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POLITECNICO MILANO 1863

A ROBUST ENERGY SYSTEM UNDER UNCERTAINTY: MULTI-LEVEL OPTIMIZATION-BASED FRAMEWORKS

Presented by

Amin Abedi

Institute for Environmental Sciences (ISE), UNIGE, Switzerland
Laboratory of signal and risk analysis
Energy department, Politecnico di Milano, Italy

A brief bio

- Ongoing–Postdoc researcher (Remotely in Ann Arbor)

Politecnico di Milano, Energy department, Laboratory of signal and risk analysis
Prof. Enrico Zio (lab leader)
Topic of research: Enhancing the Robustness of the IEGS Considering the Bidirectional Physical-Economic Interdependencies: A Quasi Steady-State Multilevel Optimization Model.

- PhD in Science- Environmental Science-Energy section (Defended, 31.03.2021)

Institute for Environmental Sciences, University of Geneva, Switzerland
Topic of research: Optimization-based Frameworks for Systemic Vulnerability Assessment in the Electric Power Systems.

- M.Sc. in Energy Engineering,

Sharif university of technology, ENERGY Department

- B.Sc. in Electrical Engineering-power electrical engineering

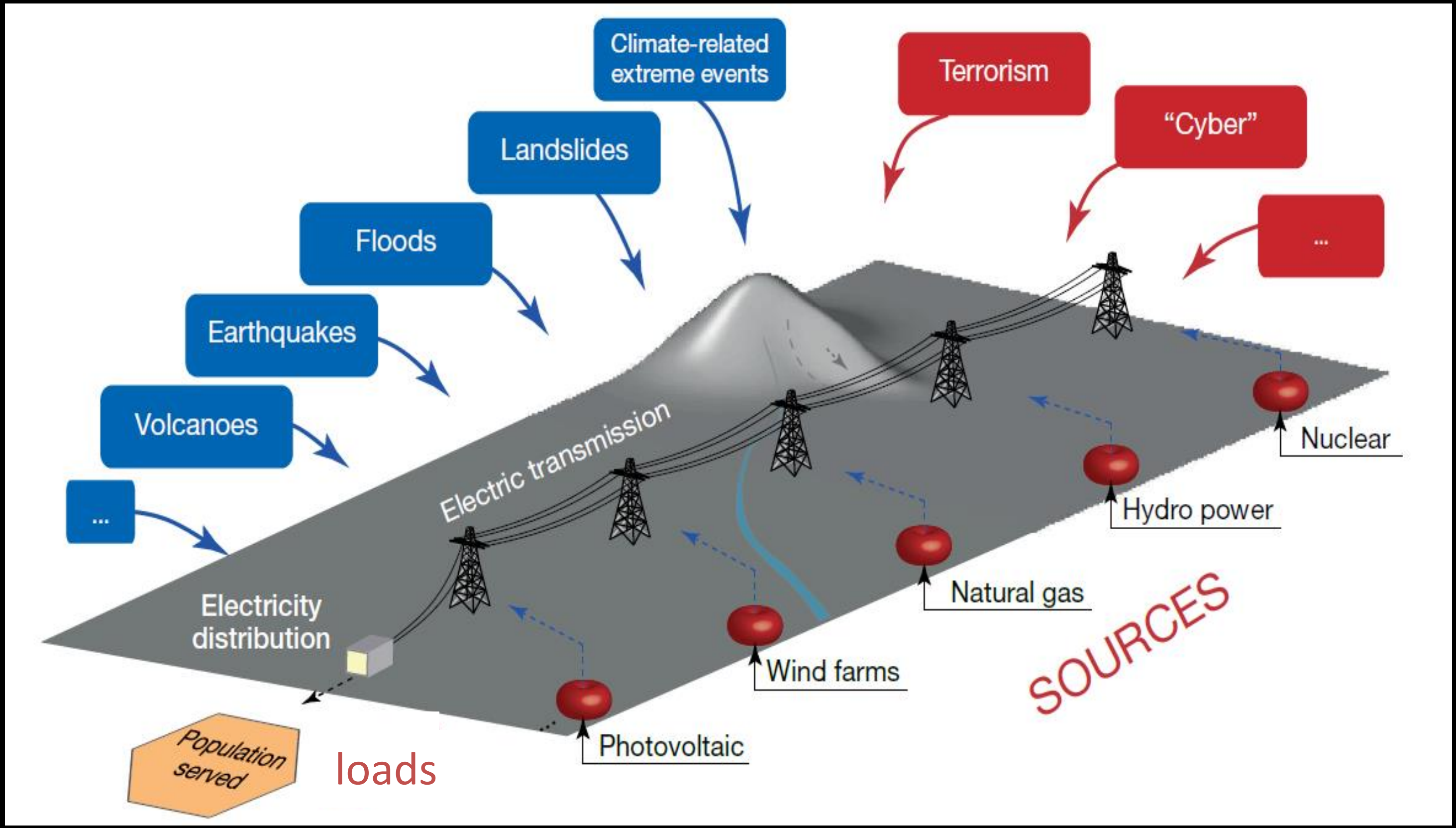
Power system and its different hazards

Intro

AC based approach

Vulnerability & uncertainty

Questions



Ref: Komendantova, Nadejda, et al. *Protecting Electricity Networks from Natural Hazards*. Organization for Security and Cooperation in Europe (OSCE), 2016

Power system and High-impact, Low-probability Events

United States

- Intro
- AC based approach
- Vulnerability & uncertainty
- Questions

Flood (aftermath of Hurricane Florence, 2018)

- Ice storm
- Snow storm
- Wind storm
- Lighting
- Flood

Climate change

Economic upswing

Mega cities

Increased demand

Heat waves

Blackout

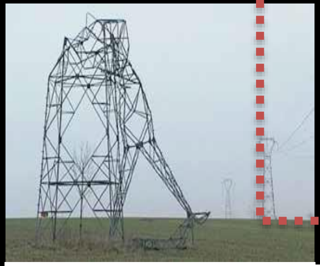
- Lack of cooling water
- Lack of hydro capacity

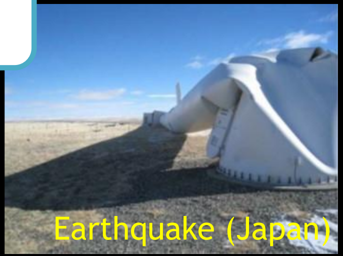
Failure of transmission

Failure of production

- Terrorism
- Earthquake
- Construction defects
- Operating errors
- Lack of investment
- Aging infrastructure

Metcalf Substation (April 2013)





Earthquake (Japan)

France: Storms in 1999

Ice crusts Austria, in winter 2014

Ukraine attack (Dec 2015-2016)
First by hackers

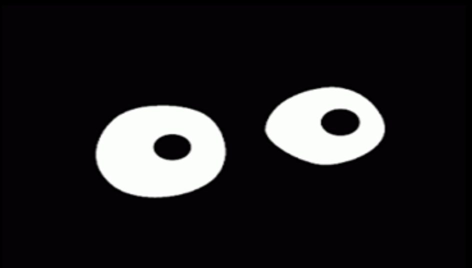
Blackout: the loss of supply to the load in the entire power system, or parts of the system,
Cascading failures: a sequence of dependent outages of individual components that successively weakens the power system.

Ref:Marika; Bruckner, Thomas (2018) : Causes and effects of historical transmission grid collapses and implications for the German power system, Beiträge des Instituts für Infrastruktur und Ressourcenmanagement
Komendantova, Nadejda, et al. *Protecting Electricity Networks from Natural Hazards*. Organization for Security and Cooperation in Europe (OSCE), 2016

Economic loss to sense the consequences

No.	Country	Year	Load loss (GW)	Economic loss	People affected (*Million)
1	USA, Canada	2003	61.8	$ 6.4 billion	50
2	Italy	2003	24	Over €120 million	~56
3	Russia	2005	~3.5	$ 1-2 billion	4
4	USA and Mexico	2011	4.3	Up to $118 million	Over 5

In the USA, the annual cost of weather-related blackouts ranges from $20 to $55 billion.



VSE reported the costs of a blackout which is 2–4 billion CHF per day. For comparison, the Swiss GDP per day was (2012) 2.4 billion CHF.

Ref: VSE, *Wege in die neue Stromzukunft Gesamtbericht* 2012, Verband Schweizerischer Elektrizitätsunternehmen (VSE), Aarau.
Abedi, A., L. Gaudard, and F. Romerio-Giudici, Review of major approaches to analyze vulnerability in power system. Reliability Engineering and System Safety, 2019. 183: p. 153-172.

So…

The past blackout reports

N-1 criteria is not enough

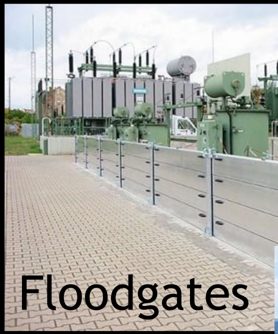
Secure for all possible outages

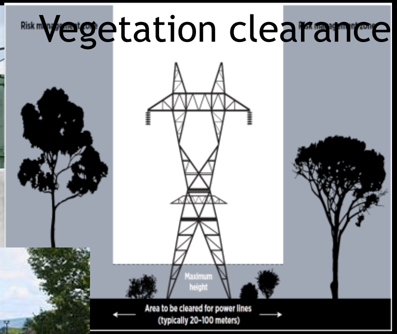
lessons learned from the past blackouts

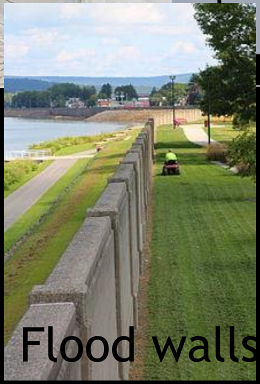
The outages don't have the same consequences

Find combinations of assets that their simultaneous outages cause more damage to the system (N-2,N-3,…)

Focus on those Critical assets that their simultaneous outages lead to major damage and then try to harden them "proactively" based on their exposed hazards







Measures to harden infrastructure

Adding assets VS. Braess paradox

N-1 security criterion: If any single component fails, the loads can be restored without load shedding

Ref: https://en.wikipedia.org/wiki/North_American_power_transmission_grid

Arulampalam Atputharajah,Tapan Kumar Saha,Power System Blackouts - Literature review, *2009*

So…

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Intro

AC based approach

Vulnerability & uncertainty

Questions

Find combinations of assets that their simultaneous outages cause more damage to the system (N-2,N-3,…)

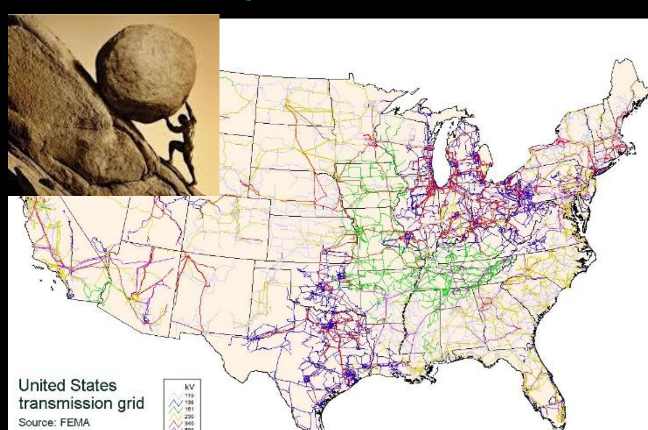
Introducing an index and ranking all assets based on that index OR enumeration

Developing models to directly find the worse case scenario or the critical assets

N=1000

- N-1=1000 cases
- N-2=499000 cases
- N-3=160 million cases
- N-4=40 billion cases
- …

$$\binom{n}{k} = \frac{n!}{k!(n-k)!}$$



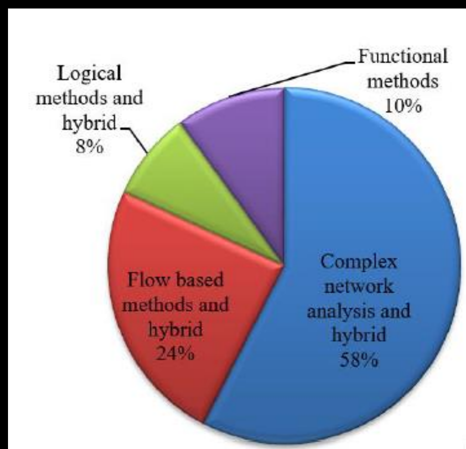
Follower

Leader

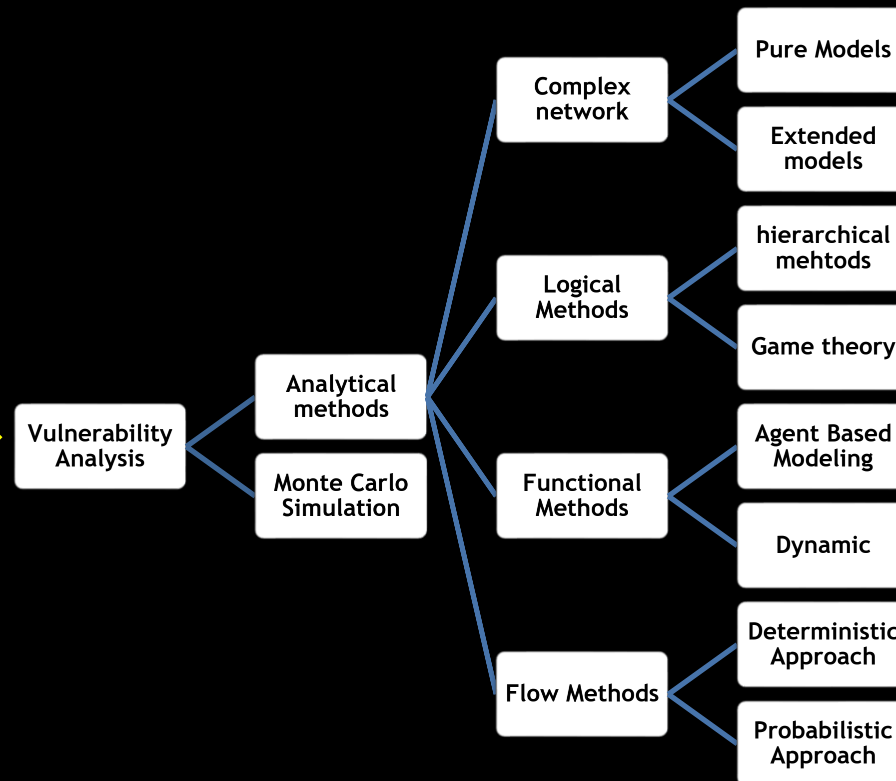
Ref: https://en.wikipedia.org/wiki/North_American_power_transmission_grid, Abedi, A. and F. Romerio, Multi-period vulnerability analysis of power grids under multiple outages: An AC-based bilevel optimization approach. International Journal of Critical Infrastructure Protection, 2020: p. 100365.

Methods for Vulnerability analysis

About 300 articles reviewed and about 100 summarized in four tables

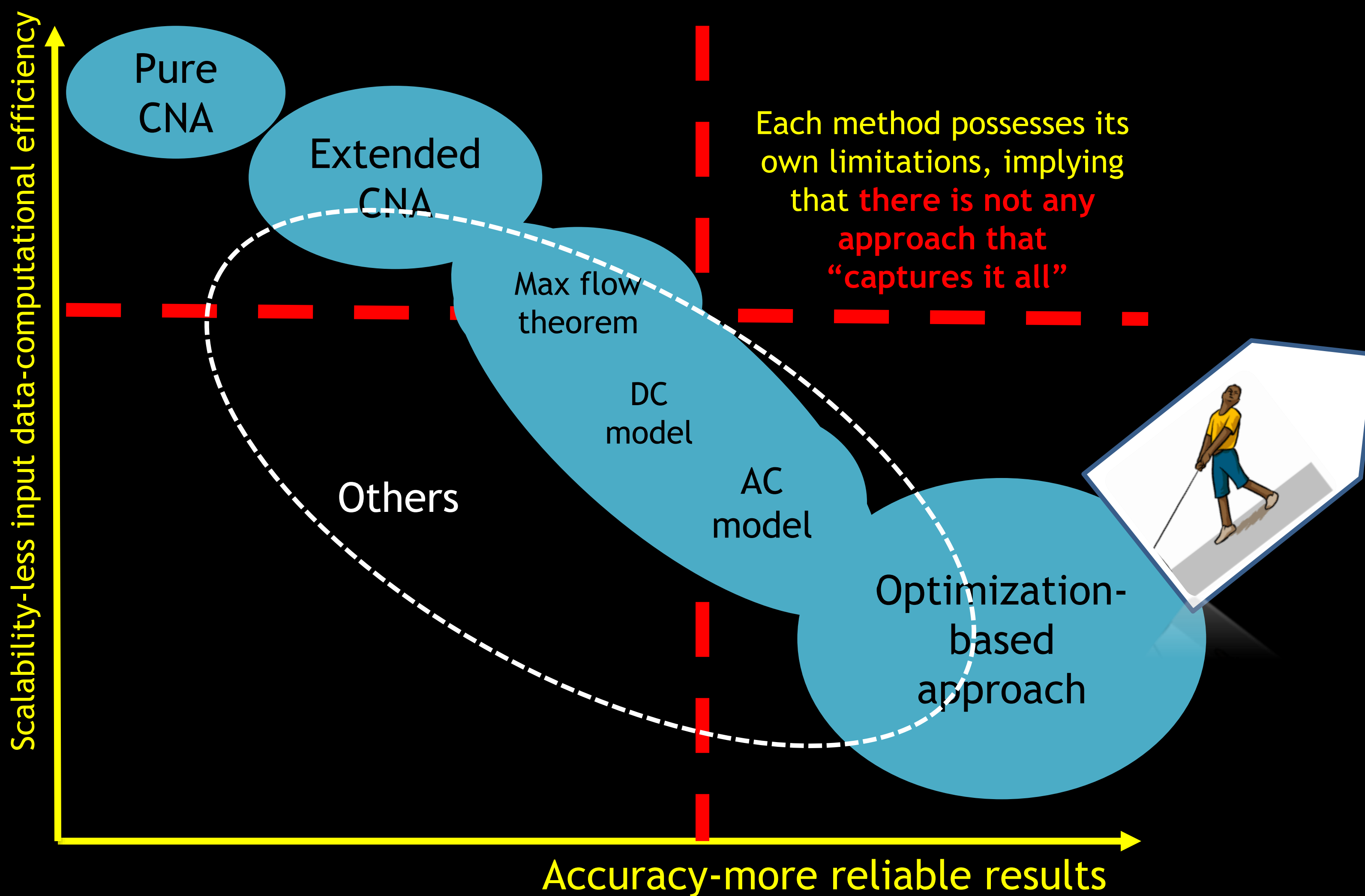


- ❖ The methodology used,
- ❖ Assumptions,
- ❖ Test cases,
- ❖ Failure scenarios, and
- ❖ Modeling capability



Ref:. Abedi, A., L. Gaudard, and F. Romerio-Giudici, Review of major approaches to analyze vulnerability in power system. Reliability Engineering and System Safety, 2019. 183: p. 153-172.

Comparison of methods



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Leader-follower approach as a good solution

Follower

(2) Leader announces its strategy

Leader

(3) Follower observes the leader's action and adapts its strategy so as to minimize its own cost

(4) Follower announces its strategy

(1) Leader optimizes its strategy given the follower's actions

Ref: Abedi, A., M.R. Hesamzadeh, and F. Romerio, An ACOPF-based bilevel optimization approach for vulnerability assessment of a power system. International Journal of Electrical Power & Energy Systems, 2021. 125: p. 106455.

Leader-follower approach as a good solution

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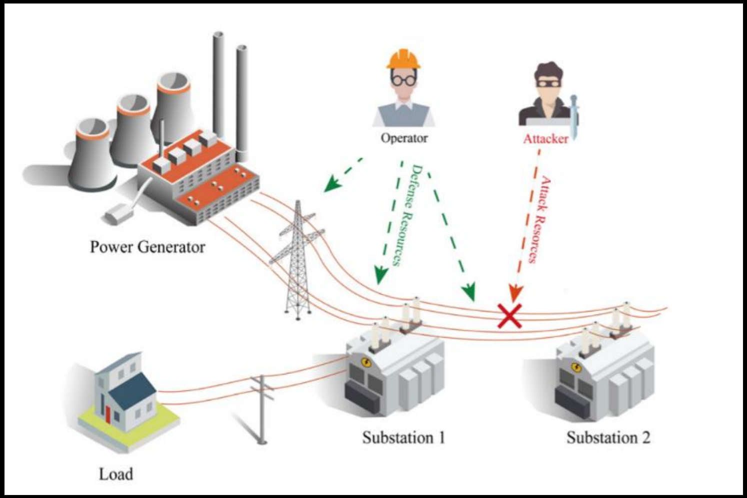
Questions

Follower		Leader
Consumer	Economy	Producer
Factory owner	Taxation	Government
Defender	Security	Attacker



Ref: GAO et al. Modeling an Attack-Mitigation Dynamic Game-Theoretic Scheme for Security Vulnerability Analysis in a Cyber-Physical Power System, IEEE Access, 2020

Leader-follower approach as a good solution

Follower

Leader

General form of a bilevel problem to show a leader follower structure

$$\min_{x \in X} F(x, y) = c_1 x + d_1 y$$

subject to $A_1 x + B_1 y \leq b_1$

$$\min_{y \in Y} f(x, y) = c_2 x + d_2 y$$

subject to $A_2 x + B_2 y \leq b_2$

An optimization problem that contains another optimization problem as a constraint

Ref: Abedi, A., M.R. Hesamzadeh, and F. Romerio, An ACOPF-based bilevel optimization approach for vulnerability assessment of a power system. International Journal of Electrical Power & Energy Systems, 2021. 125: p. 106455.

A real bilevel example

$$\min_{x\in X} F(x,y) = c_1x + d_1y$$
subject to $A_1x + B_1y \le b_1$
$$\min_{y\in Y} f(x,y) = c_2x + d_2y$$
subject to $A_2x + B_2y \le b_2$

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Intro

AC based approach

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Questions

These problems are also known as the hierarchical leader-follower problem or Stackelberg game.

AC-OPF

$$\mathop{Max}_{z} \sum_{i\in N} Ls_i^*$$ Total load shedding

MIBNLP

$$\text{s.t.} \quad 0.5\times\sum_{i,j\in N}(1-z_{ij}) = NPO; \quad z_{ij}\in\{0,1\} \quad \forall i,j\in N$$

$$z_{ij} = z_{ji}; \quad z_{ij}\in\{0,1\} \quad \forall i,j\in N$$

$$\text{where: } \sum_{i\in N} Ls_i^* \in \arg\left\{ \mathop{Min}_{\substack{Pg,Qg,Ls,Lsq,\\ P,Q,V,\theta}} \sum_{i\in N} Ls_i \right\}$$

$$\text{s.t.} \quad Pg_{i|i\in G} + Ls_{i|i\in D} - Pd_{i|i\in D} = \sum_{j\in N} P_{ij}; \quad \forall i,j\in N:(\alpha_i)$$

$$Qg_{i|i\in G} + Lsq_{i|i\in D} - Qd_{i|i\in D} = \sum_{j\in N} Q_{ij}; \quad \forall i,j\in N:(\beta_i)$$

$$P_{ij} = z_{ij}\left(V_i^2 G_{ij} - V_iV_j(G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij})\right); \quad \forall i,j\in N:(\lambda_{ij})$$

$$Q_{ij} = z_{ij}\left(-V_i^2\left(B_{ij} + \frac{B_{ij}^{sh}}{2}\right) - V_iV_j(G_{ij}\sin\theta_{ij} - B_{ij}\cos\theta_{ij})\right); \quad \forall i,j\in N:(\mu_{ij})$$

$$0 \le Pg_i \le Pg_i^{max}; \quad \forall i\in G:(\overline{\delta_i})$$

$$Qg_i^{min} \le Qg_i \le Qg_i^{max}; \quad \forall i\in G:(\underline{\sigma_i},\overline{\sigma_i})$$

$$(P_{ij})^2 + (Q_{ij})^2 \le (S_{ij}^{max})^2; \quad \forall i,j\in N$$

$$V_i^{min} \le V_i \le V_i^{max}; \quad \forall i\in N:(\underline{\upsilon_i},\overline{\upsilon_i})$$

$$\theta_{ij}^{min} \le \theta_{ij} \le \theta_{ij}^{max}; \quad \forall i,j\in N$$

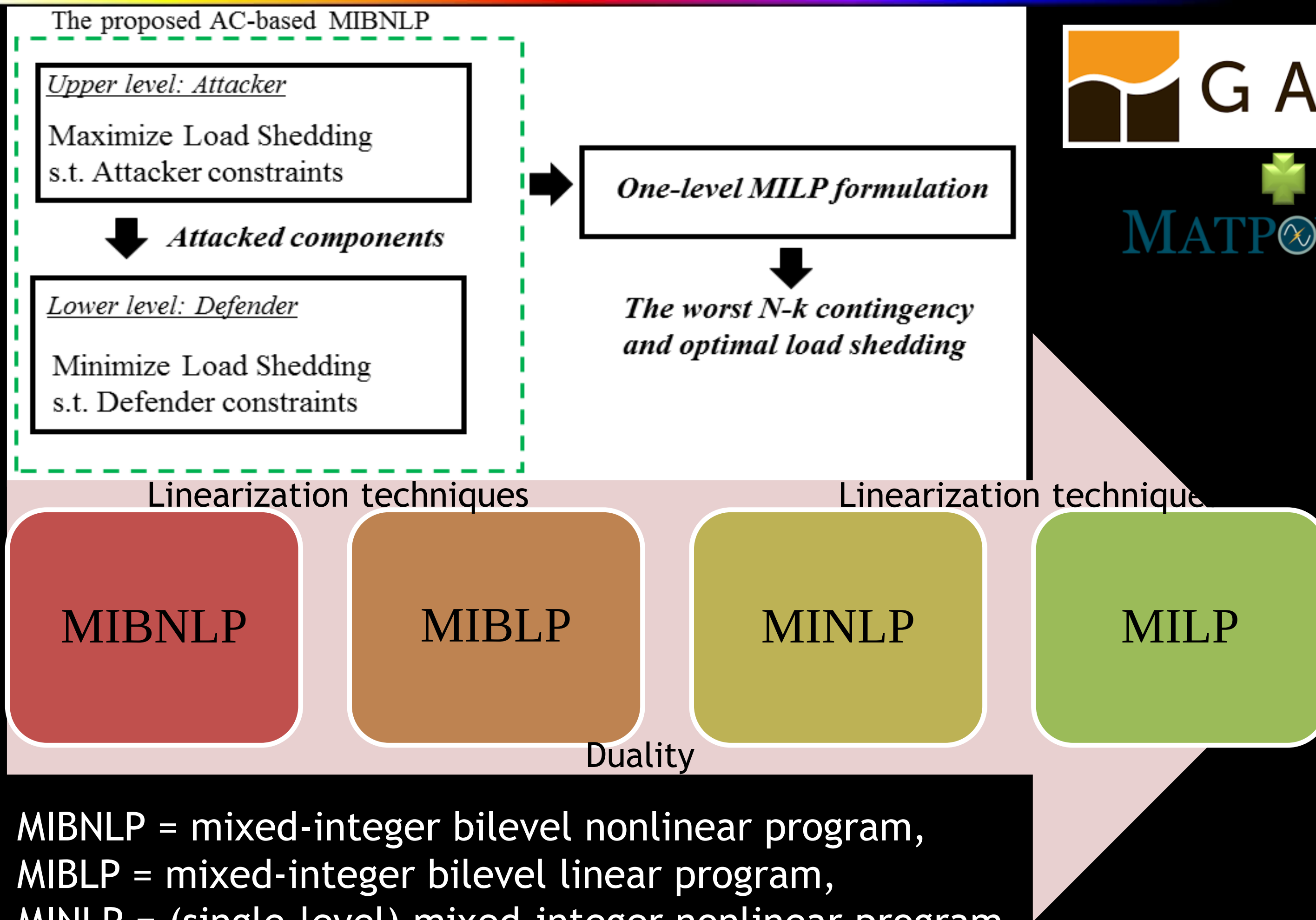
$$0 \le Ls_i \le Pd_i; \quad \forall i\in D:(\overline{\omega_i})$$

$$Lsq_i = Ls_i \tan\phi_i; \quad \forall i\in D$$

Non linear equations

Ref: Abedi, A., M.R. Hesamzadeh, and F. Romerio, An ACOPF-based bilevel optimization approach for vulnerability assessment of a power system. International Journal of Electrical Power & Energy Systems, 2021. 125: p. 106455.

Methods and scenarios



MIBNLP = mixed-integer bilevel nonlinear program,
MIBLP = mixed-integer bilevel linear program,
MINLP = (single-level) mixed-integer nonlinear program,
MILP = mixed-integer linear program,
GAMS= General Algebraic Modeling System platform

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Linearization techniques

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Intro

AC based approach

Vulnerability & uncertainty

Questions

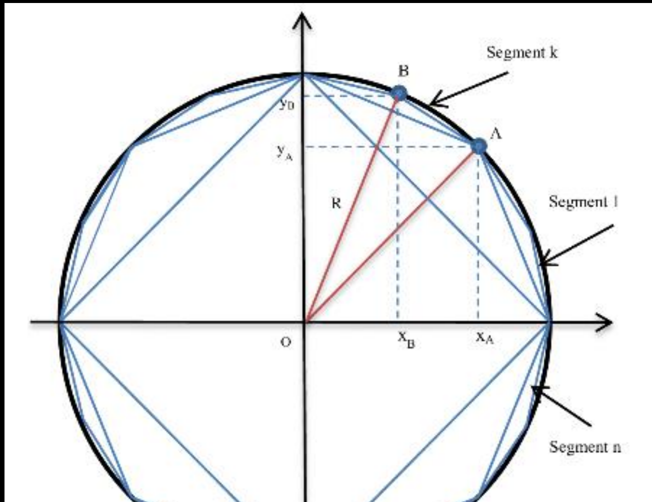
$$\left(P_{ij}\right)^2+\left(Q_{ij}\right)^2\le\left(S_{ij}^{\max}\right)^2;\quad \forall i,j\in N$$

$$P_{ij}=z_{ij}\left(V_i^2G_{ij}-V_iV_j\left(G_{ij}\cos\theta_{ij}+B_{ij}\sin\theta_{ij}\right)\right);\quad \forall i,j\in N:(\lambda_{ij})$$

$$Q_{ij}=z_{ij}\left(-V_i^2\left(B_{ij}+\frac{B_{ij}^{sh}}{2}\right)-V_iV_j\left(G_{ij}\sin\theta_{ij}-B_{ij}\cos\theta_{ij}\right)\right);$$

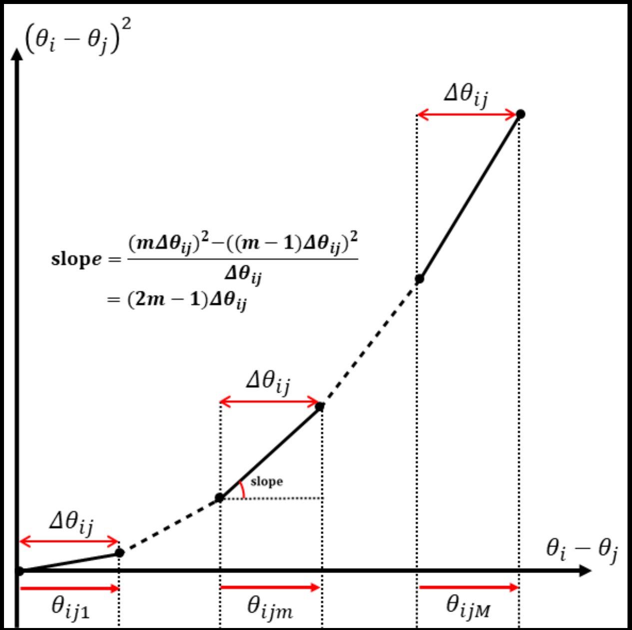
Bilinear terms

N-sided convex regular polygon



$$\left(\sin\left(\frac{2\pi k}{n}\right)-\sin\left(\frac{2\pi(k-1)}{n}\right)\right)P_{ij}-\left(\cos\left(\frac{2\pi k}{n}\right)-\cos\left(\frac{2\pi(k-1)}{n}\right)\right)Q_{ij}$$
$$-S_{ij}^{\max}\sin\left(\frac{2\pi}{n}\right)^{\eta_{k,l}}\le 0;\quad k=1\cdots n,\forall i,j\in N$$

Piecewise linear (PWL)



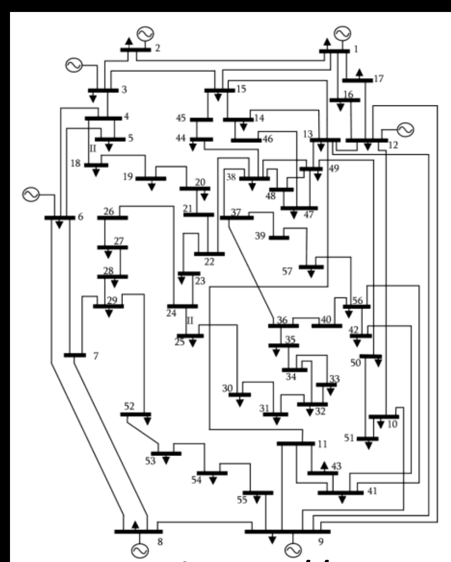
Big-M technique

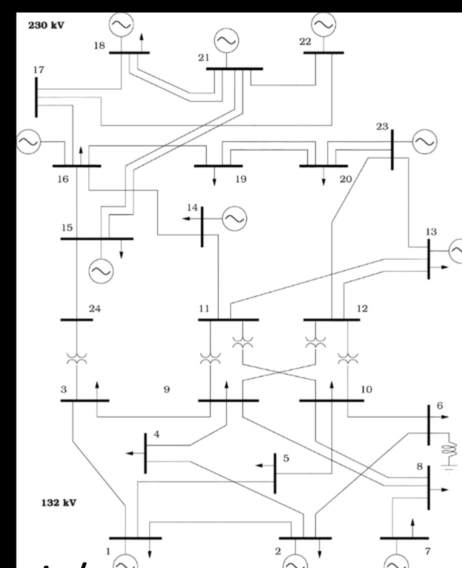
Ref: Abedi, A., M.R. Hesamzadeh, and F. Romerio, An ACOPF-based bilevel optimization approach for vulnerability assessment of a power system. International Journal of Electrical Power & Energy Systems, 2021. 125: p. 106455.

Test systems

IEEE 57-bus : 57 buses, 7 generators, and 80 branches and transformers

IEEE 24-bus reliability test systems (RTS): 24 buses, 32 generators, and 38 branches and transformers





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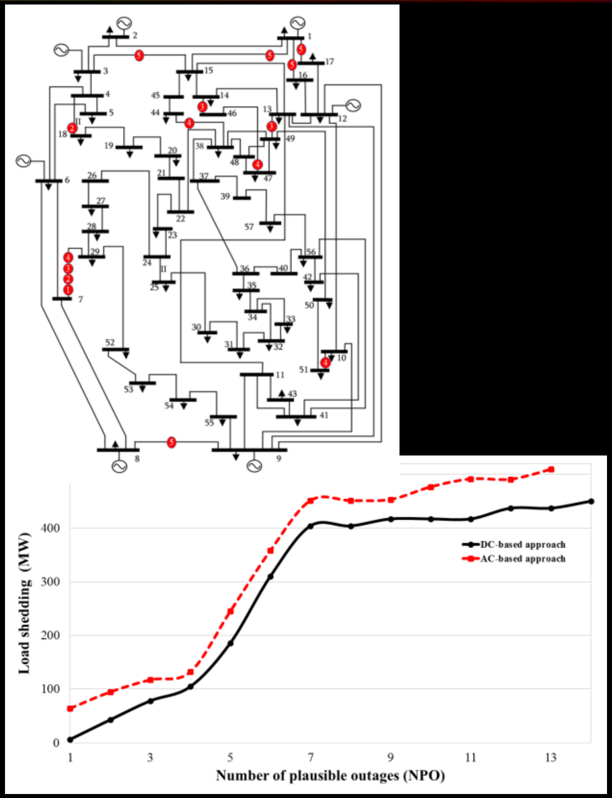
IEEE 57-bus system



NPO	DCOPF-based approach*	LS (MW)	ACOPF-based approach	LS (MW)	JSI
1	25-30	6	7-29	64	0
2	1-16, 12-16	43	4-18, 7-29	95	0
3	7-29, 9-55, 21-22	78	7-29, 13-49, 14-46	118	0.2
4	7-29, 8-9, 12-17, 21-22	105	7-29, 10-51, 38-44, 46-47	132	0.1
5	1-16, 7-29, 8-9, 12-17, 21-22	186	1-15, 1-16, 1-17, 3-15, 8-9	245	0.3

*** This approach is also used with different objective functions and case studies in [347, 352-354].**

The five worst-case load shedding scenarios and their related lines for the IEEE 57-bus system calculated using our MILP model

Ref: Abedi, A., M.R. Hesamzadeh, and F. Romerio, An ACOPF-based bilevel optimization approach for vulnerability assessment of a power system. International Journal of Electrical Power & Energy Systems, 2021. 125: p. 106455.

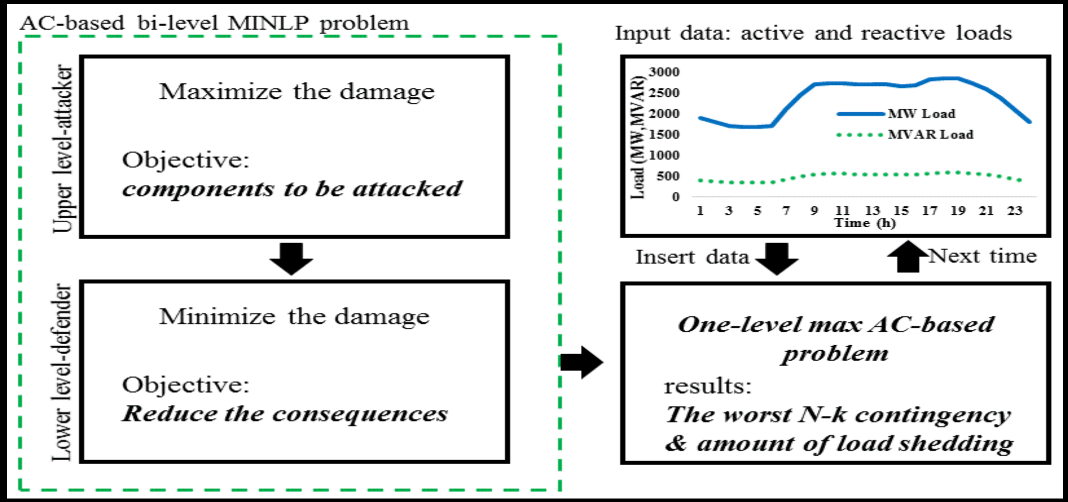
Trigger point for Chapter 6
(Peak load and Load profile)

Peak load

Load profile

Ref: Abedi, A. and F. Romerio, Multi-period vulnerability analysis of power grids under multiple outages: An AC-based bilevel optimization approach. International Journal of Critical Infrastructure Protection, 2020: p. 100365.

Methods and scenarios



Linearization techniques

Linearization techniques

MIBNLP → MIBLP → MINLP → MILP

Duality theory

MIBNLP=mixed-integer bilevel nonlinear program,
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Test system

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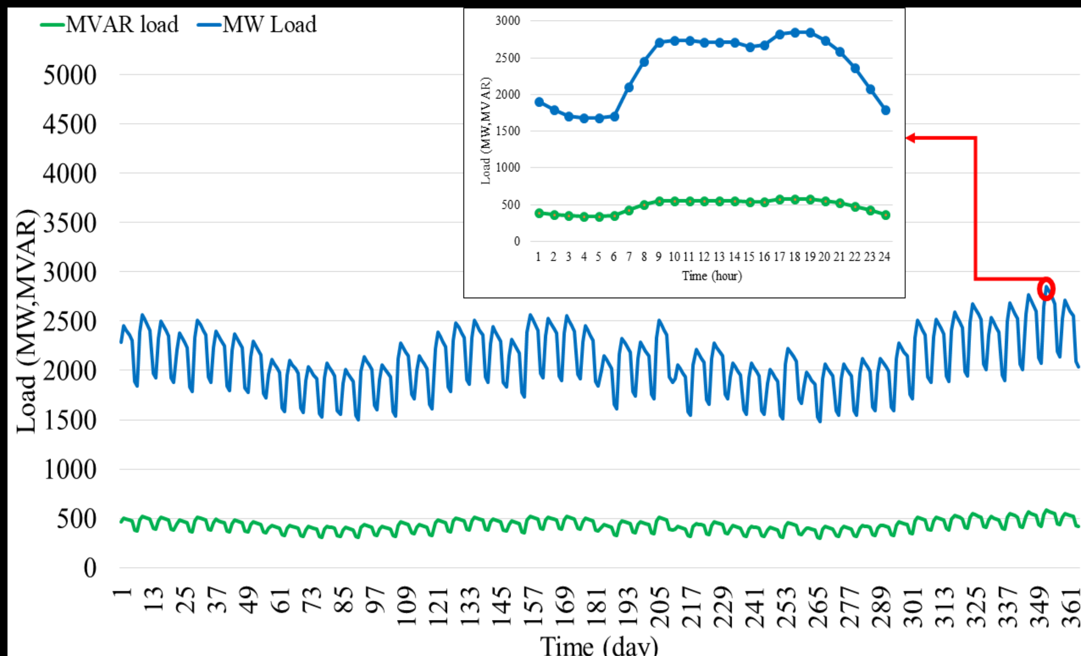
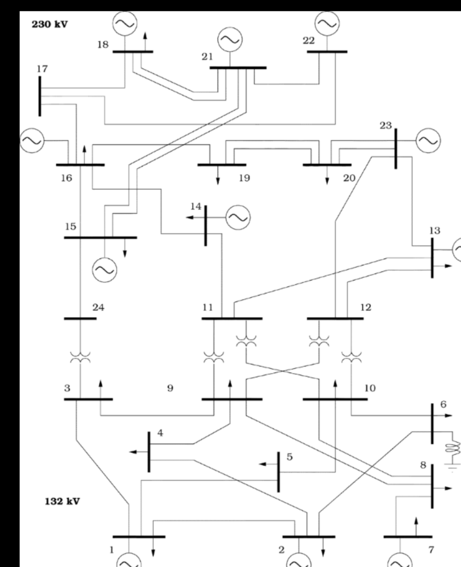
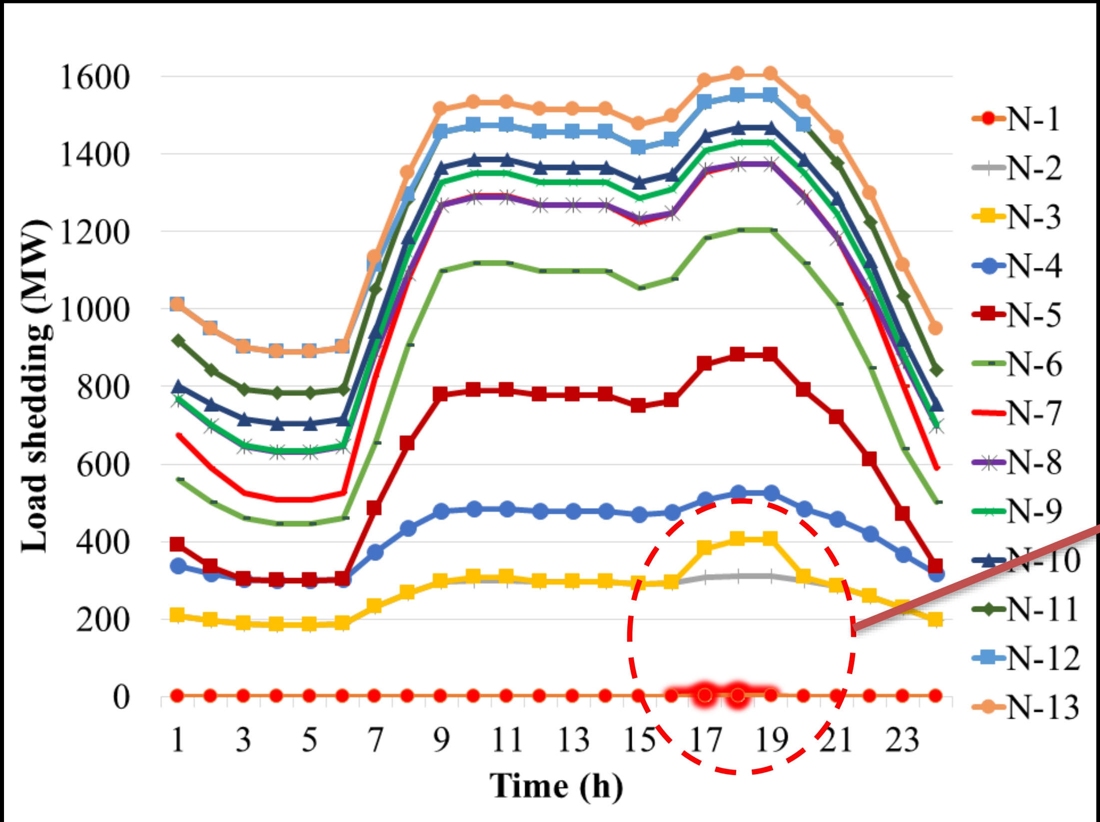
IEEE 24-bus reliability test systems (RTS): 24 buses, 32 generators, and 38 branches and transformers





Ref: Abedi, A. and F. Romerio, Multi-period vulnerability analysis of power grids under multiple outages: An AC-based bilevel optimization approach. International Journal of Critical Infrastructure Protection, 2020: p. 100365.

Effects of the contingencies with hourly peak loads

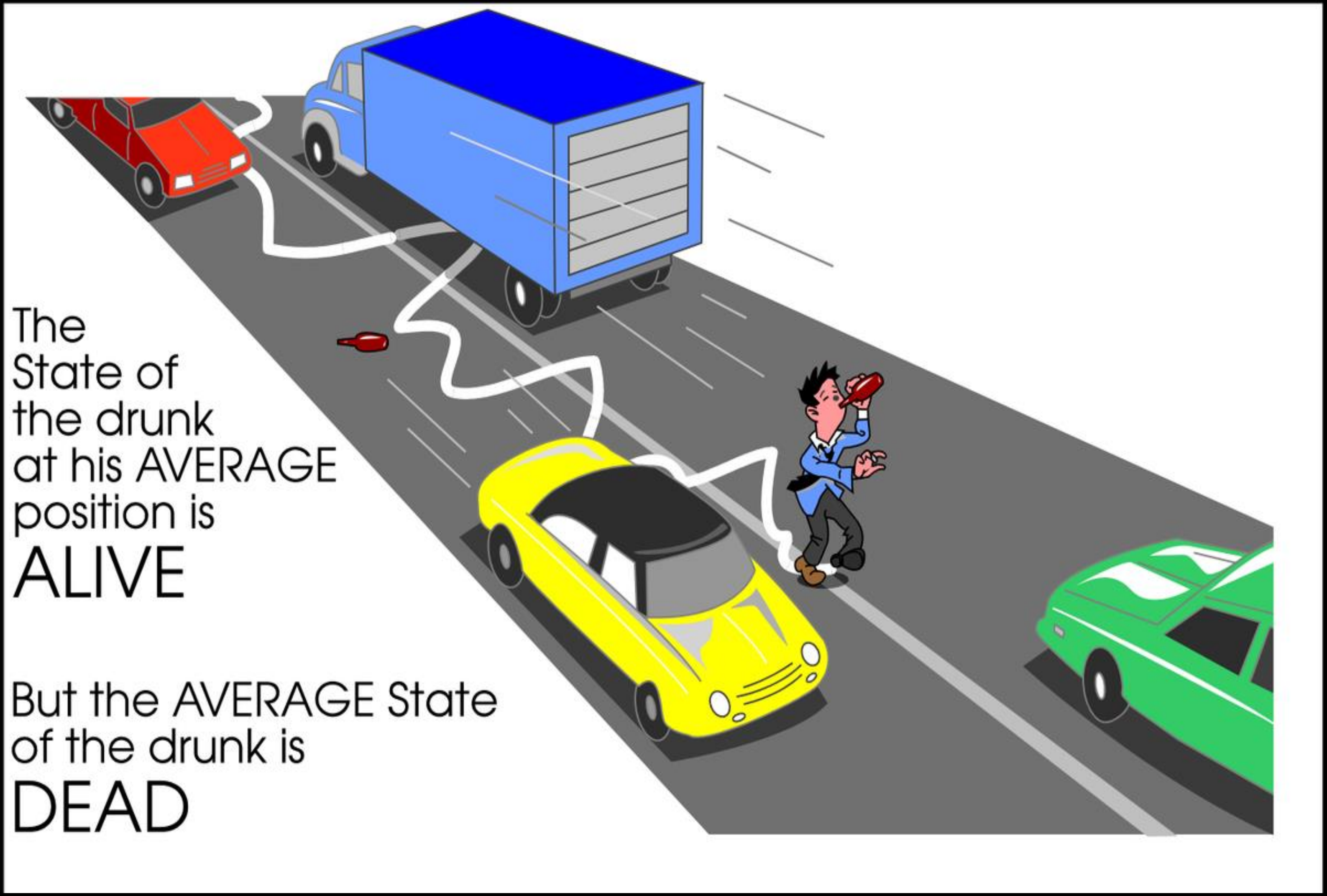


Let us to use load management or even increasing efficiency as one of the measures for increasing robustness.

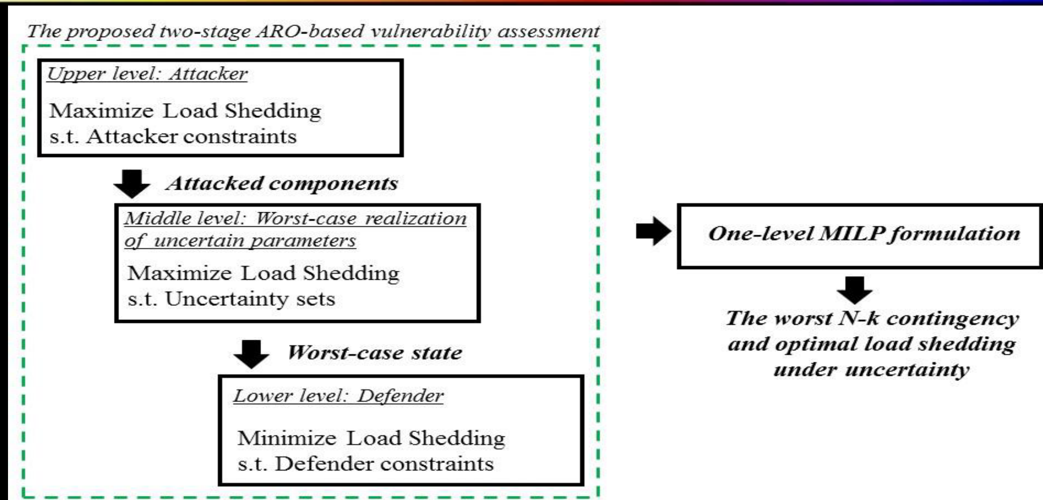
"where and which" as well as "when" the system is more vulnerable?

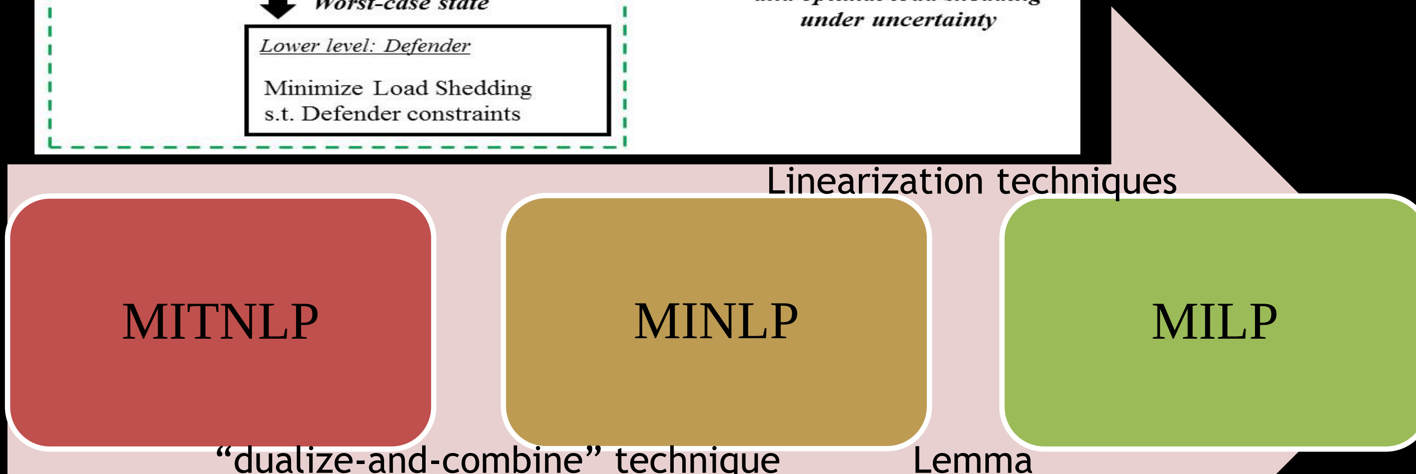
Ref: Abedi, A. and F. Romerio, Multi-period vulnerability analysis of power grids under multiple outages: An AC-based bilevel optimization approach. International Journal of Critical Infrastructure Protection, 2020: p. 100365.

Trigger point
(Security assessment and average data)



Methods and scenarios





MITNLP =mixed-integer trilevel nonlinear program,
MINLP =(single-level) mixed-integer nonlinear program,
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Formulation and Uncertainty Characterization

Intro

AC based approach

Vulnerability & uncertainty

Questions

$$\underset{Z}{Maximize}\sum_{i\in N} Ls_i^{**} \tag{7-2}$$

subject to:

$$0.5\times\sum_{i,j\in N}(1-z_{ij}) = NPO;\quad z_{ij}\in\{0,1\}\quad \forall i,j\in N \tag{7-3}$$

$$z_{ij}=z_{ji};\quad z_{ij}\in\{0,1\}\quad \forall i,j\in N \tag{7-4}$$

where:

$$\sum_{i\in N} Ls_i^{**}\in\arg\left\{\underset{\tilde{P}g,\tilde{P}d}{Maximize}\sum_{i\in N}Ls_i^{*}\right\} \tag{7-5}$$

subject to:

$$\bar{P}g_i-\hat{P}g_i\le\tilde{P}g_i\le\bar{P}g_i+\hat{P}g_i;\quad \forall i\in G \tag{7-6}$$

$$\sum_{i\in G}\left|\frac{\tilde{P}g_i-\bar{P}g_i}{\hat{P}g_i}\right|\le DR^{g};\quad \forall i\in G \tag{7-7}$$

$$\bar{P}d_i-\hat{P}d_i\le\tilde{P}d_i\le\bar{P}d_i+\hat{P}d_i;\quad \forall i\in D \tag{7-8}$$

$$\sum_{i\in D}\left|\frac{\tilde{P}d_i-\bar{P}d_i}{\hat{P}d_i}\right|\le DR^{d};\quad \forall i\in D \tag{7-9}$$

where:

$$\sum_{i\in N} Ls_i^{*}\in\arg\left\{\underset{Pg,Ls,P,\theta}{Minimize}\sum_{i\in N}Ls_i\right\} \tag{7-10}$$

subject to:

$$Pg_{i|i\in G}+Ls_{i|i\in D}-\tilde{P}d_{i|i\in D}=\sum_{j\in N}P_{ij};\quad \forall i\in N:(\lambda_i) \tag{7-11}$$

$$P_{ij}=z_{ij}B_{ij}\theta_{ij},\theta_{ij}=\theta_i-\theta_j;\quad \forall i,j\in N:(\mu_{ij}) \tag{7-12}$$

$$0\le Pg_i\le\tilde{P}g_i;\quad \forall i\in G:(\overline{\gamma}_i) \tag{7-13}$$

$$-S_{ij}^{\max}\le P_{ij}\le S_{ij}^{\max};\quad \forall i,j\in N:(\underline{\varphi}_{ij},\overline{\varphi}_{ij}) \tag{7-14}$$

$$-\theta_i^{\max}\le\theta_i\le\theta_i^{\max};\quad \forall i\in N:(\underline{\omega}_i,\overline{\omega}_i) \tag{7-15}$$

$$0\le Ls_i\le\tilde{P}d_i;\quad \forall i\in D:(\overline{\alpha}_i) \tag{7-16}$$

Uncertainty definition:

- Two set of equations for loads and generations,
- DRs are the budget of uncertainty,
- an interval

The lemma and its results

$$\underset{\substack{\lambda_i,\mu_{ij},\overline{\alpha}_i,\overline{\omega}_i,\\ \underline{\omega}_i,\overline{\gamma}_i,\underline{\varphi}_{ij},\overline{\varphi}_{ij}}}{Maximize}\left(\sum_{i\in N}(\lambda_i+\overline{\alpha}_i)\tilde{P}d_{i|i\in D}+\sum_{i\in G}\overline{\gamma}_i\tilde{P}g_i+\sum_{i,j\in N}(\overline{\varphi}_{ij}-\underline{\varphi}_{ij})S_{ij}^{\max}+\sum_{i\in N}(\overline{\omega}_i-\underline{\omega}_i)\theta_i^{\max}\right)$$

Products of two continuous variables

lemma: "An optimal solution of the middle problem is when the uncertain parameters reach either upper or lower bounds."

Model statistics		**Binary expansion formulation**	**Extreme points**
Single equations		3121	1046
Single variables		1906	766
Binary variables		409	130
Average elapsed time/simulation (sec)*	scenario I	5.2	0.9
	scenario II	11.2	0.8
	scenario III	7.4	2.1
	scenario IV	2.8	0.7
	scenario V	553	3.0
	scenario VI	471	2.1

*In all scenarios, NPO is fixed to 13.

Vulnerability analysis with load and generation separately

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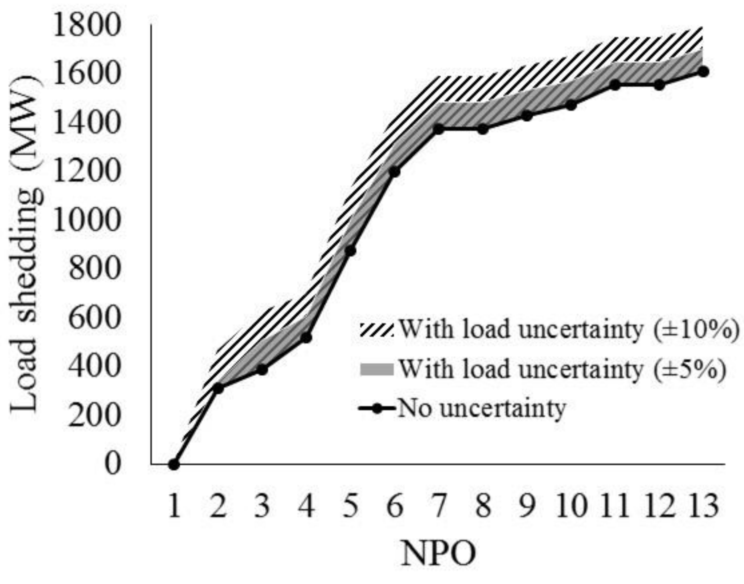
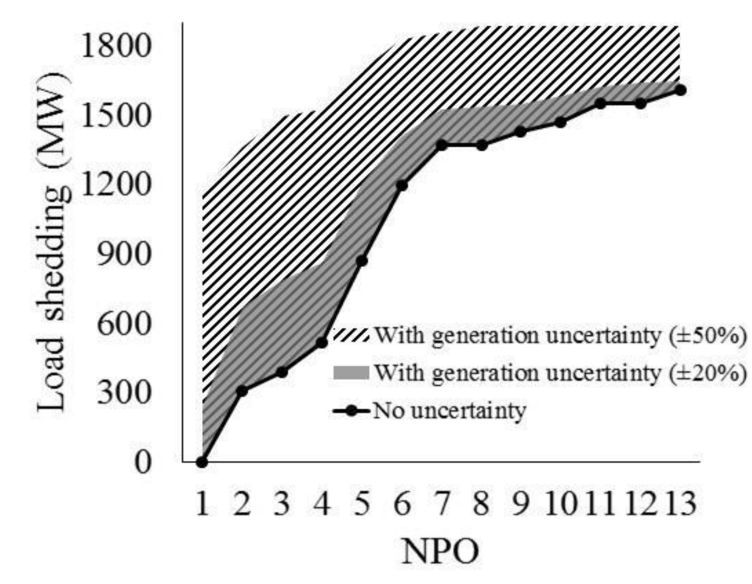
- Load variation: 5%-10%,
- The uncertainty budget: 0-17,
- The maximum differences: 30% and 60% when NPO=3,
- The results without uncertainty is optimistic, and proposing different critical lines.

- Generation variation : 20 % and 50 %,
- The uncertainty budget: 0-14,
- The maximum differences: 118% and 342%, when NPO=1,
- The results without uncertainty is optimistic, and proposing different critical lines .



(a)



(a)

Vulnerability analysis with both uncertainties

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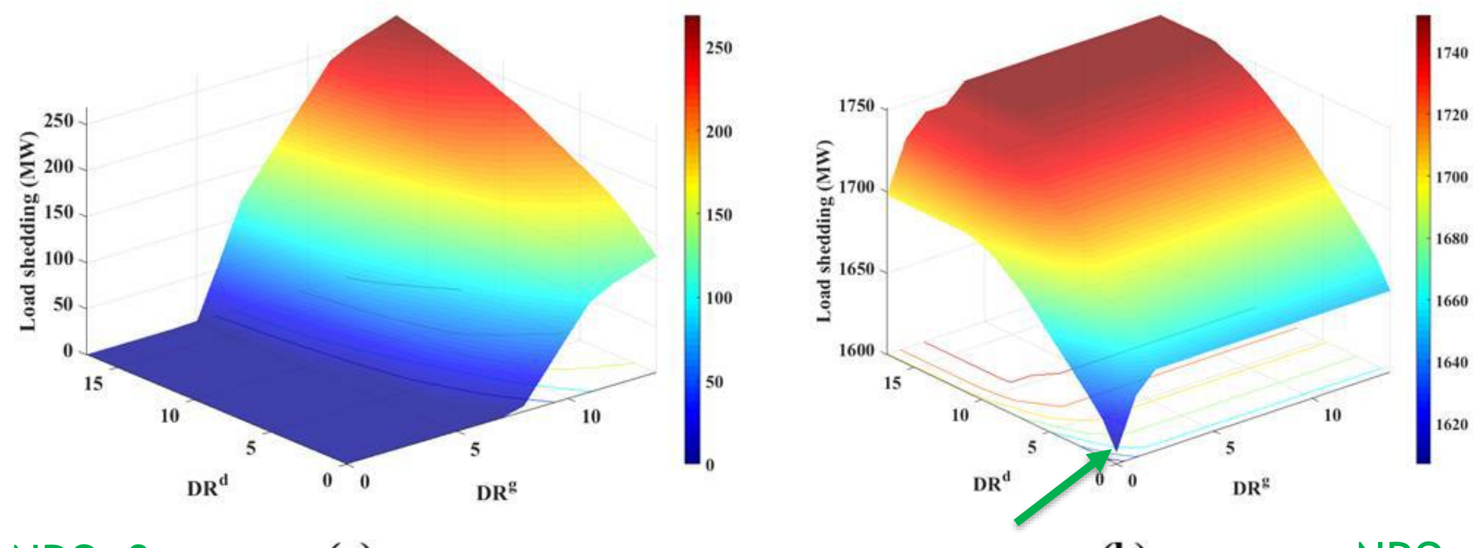
The results without uncertainty is optimistic, and proposing different critical lines .



NPO=0

NPO=13

What we have from the model ???

DR^g $=DR^d$=NPO	Critical lines	Generation unit*	Load bus number*	LS (MW)
1	-	-	-	0
2	15-21,16-17	G6,G14	13,15	429
3	7-8,15-21,16-17	G6,G13,G14	10,13,15	676
4	3-24,12-23,13-23,14-16	G2,G4,G5,G6	3,10,13,14	797
5	12-23,13-23,15-21,16-17,20-23	G4,G5,G6,G8,G9	10,13,14,15,19	1200
6	11-13,12-13,12-23,15-21,16-17,20-23	G2,G4,G5,G7,G8,G9	3,9,10,14,15,19	1455

* In these components, when the uncertain parameters reach the boundary of their intervals, the worst-case scenario occurs.

Thank you for your time and attention

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