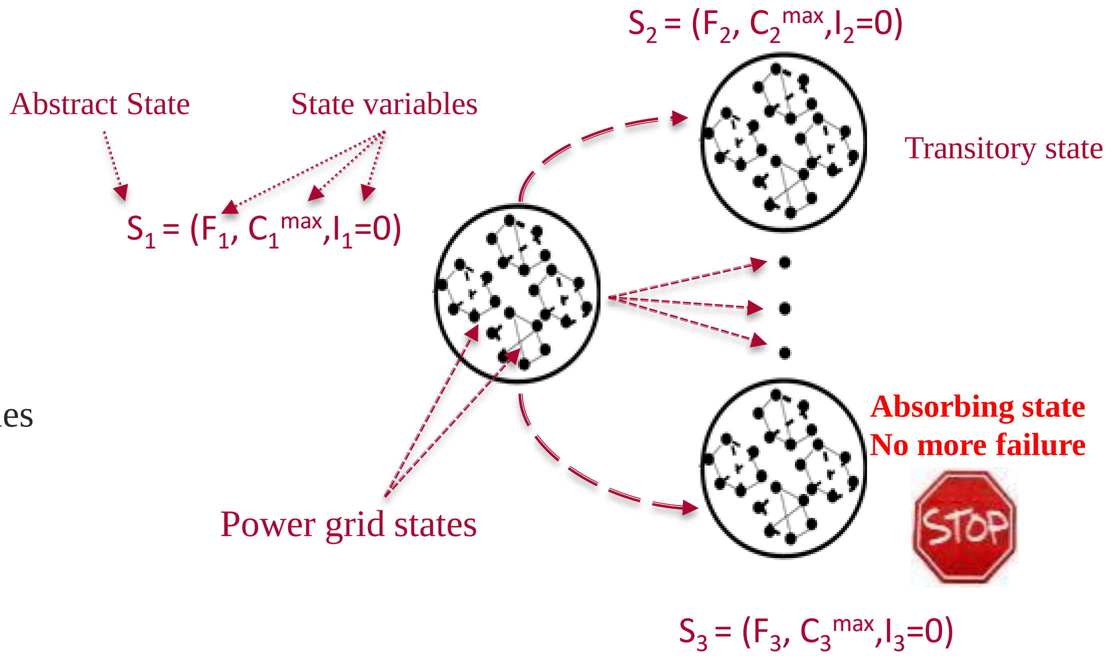
Main ideas of the *stochastic abstract-state evolution (SASE) approach:*

- Simplify the state space of the complex power system (**equivalence classes**)

Aggregate state variables: $S_i = (F_i, C_i^{max}, I_i)$

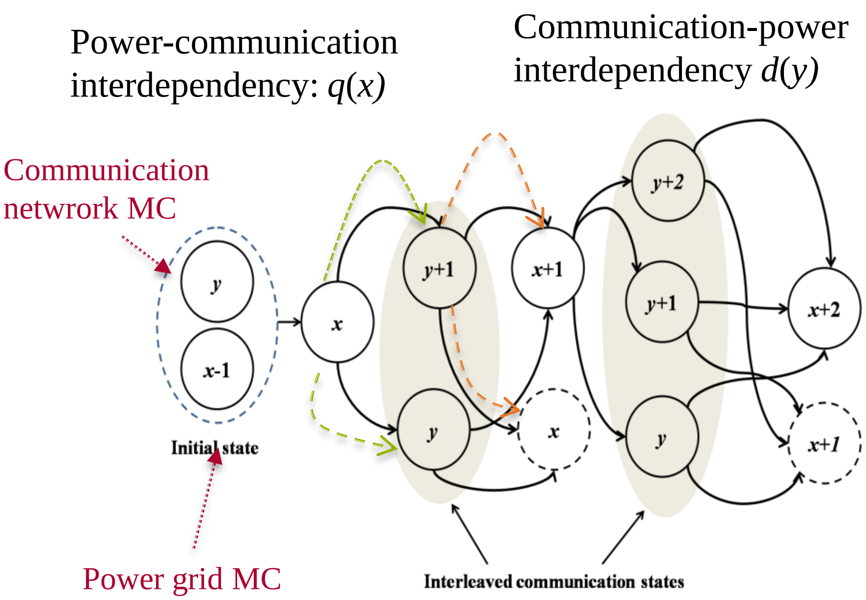
F: number of failed lines
C_{max}: maximum capacity of failed lines
I: Cascade-stability of power grid

- Capturing the effects of the omitted variables through the transition probabilities and their parametric dependence on physical attributes and **operating characteristics** of the system.



Review of Interdependent Markov-chain (IDMC) model

- Each network is represented by a Markov chain
  - Number of failures in the power grid: ***x***
  - Number of failures in the communication system: ***y***
- Failure in one chain is correlated with failure in the other chain via state-dependent coupling variables
- Transition probabilities are influenced by communication-network topology via state-dependent variables representing significance of failed nodes/links



IDMC state transitions

Review of hSASE model (coupling power system and human factors)

- The hSASE (human-error-driven SASE) model features

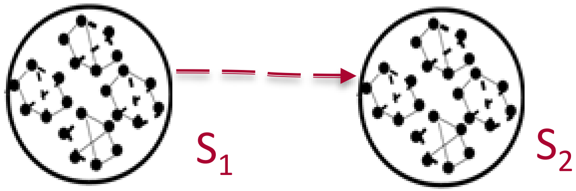
  1. Abstract state space to handle the scalability problem
  2. A **reducible** (due to the absorbing states) Markov chain, whose transition matrix is governed by the coupling between power system and human error
  3. Uses Standardized Plant Analysis Risk-Human Reliability Analysis Method (SPAR-H) to calculate human-error probability (HEP) through performance shaping factors (PSFs)
  4. Coupling between *F*, C_{max} and *H* has been considered while taking into account human-error probability, HEP

State variables

Abstract State

$$S_i = (F_i, C_i^{\max}, H_i, I_i)$$

H_i = operator reaction levels



SPAR-H PSFs	SPAR-H PSF levels
NHEP: Diagnosis / Action	
Available time	Inadequate time Barely time / time available = time required Nominal time Extra time (between 1 and 2 times nominal time and more than 30 min) Expansive time (more than 2 times nominal time and more than 30 min)
Stress/Stressors	Extreme High Nominal

J. M. Abreu, *et al*., "Modeling Human Reliability in the Power Grid Environment: An Application of the SPAR-H Methodology," International Annual Meeting of the Human Factors and Ergonomics Society, Los Angeles, CA, Oct. 2015, accepted.

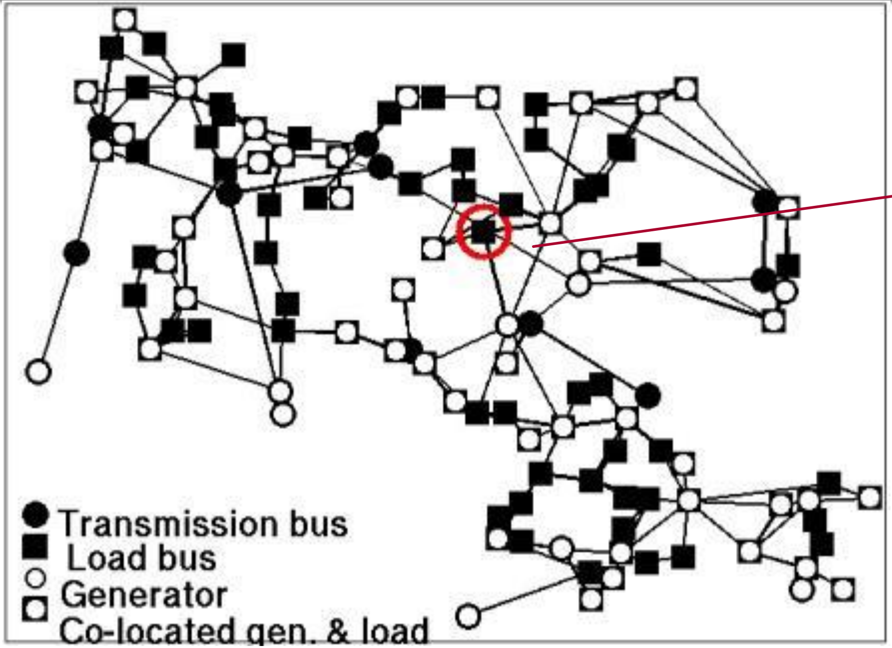
Interdependent three layer Model

3-layer model: coupling power system, communication network and human factors

3-D model features

- Additional capability to capture coupling of communication network with power system and human factors
- Four variables in the state $S_i = (F_i, Y_i, H_i, I_i)$
  - Number of failed transmission lines, *F*
  - Number of failed components in communication network, *Y*
    - impact of topological factors *h* and *d* is also implicitly embedded
  - Human factor, *H*
    - determined by *F* and *Y*
  - Cascade-stability of power grid, *I*

Communication/control network over-layed on IEEE 118-bus topology



control center, center connected with 12 nodes

R. A. Shuvro et al., “Modeling impact of communication network failures on power grid reliability,” North American Power Symposium(NAPS), IEEE,2017

Coupling between communication/control and transmission networks

- **Consequence of power loss on communication:**
  - A failure in a transmission line may triggers a communication-link failure with probability $\boldsymbol{q}$.

- **Consequence of communication-link failure on power loss:**
  - Without communication influence, cascading failures stop in the power grid with probability $\boldsymbol{p(x)}$, which depends on the number of failures in the power grid: this is the cascade-stop probability. [earlier SASE model]

  - A communication-link failure reduces the cascade-stop probability in the power grid from $\boldsymbol{p(x)}$ to $\boldsymbol{p(x)(1-d(y))}$, where $\boldsymbol{d(y)}$ (in [0,1])

  - $\boldsymbol{d(y)}$ is an interdependency function that depends on the dynamic functionality and topological attributes of the communication network.

  - $\boldsymbol{d(y)}$ should represent the "significance" of the failed communication links on the power grid

Role of communication/control topology

- Optimal power-flow simulations suggest that the role of communication-link failure (d(y)) can be attributed to two main connectivity and topological factors:
  - Minimum hop-distance of the failed communication nodes to the central node
  - Maximum degree of failed communication nodes
- Hence, we can propose:
  - Interdependency variable, *d*, to be a weighted sum of two probabilities
    - $\boldsymbol{p_{hop}^{fail}(h_n)}$: probability of communication-link failure resulting from the state of the connectivity to the central node (hop distance of the failed lines to the central node)
    - $\boldsymbol{p_{deg}^{fail}(d_n)}$: probability of communication-link failure resulting from the state of the degree of failed communication nodes

we can represent the interdependency variable as:

- $d = w\, \boldsymbol{p_{hop}^{fail}(h_n)} + (1-w)\, \boldsymbol{p_{deg}^{fail}(d_n)}$; w is a weight factor between 0 and 1.

R. A. Shuvro et al., "Modeling impact of communication network failures on power grid reliability," North American Power Symposium(NAPS), IEEE,2017

Accounting for operator influence

Human factor influences transition probabilities through the human-error probability (HEP)

- HEP is an explicit function of performance-shaping factors (PSFs)

$$PSF < 3 \rightarrow HEP = NHEP.\prod_{i=1}^{2} PSF_i$$

$$PSF \geq 3 \rightarrow HEP = \frac{NHEP.\prod_{i=1}^{8} PSF_i}{NHEP.(\prod_{i=1}^{8} PSF_i - 1) + 1}$$

- It can be approximated as an Implicit function of a function of cascading phase, i.e., function of X_n and Y_n

SPAR-H PSFs	SPAR-H PSF Levels	Multiplier	Pr.(escalation)
Diagnosis / Action		0.01/0.001	
Available time	Inadequate time	1	0.0
	Time available = time required	10	0.9
	Nominal time	1	0.1
	Time available≥ 5x time required	0.1	0.0
	Time available > 50x time required	0.01	0.0
Stress/Stressors	Extreme	5	0.4
	High	2	0.6
	Nominal	1	0.0
Complexity	Highly complex	5	0.4
	Moderately complex	2	0.6
	Nominal	1	0.0
	Obvious diagnosis	0.1	0.0
Experience	Low	10	0.6
/	Nominal	1	0.2
Training	High	0.1	0.3
Procedures	Not available	50	0.0
	Incomplete	20	0.2
	Available, but poor	5	0.1
	Nominal	1	0.7
	Diagnostic/ system oriented	0.5 (Diagnosis only)	0.0
Ergonomics	Missing/ misleading	50	0.2
/	Poor	20	0.0
HMI	Nominal	1	0.8
	Good	0.5	0.0
Fitness for duty	Unfit	p(failure)= 1.00	0.0
	Degraded fitness	5	0.1
	Nominal	1	0.9
Work processes	Poor	2	0.0
	Nominal	1	1
	Good	0.8	0.0

J. M. Abreu, *et al*., "Modeling Human Reliability in the Power Grid Environment: An Application of the SPAR-H Methodology," International Annual Meeting of the Human Factors and Ergonomics Society, Los Angeles, CA, Oct. 2015

Calculation of HEP and Human operator response level

Table 1: Performance-shaping factors and their multipliers (Source: Gertman *et al., 2005*)

SPAR-H PSFs	***SPAR-H PSF Levels***	***Multiplier***
NHEP: Diagnosis / Action	*0.01 / 0.001*	
Available time	Inadequate time	Pf=1
	Barely time / time available = time required	10
	Nominal time	1
	Extra time (between 1 and 2 times nominal time and more than 30 min)	0.1
	Expansive time (more than 2 times nominal time and more than 30 min)	0.01
Stress/Stressors	Extreme	5
	High	2
	Nominal	1

- We take two PSF's available time and stress level
- We calculate HEP using following equation:

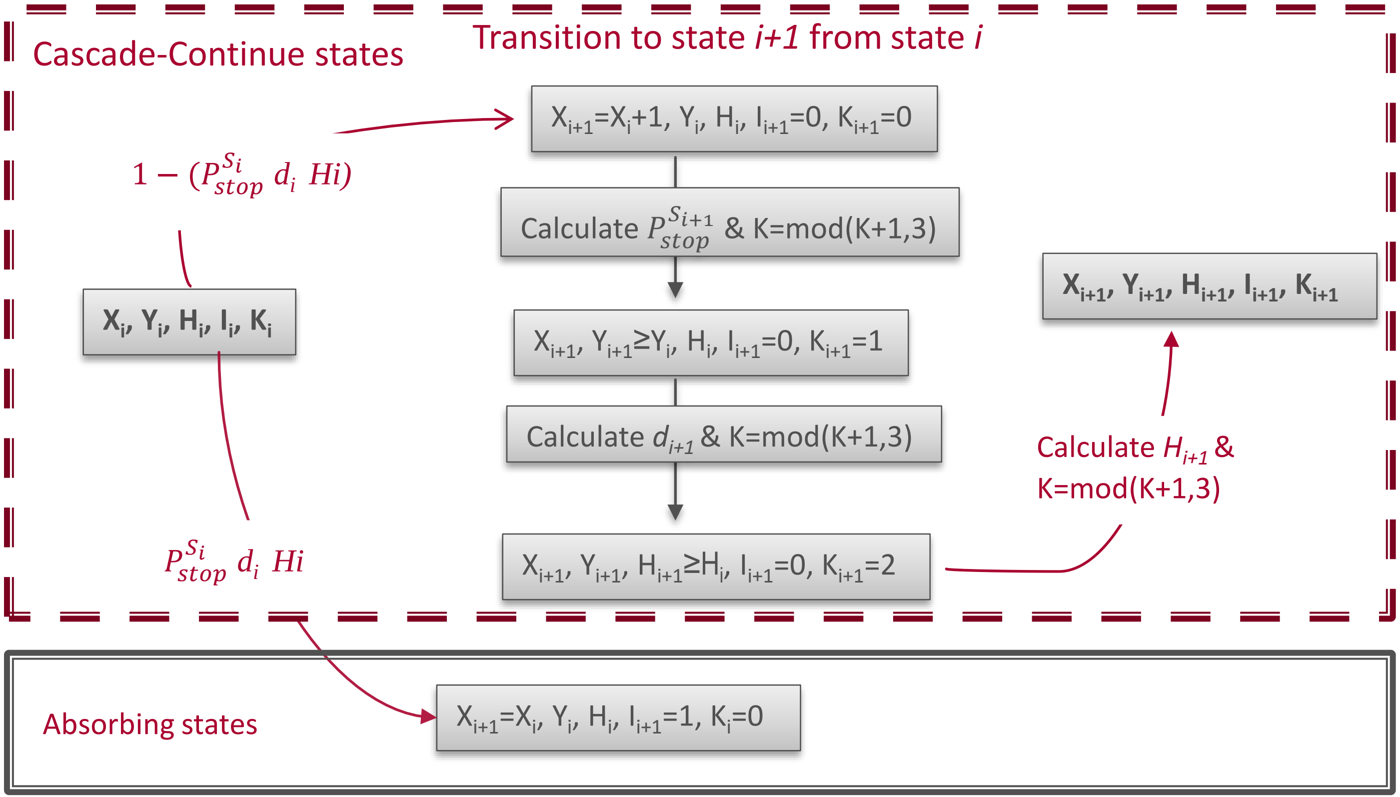
$$\mathrm{HEP} = \mathrm{NHEP} \cdot \prod_{i=1}^{2} \mathrm{PSF}_i,$$

HUMAN OPERATOR RESPONSE LEVELS BASED ON FAILURE IN POWER AND COMMUNICATION NETWORK

Level	Definition	Available action time	Stress
1	$X \leq 5$ and $Y \leq 10$	Normal	Normal
2	$5 < X \leq 10$ and $10 < Y \leq 30$	Low	High
3	$10 < X \leq 50$ and $Y > 30$	Extremely low	Extreme
4	$X > 50$	N/A	N/A

- We map the PSF's with power grid and communication failures.
- We took four levels which matches with the phases of the power grid.

State transition dynamics for the 3-layer model



- Cascade-stop probability becomes $\boldsymbol{P_{stop}(F, \delta(y), H)}$

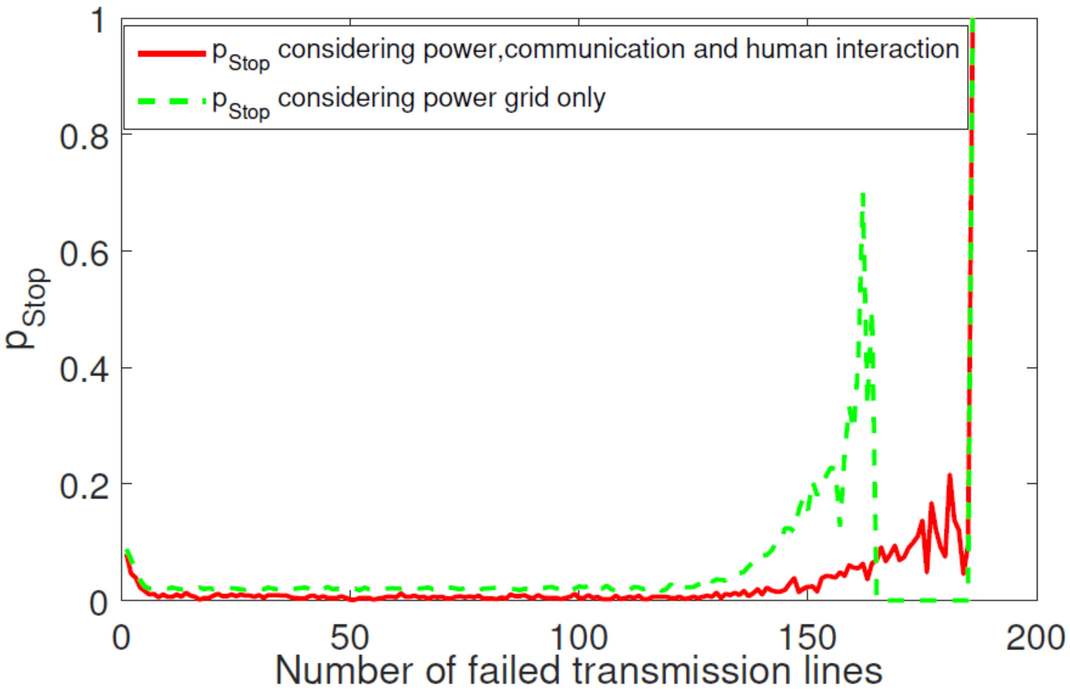
- *H* is a function of *F* and Y *Y*

- Update $\boldsymbol{P_{stop}}$, **δ(y) and *H*** during each layer transition.

- Use an variable parameter ***K*** to track the state transitions between different layers

Simulation Results

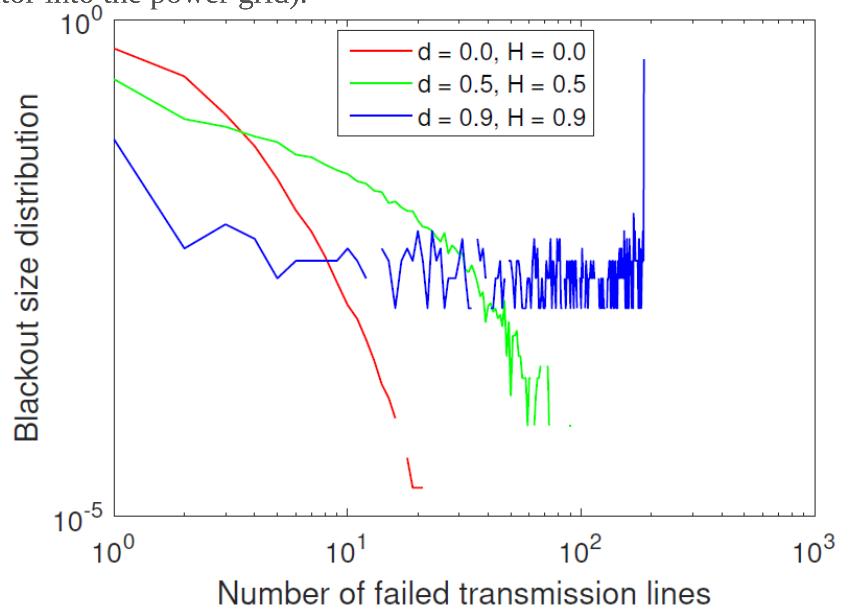
Cascade-stop probability with and without the influence of communication and human response



Observation: poor human operator performance and failure in the communication network can lead to greater blackout size

Impact of communication network and human behavior on blackout-size distribution

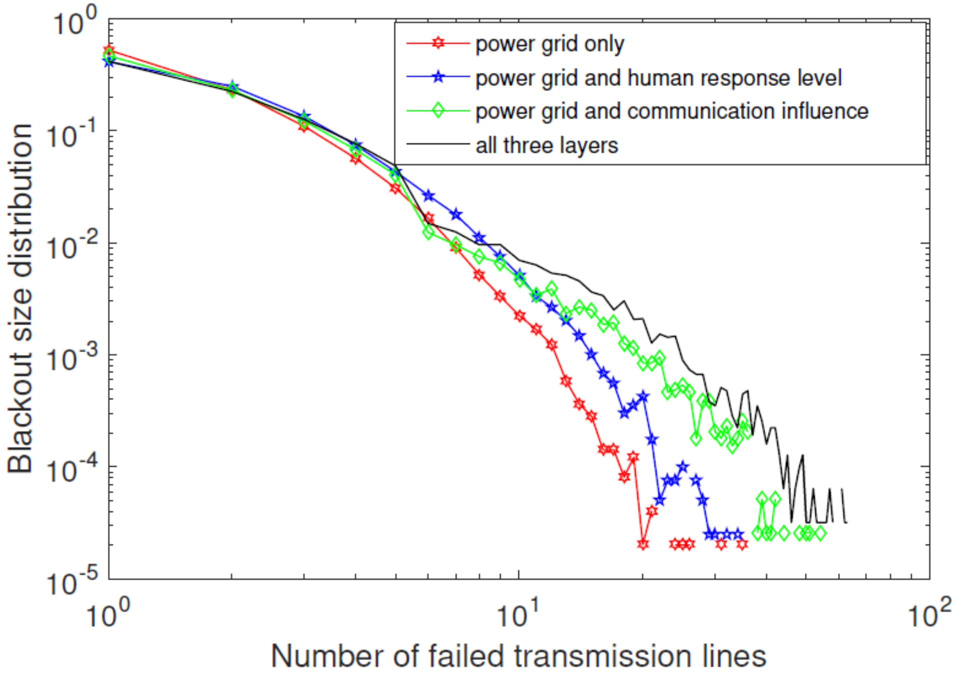
- impact of blackout size for three cases (with no influence, moderate influence and high influence from communication network and human operator into the power grid).

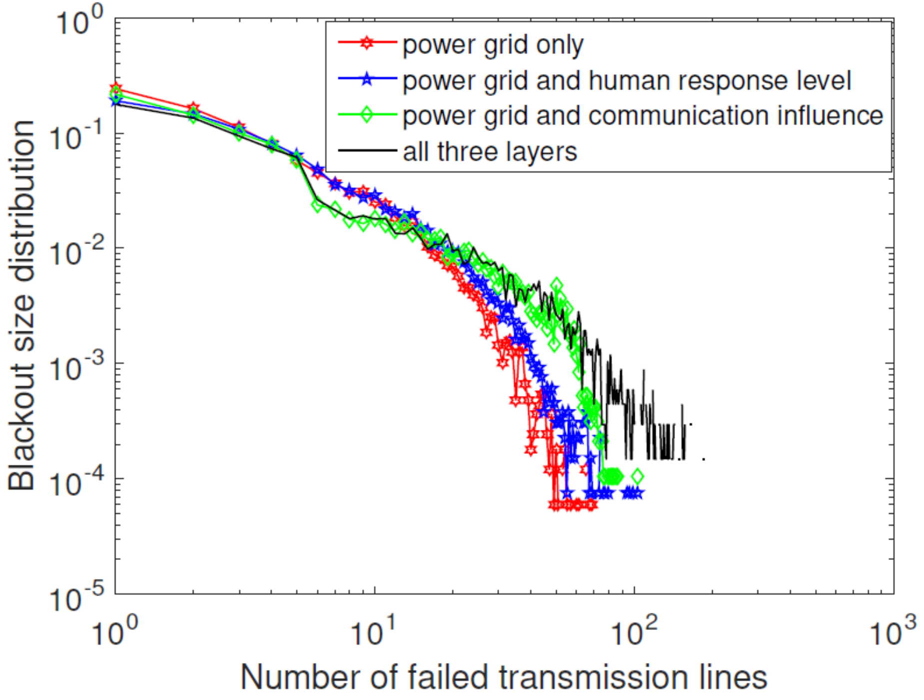


- **Red:** no coupling from communication network and human factors (benchmark)
- **Green:** medium coupling from communication network and human factors
- **Blue:** strong coupling from communication network and human factors (heavy tail)

- without any influence, the blackout size follows an exponential distribution.
- high deterministic influence the blackout size follows power law distribution.

Blackout size (log-log scale) comparison when the grid is under No-stress/stress

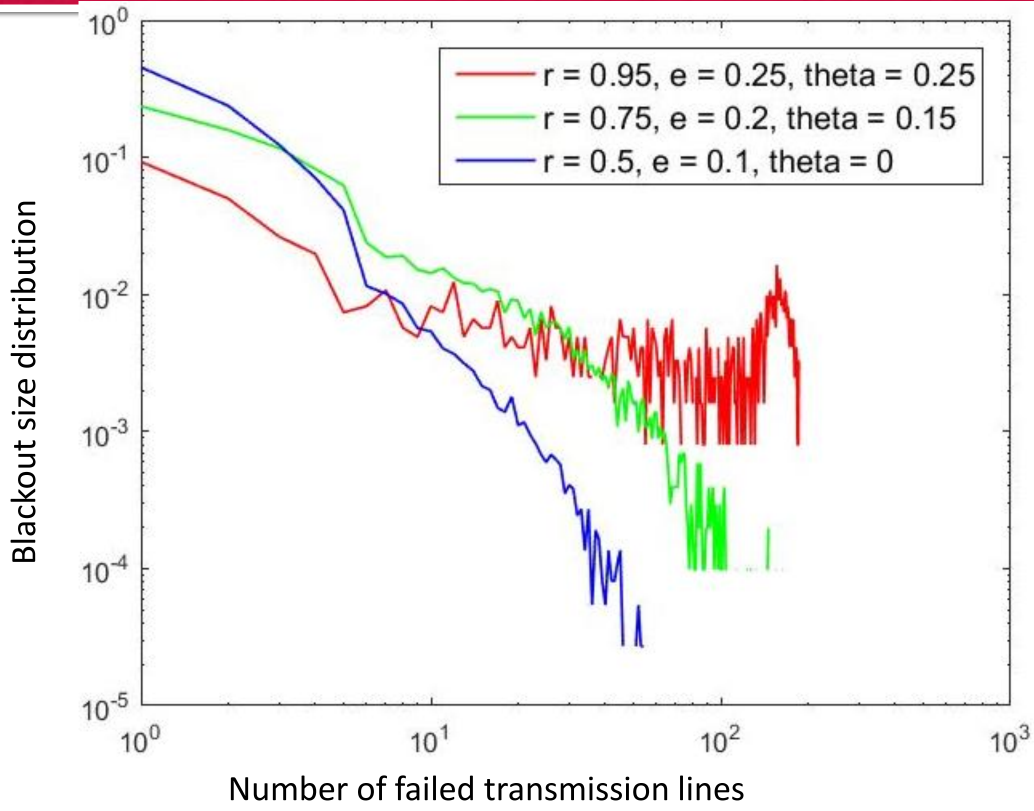




r = 0.5, e = 0.1 and = 0.1 for no stress and r = 0.8, e = 0.2 and = 0.2 for stress

All three layers lead to greater blackout size

Impact of operating characteristics on blackout-size distribution



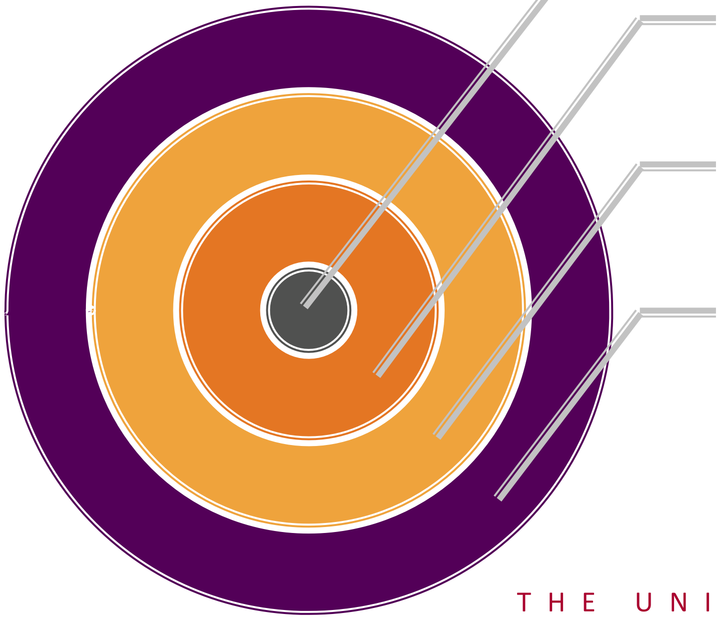
- **Red:** power system is aggressively loaded and vulnerable to cascading failures
- **Green:** power system is moderately loaded and kind of vulnerable to cascading failures
- **Blue:** power system is lightly loaded and robust to cascading failures

***High operating characteristics* lead to greater blackout size**

Summary of 3-layer model (coupling power system, communication network, and human factors)

- Extends hSASE model to include interdependency with communication network. State vector: $S_i = (F_i, C_i^{\max}, Y_i, H_i, I_i)$
- When human factor is ignored it collapses to the IDMC model reported last year
- Captures the role of communication-network topology
- Enables criticality analysis of cascading failures and quantifying the impacts of power-system operating characteristics, communication topology and human error

Conclusion



We proposed a three layer Markov chain based model to demonstrate cascading failure dynamics in power Grid.

It captures the influence of communication network and Human operator responses on the power grid under different stress levels during cascading failures.

We devised a coupled simulator and conducted extensive simulations to validate the proposed model

Blackout probability in the power grid can be significantly impacted by the failures in the communication network and higher stress level for the human operator when the power grid is under stress.

Ongoing Works

- Impact of Initial Conditions due to natural disaster, WMD’s on Cascading Failures in Power-grid
- Analytical and tractable closed form solution for the three layer model
- Analyzing the impact of topology of the power grid during cascading failures

Thank you for your Attention

Questions?

References

[1] M. Amin and P. F. Schewe, "Preventing blackouts," Scientific American, vol. 296, no. 5, pp. 60–67, 2007.
[2] A. Veremyev, A. Sorokin, V. Boginski, and E. L. Pasiliao, "Minimum vertex cover problem for coupled interdependent networks with cascading failures," European Journal of Operational Research, vol. 232, no. 3, pp. 499–511, 2014.
[3] https://energy.gov/oe/downloads/blackout-2003-final-report-august-14-2003-blackout-united-states-and-canada-causes-and
[4] M. Rahnamay-Naeini and M. M. Hayat, "Cascading failures in interdependent infrastructures: An interdependent markov-chain approach," IEEE Transactions on Smart Grid, vol. 7, no. 4, pp. 1997– 2006, 2016.
[5] Rahnamay-Naeini et al., "Stochastic analysis of cascading-failure dynamics in power grids," IEEE Transactions on Power Systems, vol. 29, no. 4, pp. 1767–1779, 2014.
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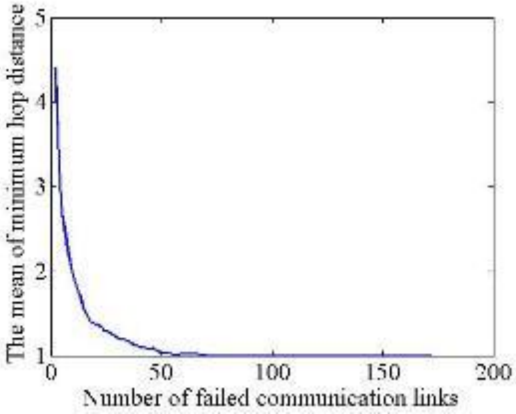
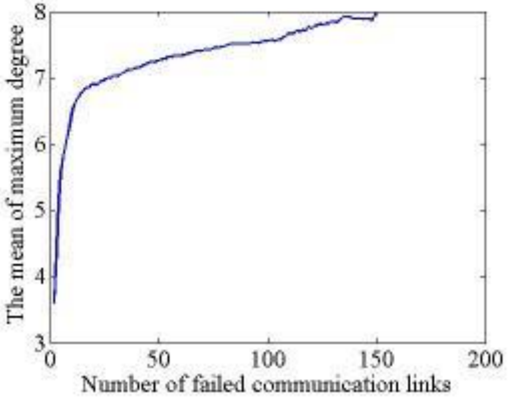
[7] R. A. Shuvro et al., "Modeling impact of communication network failures on power grid reliability," North American Power Symposium(NAPS), IEEE,2017
[8] J. M. Abreu, *et al*., "Modeling Human Reliability in the Power Grid Environment: An Application of the SPAR-H Methodology," International Annual Meeting of the Human Factors and Ergonomics Society, Los Angeles, CA, Oct. 2015, accepted.

Role of communication/control topology

- Optimal power-flow simulations suggest a relationship between:
  - Maximum degree of failed nodes in communication network and number of failed links in communication network.
  - Minimum hop-distance between central control node and failed nodes in communication

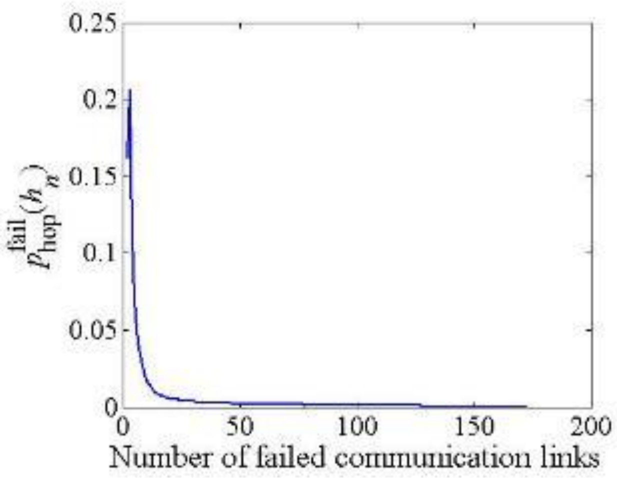


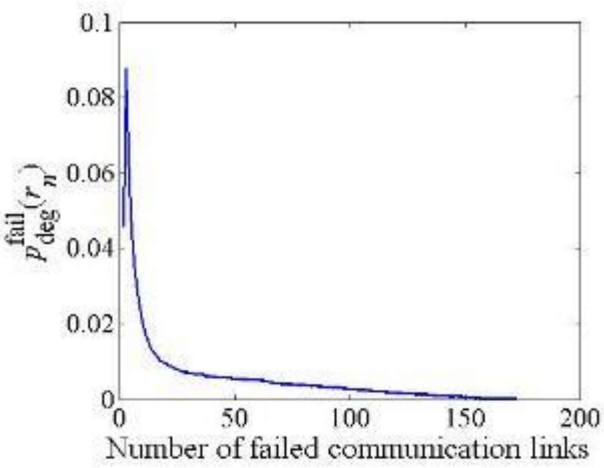


Parametric approximation

$$p_{hop}^{fail}(h_n) = \begin{cases} \dfrac{a_1}{{h_n}^4} + \epsilon & 1 \le h_n \le m \\ \epsilon & h_n > m \end{cases} \qquad p_{degree}^{fail}(d_n) = \begin{cases} \epsilon & 1 \le d_n < n \\ a_2 {d_n}^4 + \epsilon & d_n \ge n \end{cases}$$

Role of communication/control topology





- Hence, we can represent the interdependency variable

$$d = w\, p_{hop}^{fail}(h_n) + (1\text{-}w)\, p_{deg}^{fail}(d_n)$$

as

$$d\,(y_n) = w\, p_{hop}^{fail}(y_n) + (1\text{-}w)\, p_{deg}^{fail}(y_n)$$