CORRELATING GRID-OPERATORS' PERFORMANCE WITH CASCADING FAILURES IN SMART-GRIDS

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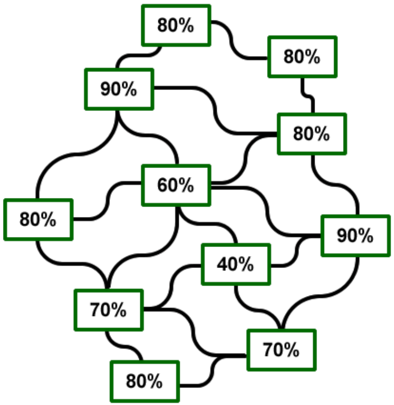
Cascading Failures in Power Grid : Overview



Network running normally

Source: Wikipedia

A few lines/generators trip initially

→ Loads shifted to nearby elements in the system

→ Nearby elements are overloaded beyond their capacity

→ Elements are tripped; load are shifted onto other elements

→ Cascading chain of failures starts, which can lead to system blackout

Outline of the Presentation

- Background works
- Contribution of this work
- Methodology
- Results
- Conclusions and Extensions

Background: *Interdependency between power grid and human operators*

- Coupling between (F, C_{max}) and operator response level, H has been considered while taking into account human-error probability, HEP
- Uses Standardized Plant Analysis Risk-Human Reliability Analysis Method (SPAR-H) to calculate human-error probability (HEP) through performance shaping factors (PSFs)
- Idea: number and maximum capacity of failed transmission lines increase the human-error probability in decision making
- Four operator response levels H_i during a cascading failure in IEEE-118 bus system

Operators' Response	Definition	Available time (respond to contingencies)	Stress (of operators)
Level 1	$F \leq 5$ and $C^{max} \leq 80$MW	Extra time	Nominal
Level 2	$5 < F \leq 10$ or $80\text{MW} < C^{max} < 500$MW	Nominal time	High
Level 3	$10 < F \leq 50$ or $C^{max} \geq 500$MW	Minimum required time	Extreme
Level 4	$F > 50$	Inadequate time	N/A

H_i as a function of (F, C^{max}) =

Level 1 → **Precursor phase**

Level 2 → **Escalation phase**

Level 3 → **Advanced escalation phase**

Level 4 → **Fade-away phase**

1. D. Gertman, H. Blackman, J. Marble, J. Byers, C. Smith et al., "The spar-h human reliability analysis method," US Nuclear Regulatory Commission, 2005
2. 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

Background: *Model included human-error probability calculated from two performance shaping factors*

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

- Operator response level, H, is approximated as an explicit function of the cascading phases, i.e., function of F_i ,

- HEP was considered as an implicit function of two performance-shaping factors (PSFs): **available time** and **stress**

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

Performance-shaping factors and their multipliers (Source: [6])

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)	0.1
Stress/Stressors	Extreme	5
	High	2
	Nominal	1

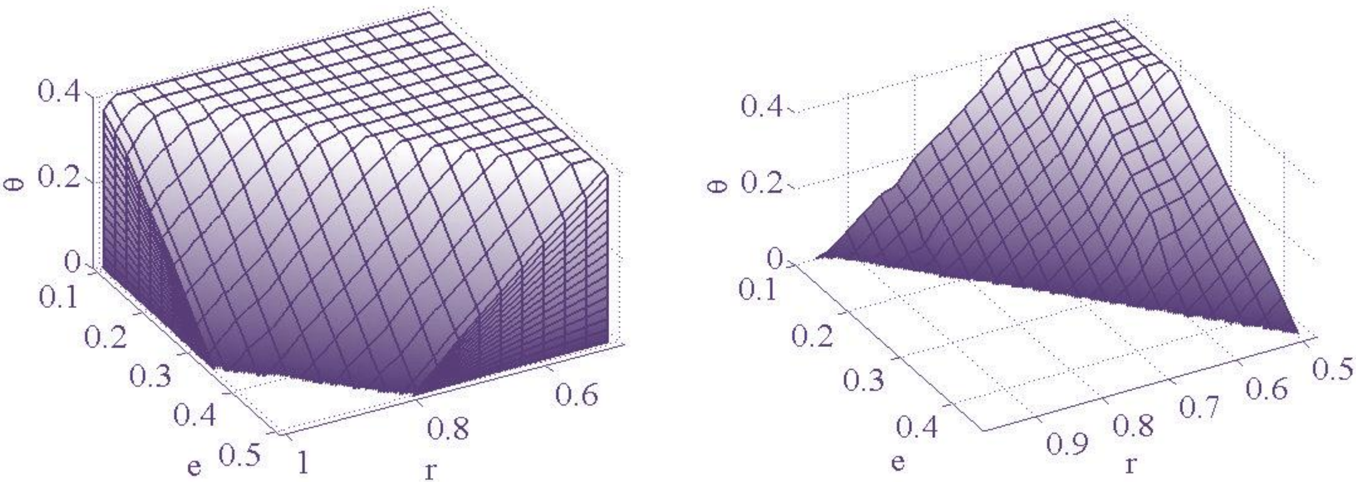
Example

Calculate HEP for state S_i with $H_i = 1$. If H_1 implies nominal time and nominal stress, then $\mathrm{PSF}_1 = 1$ and $\mathrm{PSF}_2 = 1$ for state S_i .Multiplier for diagnosis is 0.01

Hence, **$\mathrm{HEP}(H_i) = 0.01 \bullet 1 \bullet 1 = 0.01$**

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,.
2. Z. Wang, M. Rahnamay-Naeini, J. M. Abreu, R. A. Shuvro, P. Das, A. A. Mammoli, N. Ghani, and M. M. Hayat, "Impacts of Operators' Behavior on Reliability of Power Grids during Cascading Failures," IEEE Transactions on Power Systems, 2018.

Background: Model identifies region of critical grid operating settings that lead to instability



Left: no human error vs Right: with human error

Value of modeling capability: Evaluate different grid designs; understand the effect of control actions, automation; and use of distributed energy resources to increase the grid's reliability.

1. Z. Wang, M. Rahnamay-Naeini, J. M. Abreu, R. A. Shuvro, P. Das, A. A. Mammoli, N. Ghani, and M. M. Hayat, "Impacts of Operators' Behavior on Reliability of Power Grids during Cascading Failures," IEEE Transactions on Power Systems, 2018.

Motivations for this work

- Although more than **10%** large cascading failures occur due to human error, very few efforts capture human error in cascading failure models.

- Although a pioneer work in this front, [1] didn’t capture the detailed human performance factors and **their distributions**, which often mislead in portraying the role of operators.

- [1] considers a very **simple mapping** between grid state and operators’ response levels which is unrealistic.

1. Z. Wang, M. Rahnamay-Naeini, J. M. Abreu, R. A. Shuvro, P. Das, A. A. Mammoli, N. Ghani, and M. M. Hayat, “Impacts of Operators’ Behavior on Reliability of Power Grids during Cascading Failures,” IEEE Transactions on Power Systems, 2018.

Contribution of this work

A detailed mapping is established between Operator error probability and the power grid operating states based on a histogram-equalization principle.

Wide range of operator behavior and their probabilities are captured which increases the fidelity of the model significantly.

Critical PSF level combinations can be identified from various combinations of PSF levels

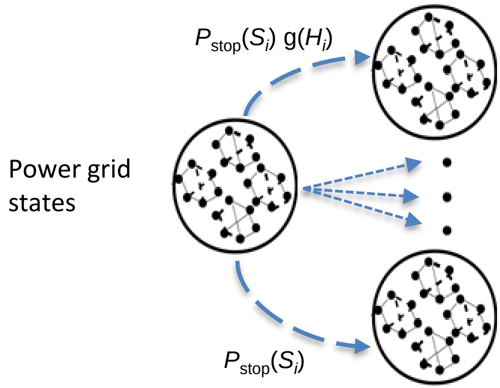
Correlating grid-operators' performance with cascading failures in smart-grids

State variables

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

Human response level, H_i

- ➢ Defined by the PSFs and mapped with F and $C^{\max}$



$$g(H_i) = 1 - \mathrm{HEP}(H_i)$$

$$\mathrm{HEP} = \frac{\mathrm{NHEP}\prod_{i=1}^{8}\mathrm{PSF}_i}{\mathrm{NHEP}\left(\prod_{i=1}^{8}\mathrm{PSF}_i - 1\right) + 1}$$

- The formulation of hSASE was refined to include the distribution of the PSFs calculated empirically
- Distribution of the PSFs are multimodal and affect the HEP calculations
- Grid operators' response levels were mapped with the grid variables of the Markov chain based on a histogram-equalization principle utilizing the probability distribution of the PSFs: ***Pstop* is multiplied by *g*(*H*)**

State transition probabilities of the Markov chain includes human operators' response

Defined in [1]

Factor captures human operator response

$g(H_i) = 1 - \mathrm{HEP}(H_i)$

$$f(S_j|S_i) = \begin{cases} 1 & \text{if } F_j = F_i, C_j^{max} = C_i^{max}, I_j = I_i = 1, \\ P_{stop}(S_i)g(H_i) & \text{if } F_j = F_i, C_j^{max} = C_i^{max}, I_j = 1, \\ P(S_j|S_i) & \text{if } F_j = F_i + 1, C_j^{max} \in \mathcal{C}, I_j = 0, \\ 0 & \text{otherwise.} \end{cases}$$

H_i represents the operator response level defined using the PSFs that are correlated with the propagation of failures

1. Rahnamay-Naeini, M., Wang, Z., Ghani, N., Mammoli, A., & Hayat, M. M. (2014). Stochastic analysis of cascading-failure dynamics in power grids. *IEEE Transactions on Power Systems*, *29*(4), 1767-1779.

Distribution of the PSFs were calculated empirically based on grid operator interviews

Two PSFs in [1]:

- Available time
- Stress

Eight PSFs in new work:

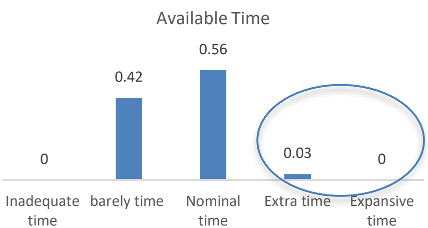
Three state-dependent PSFs:

- Available time
- Stress
- Complexity

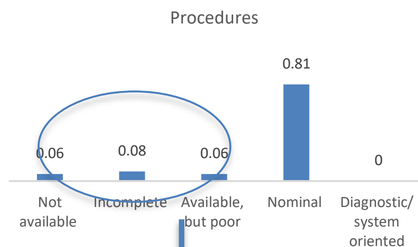
Five state-independent PSFs (used as initial condition)

- Fitness, - Ergonomics,
- Training, - Procedures,
- Work process

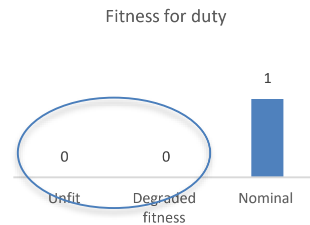
- Distribution of the PSFs were calculated empirically



There are always time constraints



Procedures are mostly available



Operators reported they were always fit.

1. Z. Wang, M. Rahnamay-Naeini, J. M. Abreu, R. A. Shuvro, P. Das, A. A. Mammoli, N. Ghani, and M. M. Hayat, "Impacts of Operators' Behavior on Reliability of Power Grids during Cascading Failures," IEEE Transactions on Power Systems, 2018.

HEP is mapped to each power grid state using histogram equalization technique

Operators response	available time	stress	complexity	HEP	joint probability	grid state(F_i,C_i^{max}), index
level 1	expansive time	nominal	obvious diagnosis	0.0000	0.0000528	(1,20), 1
level 2	expansive time	high	obvious diagnosis	0.0000	0.0000248	(1,20), 1
level 3	expansive time	extreme	obvious diagnosis	0.0001	0.000024	(1,20), 1
level 4	expansive time	nominal	nominal	0.0001	0.0000924	(1,20)-(1,80), (1-3)
level 5	extra time	nominal	obvious diagnosis	0.0001	0.001584	(1,200), 5
...	...	...	...	...	...	...
level 47	barely time	high	moderately complex	0.5025	0.008442	(185,500), 1847
level 48	barely time	extreme	highly complex	0.7163	0.001386	(185,800), 1849

PSFs that are correlated with propagation of failures

Operator response level and grid state mapping

Operator response level

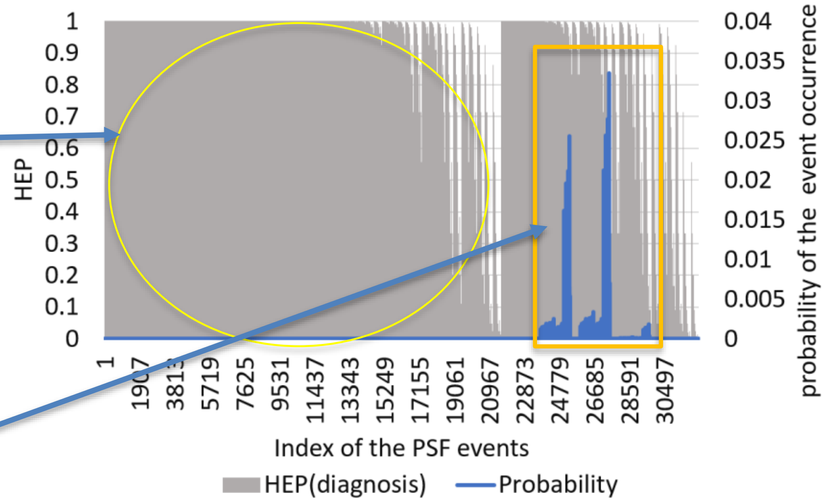
	F=1	F=2	F=3	...	F=185	F=186
$C^{max} = 20$	0.0000	0.0010	.0010	...	0.5025	1
$C^{max} = 80$	0.0001	0.0010	0.0010	...	.5025	1
$C^{max} = 200$	0.0002	0.0010	0.0010	...	.5025	1
$C^{max} = 500$	0.0006	0.0010	0.0010	...	.5025	1
$C^{max} = 800$	0.0010	0.0010	0.0010	...	.7163	1

Using histogram equalization technique, HEP is mapped to each power grid state

The combination of HEP and distribution of PSFs can be used to identify the critical combination of PSF events that have a high probability to occur with a high HEP

- See from Fig. that the grey bar, which represents the HEP is one for many indexes (≥0.9for %61 cases), seems exaggerated.

- However, the blue bar plot reveals that only a handful of those events have a non-zero probability of occurrence.

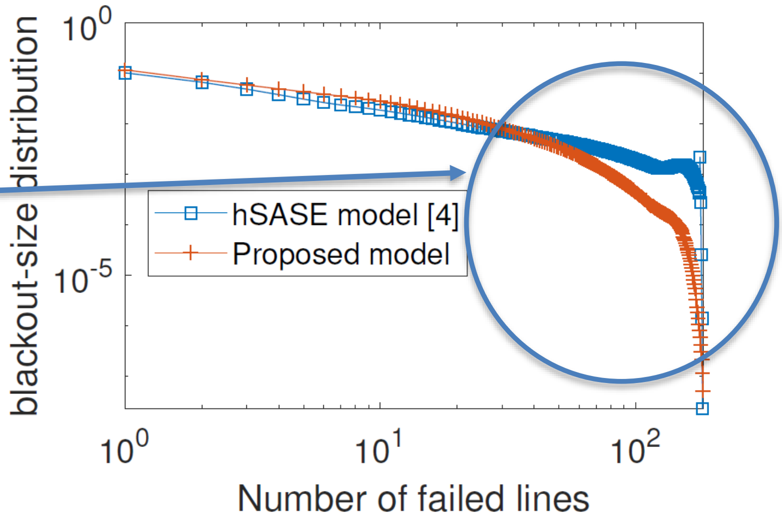


Higher number of transmission line failures and higher capacity of the failed lines

Refined model incorporates a wide range of operator behavior and their probabilities into cascading-failures dynamics

- Blackout size distribution in the refined model is exponential, in contrast to power law distribution in the older model.

- The change in the behavior is a result of deemphasizing the likelihood of the combinations that are less probable



Comparison of blackout size between this work vs hSASE model [1]

1. Z. Wang, M. Rahnamay-Naeini, J. M. Abreu, R. A. Shuvro, P. Das, A. A. Mammoli, N. Ghani, and M. M. Hayat, “Impacts of Operators’ Behavior on Reliability of Power Grids during Cascading Failures,” IEEE Transactions on Power Systems, 2018.

Critical PSF combinations that lead to high HEP

- The combination of HEP and distribution of PSFs are used to identify the critical combination of PSF events that have a high probability to occur with a high HEP.

- Table III contains an example of events that have HEP ≥0.01 and probability of that event occurring ≥ 0.01 are considered.

- Table III indicates, in general, the probability of an event with high HEP is unlikely.

TABLE III
CRITICAL PSF LEVELS WITH JOINT PROBABILITY>0.01 AND HEP >0.01

SL.	Available time		Stress		Complexity		Experience		Procedures		Ergonomics		Fitness		Work process		HEP (diagnosis)	Joint Probability
	PSF multiplier	probability	PSF multiplier	probability	PSF multiplier	probability	PSF multiplier	probability	PSF multiplier	probability	PSF multiplier	probability	PSF multiplier	probability	PSF multiplier	probability		
1	1	0.55	1	0.66	2	0.67	1	0.36	1	0.81	1	0.47	1	1	1	0.69	0.02	0.023
2	1	0.55	2	0.31	2	0.67	0.5	0.53	1	0.81	1	0.47	1	1	1	0.69	0.02	0.016
3	1	0.55	2	0.31	2	0.67	1	0.36	1	0.81	1	0.47	1	1	1	0.69	0.039	0.011
4	10	0.42	1	0.66	2	0.67	0.5	0.53	1	0.81	1	0.47	1	1	1	0.69	0.092	0.026
5	1	0.55	1	0.66	2	0.67	0.5	0.53	1	0.81	10	0.17	1	1	1	0.69	0.092	0.012
6	10	0.42	1	0.66	2	0.67	1	0.36	1	0.81	1	0.47	1	1	1	0.69	0.168	0.018
7	10	0.42	2	0.31	2	0.67	0.5	0.53	1	0.81	1	0.47	1	1	1	0.69	0.168	0.012
8	1	0.55	1	0.66	2	0.67	0.5	0.53	1	0.81	50	0.36	1	1	1	0.69	0.336	0.026
9	1	0.55	1	0.66	2	0.67	1	0.36	1	0.81	50	0.36	1	1	1	0.69	0.503	0.018
10	1	0.55	2	0.31	2	0.67	0.5	0.53	1	0.81	50	0.36	1	1	1	0.69	0.503	0.012
11	10	0.42	1	0.66	2	0.67	0.5	0.53	1	0.81	50	0.36	1	1	1	0.69	0.835	0.02
12	10	0.42	1	0.66	2	0.67	1	0.36	1	0.81	50	0.36	1	1	1	0.69	0.91	0.013

Conclusions and Extensions

- Model incorporates a wide range of operator behavior and their probabilities into cascading-failures dynamics.

- A detailed mapping between power grid states and operators' response has been established that allows to capture the operators' role in the dynamics of the Markov chain.

- Critical combination of human attributes are identified that have:

    - **High human error probability**
    - **Higher probability to occur**

- Currently we are working on a comprehensive interdependent cascading failure model including power grid, communication network and operators in the loop.

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