Enhancing Power System Resilience through Computational Optimization

Georgios Patsakis

University of California Berkeley

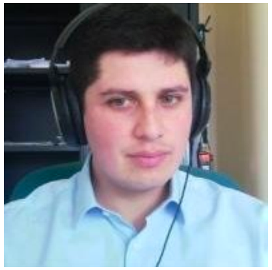
(gpatsakis@berkeley.edu)

PSERC Webinar
September 22, 2020

Collaborators

Professor Shmuel Oren (UC Berkeley)

Adjunct Professor Deepak Rajan (UC Berkeley)



Ignacio Aravena (Lawrence Livermore National Laboratory)

Outline

- Power System Resilience: Motivation and Definition
- Black Start and Restoration: Planning and Reality
- Optimal Black Start Allocation: Modeling and Solution Approach
- Optimal Black Start Allocation: Reformulations (simplified model)
- Extension: Stochastic Black Start Allocation
- Extension: Power System Restoration
- Conclusions

Outline

- **Power System Resilience: Motivation and Definition**
- Black Start and Restoration: Planning and Reality
- Optimal Black Start Allocation: Modeling and Solution Approach
- Optimal Black Start Allocation: Reformulations (simplified model)
- Extension: Stochastic Black Start Allocation
- Extension: Power System Restoration
- Conclusions

Motivation: Blackout

Electricity is often taken for granted, but is far more important than we may realize

Northeast Blackout
August 14-16, 2003

- Caused 11 deaths and $6.4 Billion in economic losses
- People trapped in subway and elevators
- No water supply in many areas (runs on electric pumps)
- Raw sewage dumping, toilet flush problems
- No lights, cell phones, air conditioning, ATMs

Photo Source: Alan Taylor, “Photos: 15 Years Since the 2003 Northeast Blackout”, The Atlantic, 08-2018.

Motivation: New Concerns

- **Natural Disasters**
  - Climate changing
  - Wildfires, earthquakes, hurricanes
  - Puerto Rico blackout after hurricane Maria in 2018: took 11 months to fully restore service

Source: https://www.telesurenglish.net/news/Governor-Puerto-Ricos-Power-Company-Will-be-Privatized-20180123-0003.html

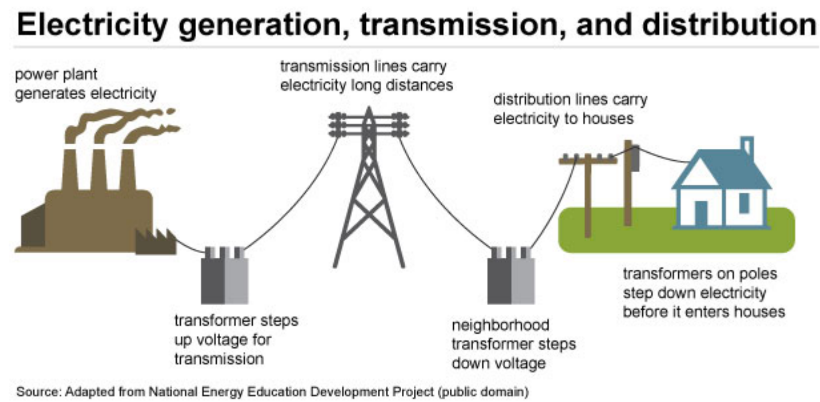
Source: https://theconversation.com/the-cyberattack-on-ukraines-power-grid-is-a-warning-of-whats-to-come-52832

- **Cyber Attacks**
  - The current power grid relies increasingly more on automation and remote control
  - Ukraine: 225,000 customers to lose power on December 2015 [1]

[1] R. M. Lee, M. J. Assante, and T. Conway, “Analysis of the cyber attack on the Ukrainian power grid,” SANS Industrial Control Systems, 2016.

Motivation: The Grid Changes

- **Generation Paradigm Change**
  - Distributed Generation (microgrids, solar installations, electric vehicles) disturbs direction of power flows
  - Renewables (uncertain generation)



Source: US Energy Information Administration, "Electricity Explained", October 2011

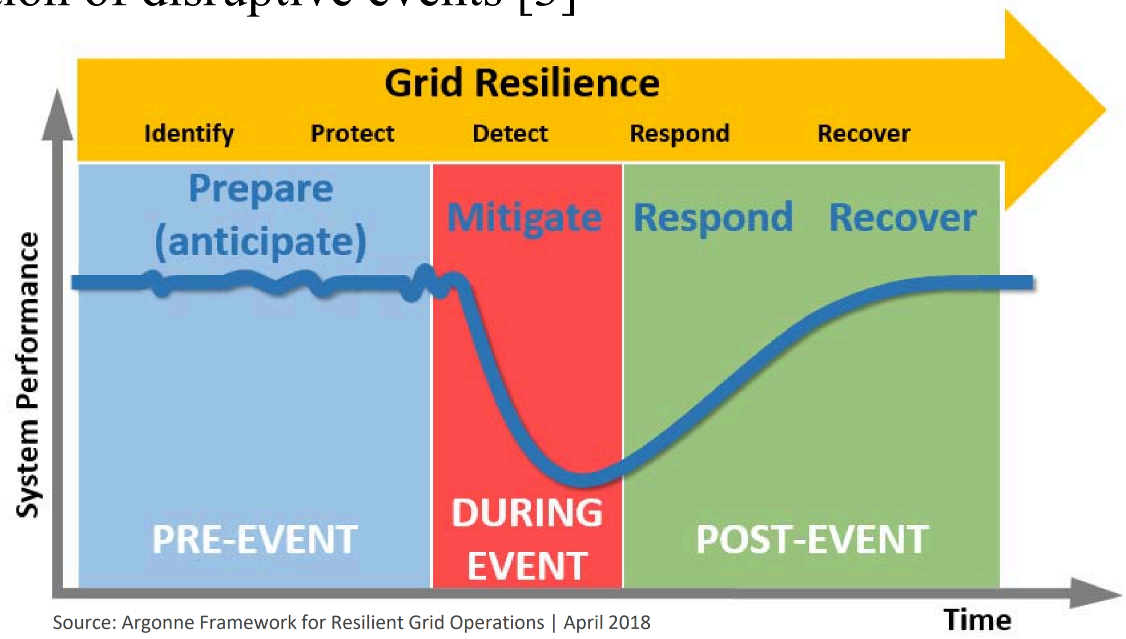
Source: Power Technology, https://www.power-technology.com/features/feature127627/

- **Aging Infrastructure**
  - The power grid was built about 50 years ago
  - Average transformer lifespan: 40-50 years
    Average utility pole lifespan: 56 years in Northeast [2]

[2] Electrocution Lawyers PLLC, [Accessed Online 2020]

Resilience: Definition

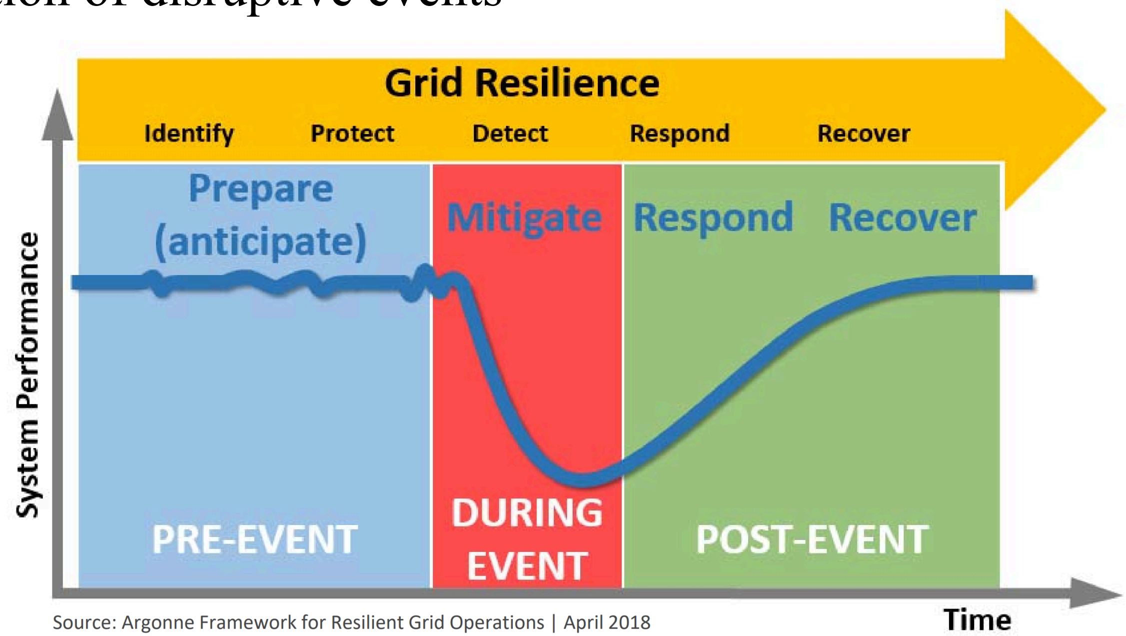
- Resilience: the ability of the system to withstand and reduce the magnitude or duration of disruptive events [3]



[3] National Infrastructure Advisory Council (2019). “Critical Infrastructure Resilience: Final Report and Recommendations”.

Resilience in this Talk

- Resilience: the ability of the system to withstand and reduce the magnitude or duration of disruptive events



Source: Argonne Framework for Resilient Grid Operations | April 2018

Black Start Allocation

Power System Restoration

Outline

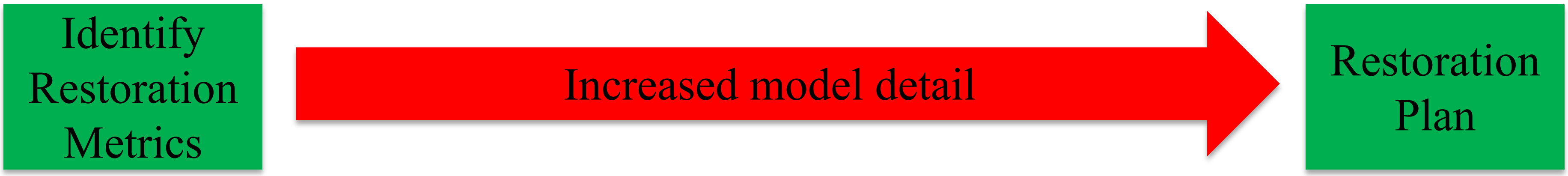
- Power System Resilience: Motivation and Definition
- **Black Start and Restoration: Planning and Reality**
- Optimal Black Start Allocation: Modeling and Solution Approach
- Optimal Black Start Allocation: Reformulations (simplified model)
- Extension: Stochastic Black Start Allocation
- Extension: Power System Restoration
- Conclusions

What is the problem?

- Most generating units can not start unless connected to the grid.
- We rely on Black Start (BS) units to restart the system after an **extended** blackout.
- Cost of allocating each unit is in the millions [4]
- Some units more suitable than others
- Goal:
  - Model and optimize the Black Start Allocation process (BSA problem)

[4] ISO New England, “Schedule 16 - Blackstart Standard Rate Report,”, 2016, [Online; accessed Aug-2017].

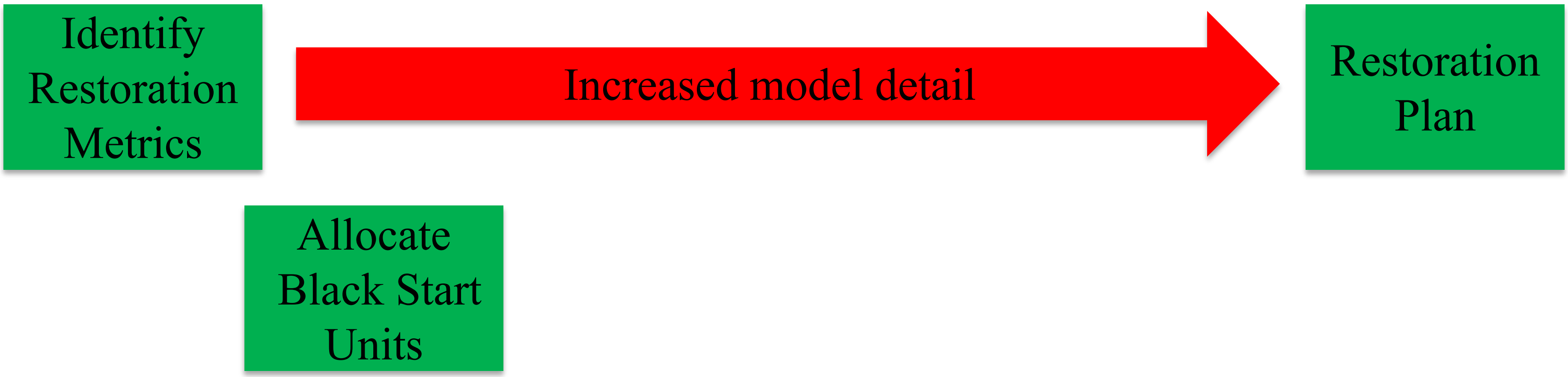
Power System Restoration: Utility Planning Approach



[5] California ISO, "Black start and system restoration Phase2" (2017), [Online; accessed Aug-2017].

[6] PJM Manual: System Restoration, PJM, 6 2017, rev. 24.

Power System Restoration: Utility Planning Approach

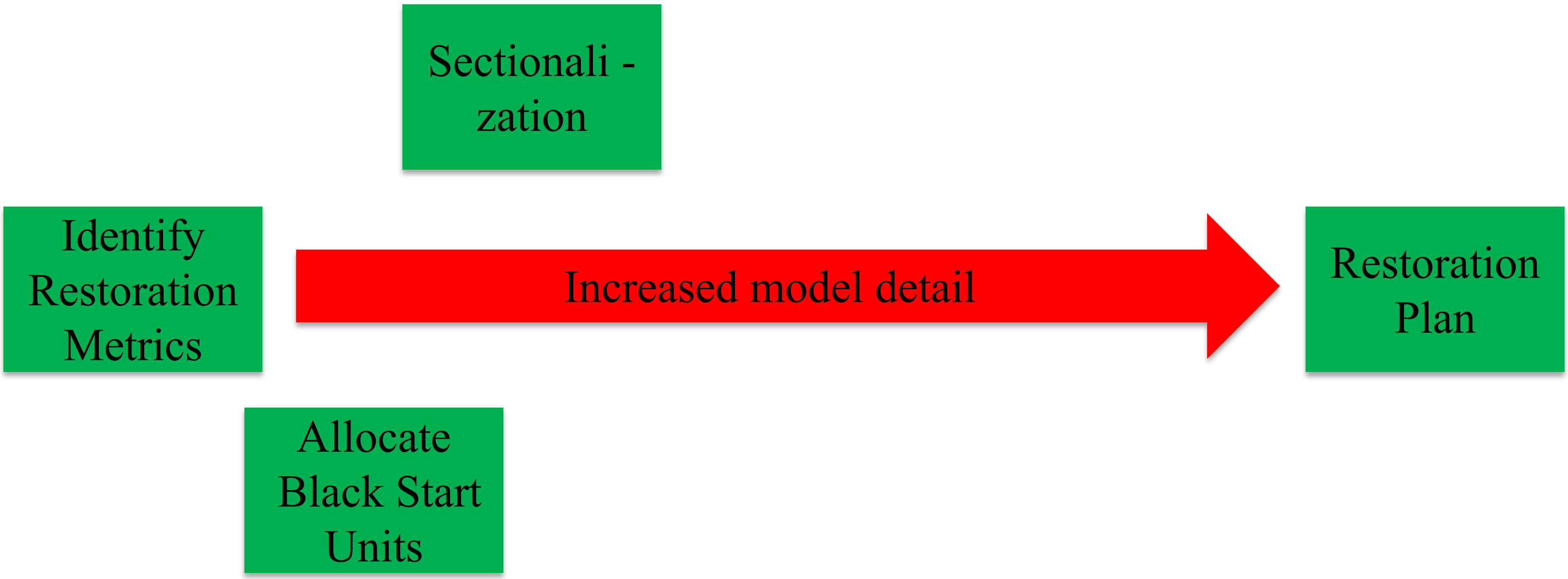


[7] Jiang, Y., Chen, S., Liu, C. C., Sun, W., Luo, X., Liu, S., ... & Forcum, D. (2017). Blackstart capability planning for power system restoration. *International Journal of Electrical Power & Energy Systems*, *86*, 127-137.

[8] Qiu, F., & Li, P. (2017). An integrated approach for power system restoration planning. *Proceedings of the IEEE*, *105*(7), 1234-1252.

[9] Qiu, F., Wang, J., Chen, C., & Tong, J. (2015). Optimal black start resource allocation. *IEEE Transactions on Power Systems*, *31*(3), 2493-2494.

Power System Restoration: Utility Planning Approach

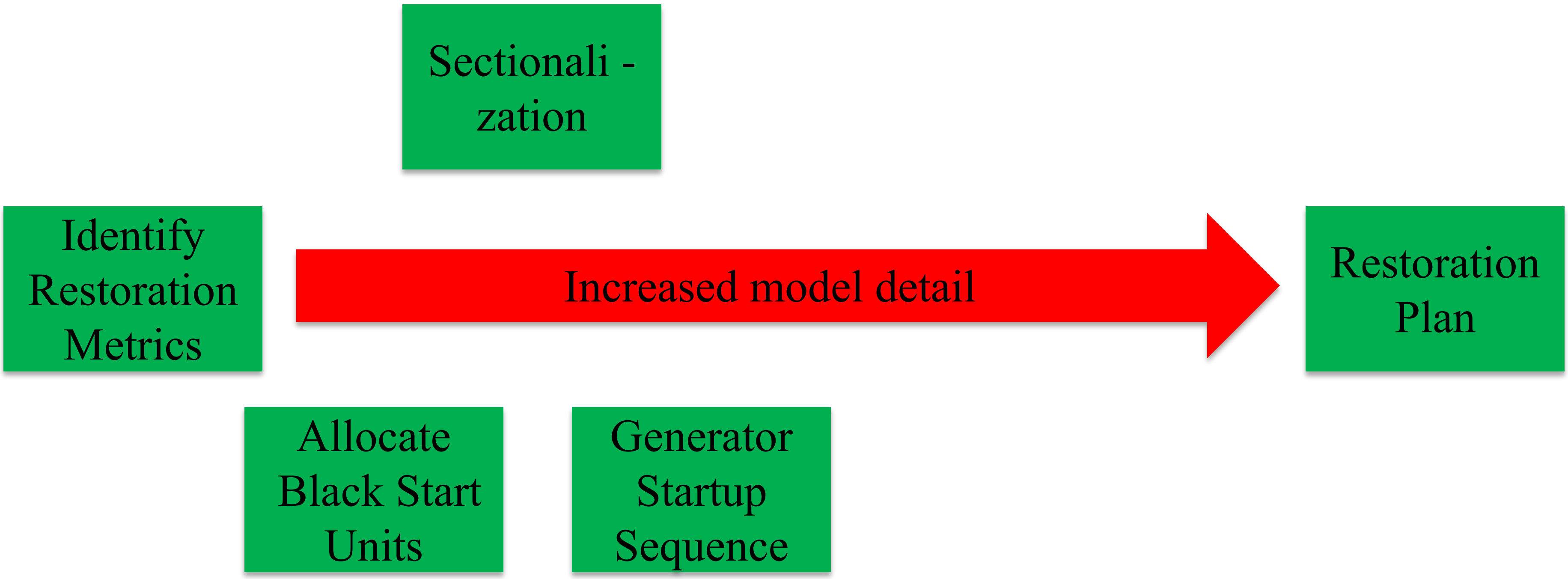


[10] Wang C, Vittal V, Sun K (2011) OBDD-based sectionalizing strategies for parallel power system restoration. IEEE Trans Power Syst 26(3):1426–1433

[11] Sarmadi SAN, Dobakhshari AS, Azizi S et al (2011) A sectionalizing method in power system restoration based on WAMS. IEEE Trans Smart Grid 2(1):190–197

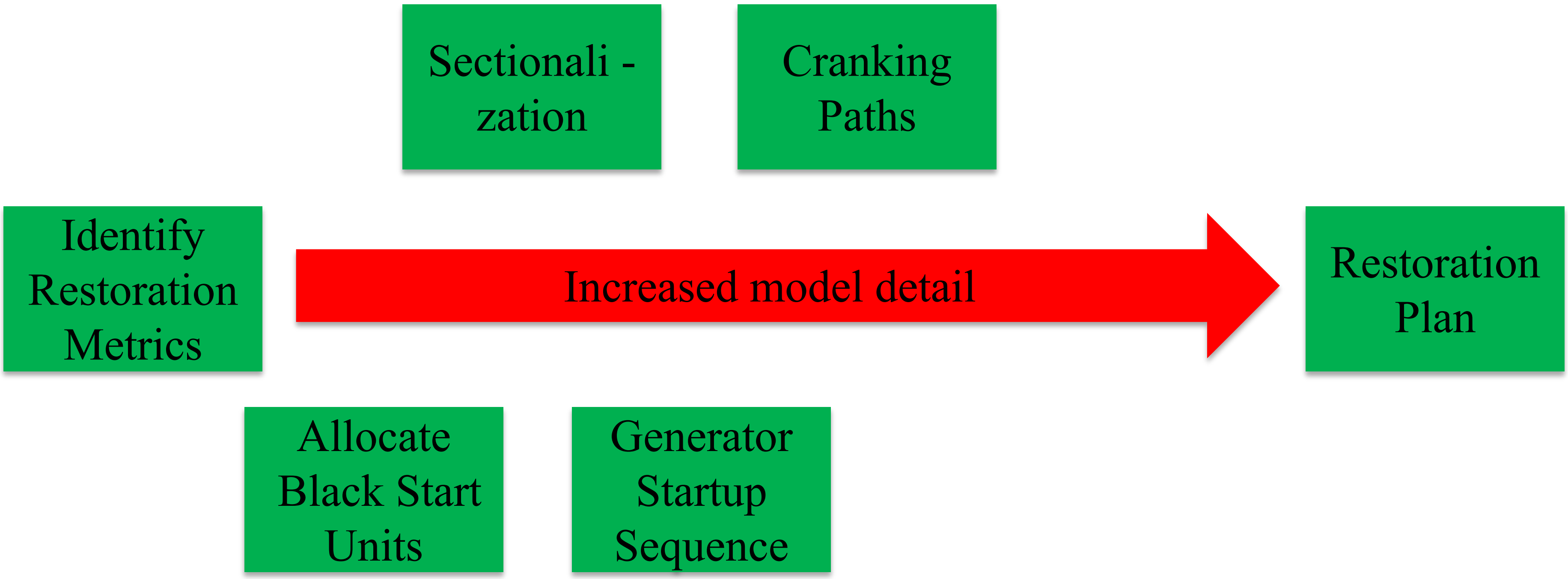
[12] Liu WJ, Lin ZZ, Wen FS et al (2015) Sectionalizing strategies for minimizing outage durations of critical loads in parallel power system restoration with bi-level programming. Int J Electr Power Energy Syst 71:327–334

Power System Restoration: Utility Planning Approach



[13] Sun W, Liu CC, Zhang L (2011) Optimal generator start-up strategy for bulk power system restoration. IEEE Trans Power Syst 26(3):1357–1366

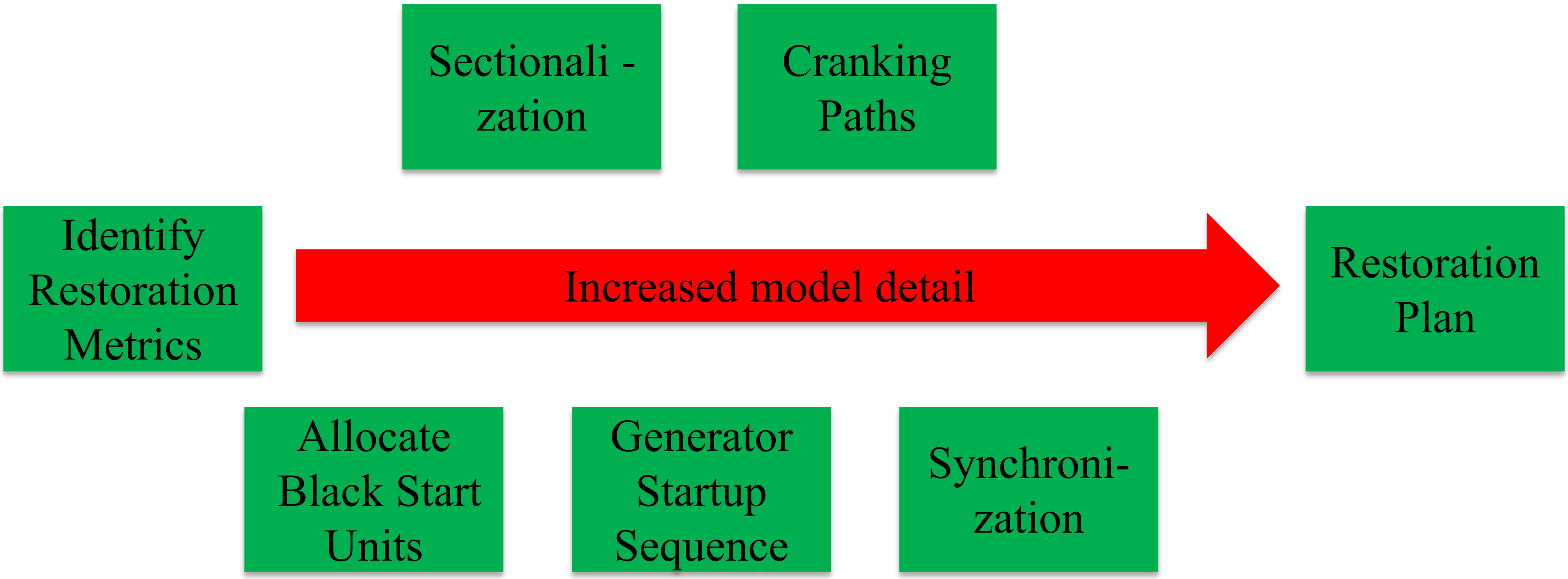
Power System Restoration: Utility Planning Approach



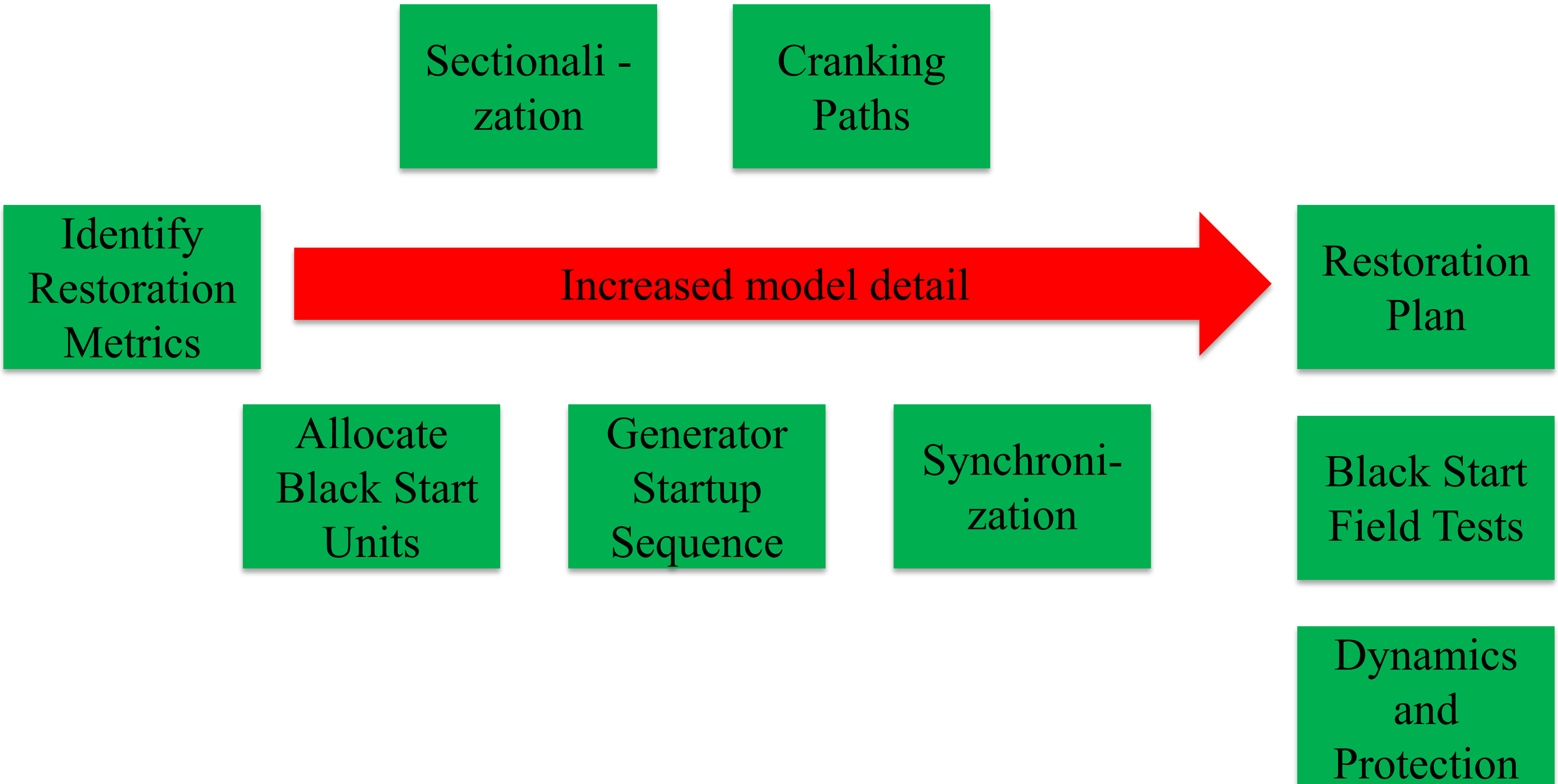
[14] Liu Y, Gu XP (2007) Skeleton-network reconfiguration based on topological characteristics of scale-free networks and discrete particle swarm optimization. IEEE Trans Power Syst 22(3):1267–1274

[15] Wang C, Vittal V, Kolluri VS et al (2010) PTDF-based automatic restoration path selection. IEEE Trans Power Syst 25(3):1686–1695

Power System Restoration: Utility Planning Approach

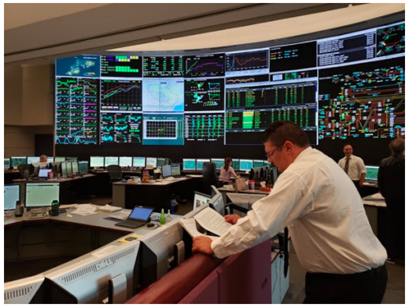


Power System Restoration: Utility Planning Approach

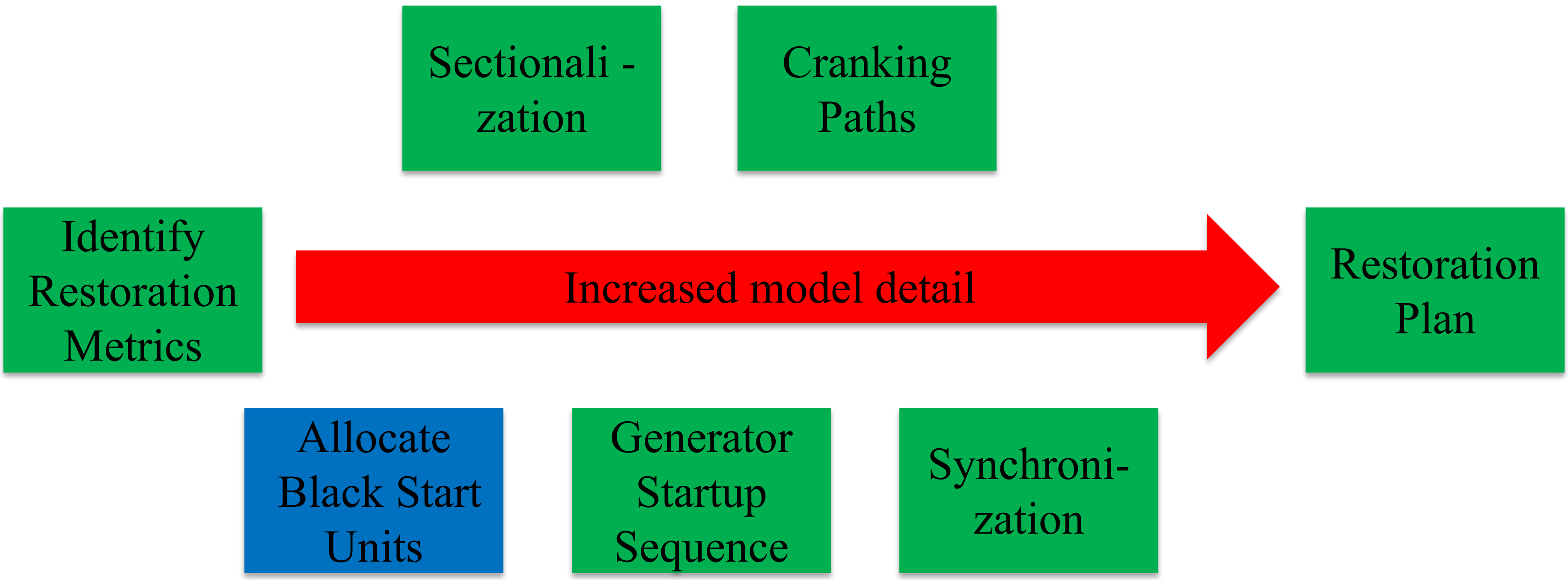


Power System Restoration: Reality

- Unknown System State
- Permanent damage to grid components
- Need for manual control
- Control centers without electricity
- Failing communications
- Cold load pickup



Power System Restoration: Planning



Outline

- Power System Resilience: Motivation and Definition
- Black Start and Restoration: Planning and Reality
- **Optimal Black Start Allocation: Modeling and Solution Approach**
- Optimal Black Start Allocation: Reformulations (simplified model)
- Extension: Stochastic Black Start Allocation
- Extension: Power System Restoration
- Conclusions

Optimal Black Start Allocation

- The work in this section has been published in [16]
- We build upon the literature [7]-[9] to:
  - Model the problem of optimal BSA, by simultaneously optimizing over the restoration sequence with an increased amount of detail
  - Solve the problem for moderate size systems (a few hundred buses)

[16] Patsakis, G., Rajan, D., Aravena, I., Rios, J., & Oren, S. (2018). Optimal black start allocation for power system restoration. IEEE Transactions on Power Systems, 33(6), 6766-6776.

[7] Jiang, Y., Chen, S., Liu, C. C., Sun, W., Luo, X., Liu, S., ... & Forcum, D. (2017). Blackstart capability planning for power system restoration. *International Journal of Electrical Power & Energy Systems*, *86*, 127-137.

[8] Qiu, F., & Li, P. (2017). An integrated approach for power system restoration planning. *Proceedings of the IEEE*, *105*(7), 1234-1252.

[9] Qiu, F., Wang, J., Chen, C., & Tong, J. (2015). Optimal black start resource allocation. *IEEE Transactions on Power Systems*, *31*(3), 2493-2494.

Optimal Black Start Allocation

Black Start Allocation Important Considerations :

- **Characteristics of generators**
  - Minimal time and power to restart
  - Sufficient capacity to restart other generators
  - Relatively cheap upgrades to become black start capable
- **Characteristics of locations of generators**
  - Close to other generating units to restart them
  - Units spread across the grid to allow quick parallel restoration from many sources and located strategically to satisfy restoration priorities
- **Resulting restoration plan**
  - Stable islands are created. Enough load to satisfy generator technical minima
  - Sufficient reactive power compensation

Optimization Problem

Objective: Minimize critical load shed/maximize component energization

Constraints:

- Budget allocation for black starts
- Generator startup profiles
- Nodal active power balance and reactive power capability
- Transmission switching (linear approximation for active and reactive power model)
- Island expansion constraints (crew constraints)
- Island energization constraints

Modeling: Variables

Black Start Allocation : u_{BS_g}

Bus Energization: u_i^t

Branch Energization: u_{ij}^t

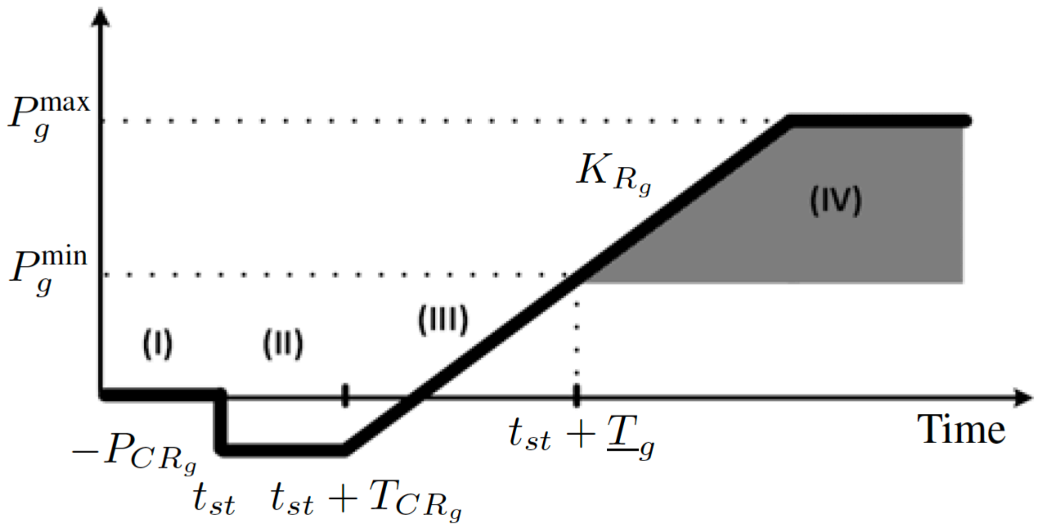
Generator Energization: u_g^t

Also variables for:

Power flows, power generations, load shed, auxiliary network flows, node voltages

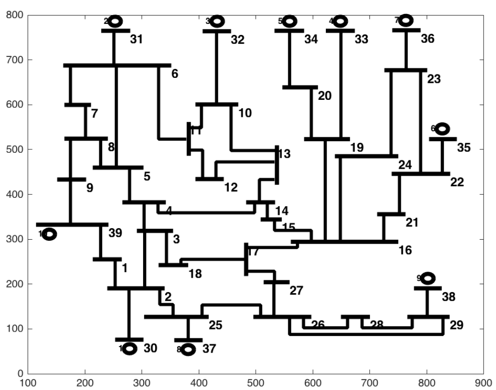
Mixed Integer Linear Program

Generator startup profiles



- Starts at time t_{st}
- Cranking for a period: T_{CR_g}
- Can increase generation at a slope: K_{R_g}
- Maximum/minimum generation: $P_g^{\max}/P_g^{\min}$

Computations



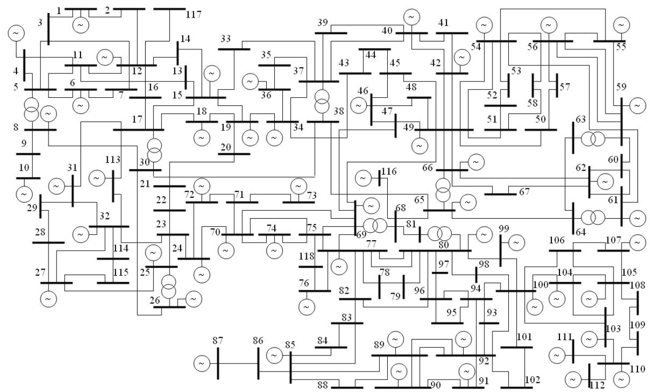
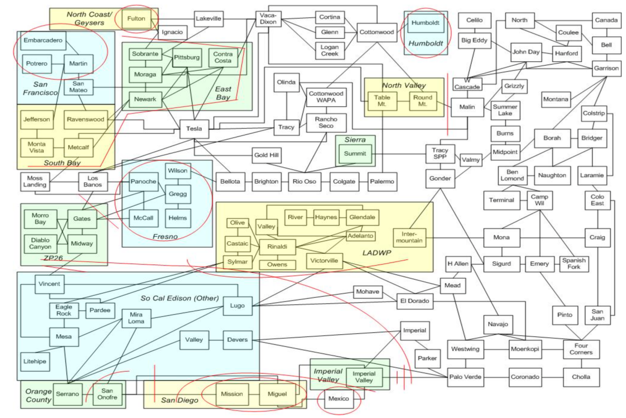


Рис.1. IEEE тестовая схема, состоящая из 118 узлов



- IEEE 39

Variables: 16380

Binaries: 3810

Constraints: 36058

- IEEE 118

Variables: 30028

Binaries: 7214

Constraints: 70704

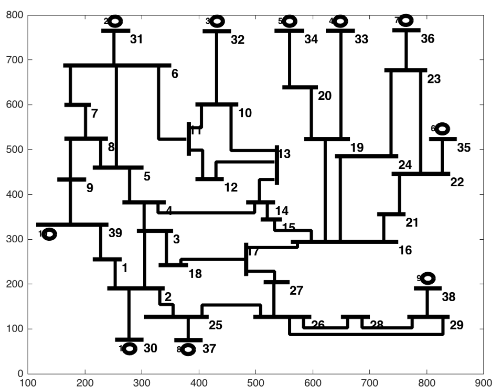
- WECC 225

Variables: 55418

Binaries: 13597

Constraints: 131470

Computations



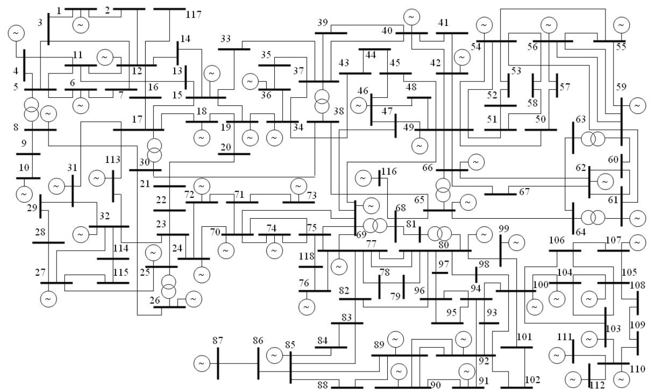
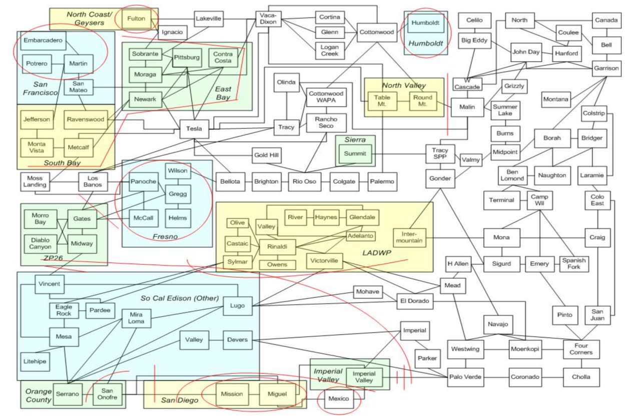


Рис.1. IEEE тестовая схема, состоящая из 118 узлов



- IEEE 39

Xpress: 43% in 30min

Gurobi: 2% in 20min

- IEEE 118

Xpress: no feasible point in 5h

Gurobi: 1 feasible point in 5h (53%)

- WECC 225

Xpress: no feasible point in 5h

Gurobi: no feasible point in 5h

(*) Using default solver settings

A Heuristic

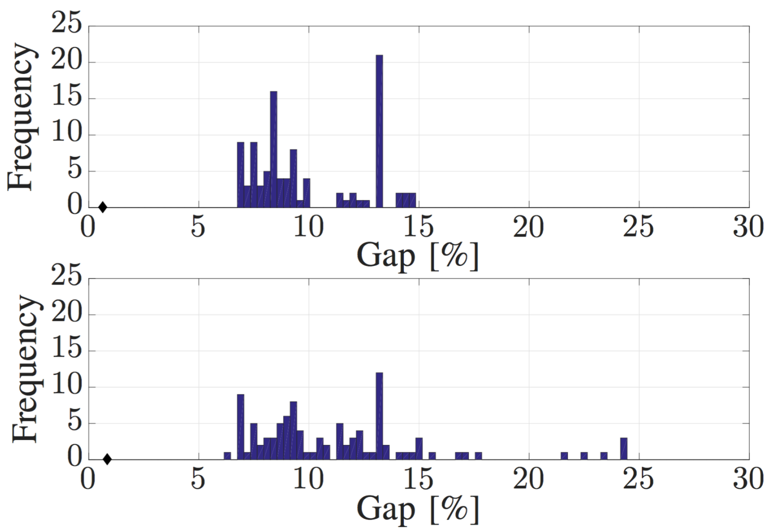
- The solver has a difficulty identifying feasible solutions
- However, given the step-wise nature of the problem, maybe easy to construct a feasible solution.
- Idea: gradually create islands and check
  - Generation startup against active power capability
  - Line energization against reactive power capability

A Heuristic

1. **Black Start Allocation (for $\tau = 0$):**
   - Solve LP
   - Perturb solution with noise – Create BS Ranking – Energize up to B
2. **Line Selection (at every $\tau > 0$):**
   - Solve LP for corresponding step
   - Perturb solution with noise – Create Line Ranking – Energize up to reactive capability of newly formed island
3. **Generator Selection (at every $\tau > 0$)**
   - Solve LP for corresponding step
   - Perturb solution with noise – Create Generator Ranking – Energize up to active capability of island

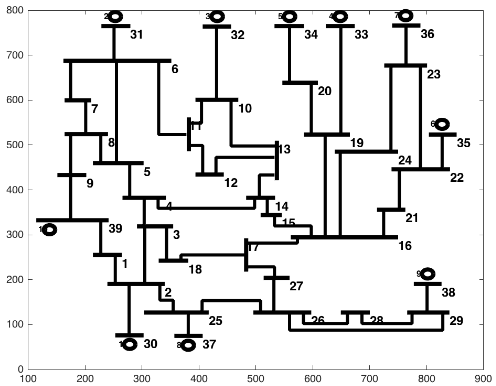
Heuristic Performance

- The heuristic executions can be launched in parallel
- The heuristic simulations were parallelized at **6 nodes** of the Cab cluster by utilizing Mosel with Xpress, with **4 jobs per node and 4 threads per job**.
- IEEE39: In approx. 15min, 100 feasible solutions are found, with a total of 110 heuristic executions necessary. Within 15min, problem is solved (1%).



- Finds good solutions but not the optimal – its goal is only to aid the solver
- Does not have some characteristics the optimal may have (say de-energize lines)

Heuristic Performance



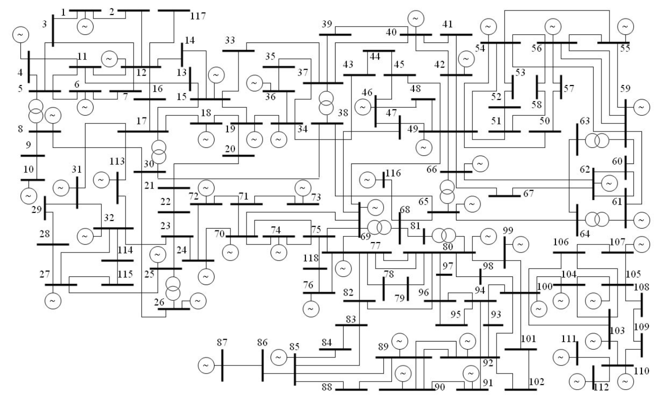
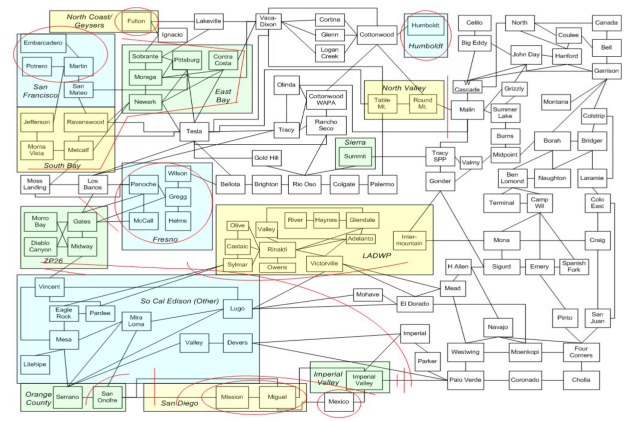


Рис.1. IEEE тестовая схема, состоящая из 118 узлов



- IEEE 39

~900s for 100 feasible points

1% solved within 15min

- IEEE 118

~1200s for 100 feasible points

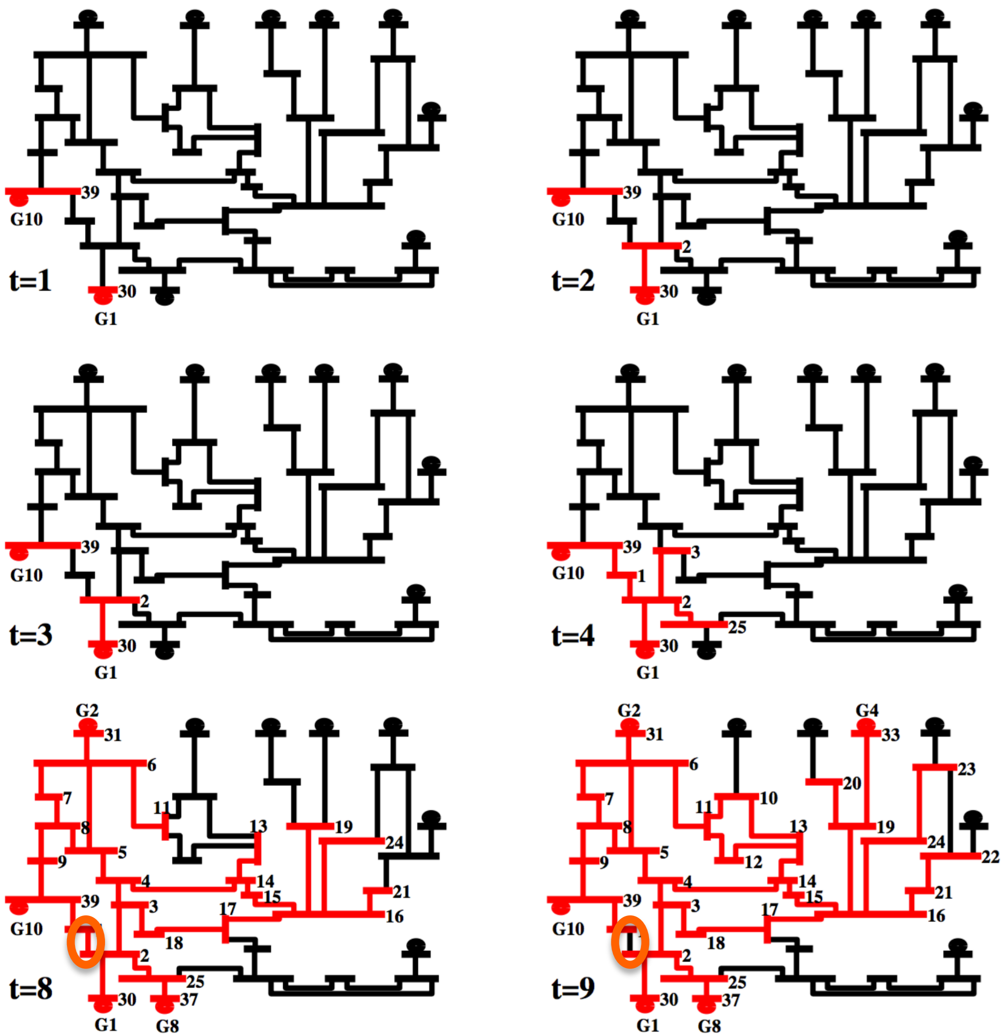
1% solved within 3hours

- WECC 225

~2300s for 20 feasible solutions

6% solved within 2hours

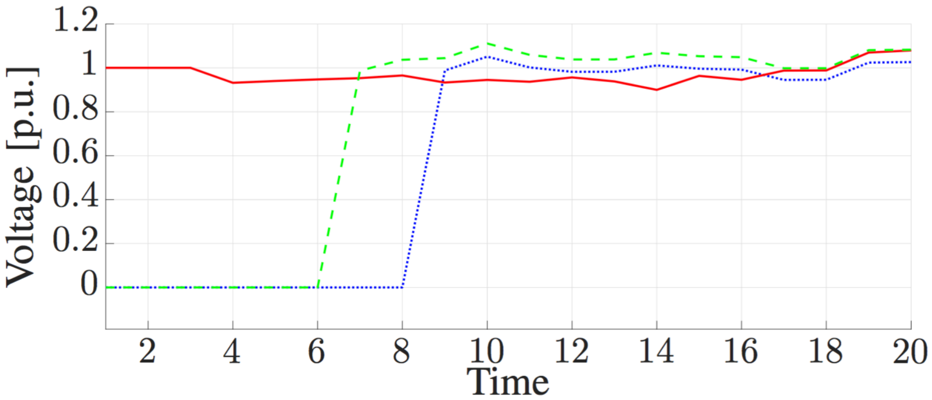
Optimal Sequence Profile for BSA



- BSA: Generators 1 and 10
- Generator 10 has small cranking time and power
- Generator 1 has large reactive power capacity
- Sample restoration profile for the optimal BSA
- Wait for cranking before energizing transmission
- De-energizing line at time 9 due to voltage considerations

Sequence Verification

- Is our sequence valid for the real system?
- Various levels of analysis depth.
- What the optimization literature does (and what PG&E does) is make sure there is an ac feasible point for every step
- Usually, set of heuristics (delay energization etc.) to get feasible point

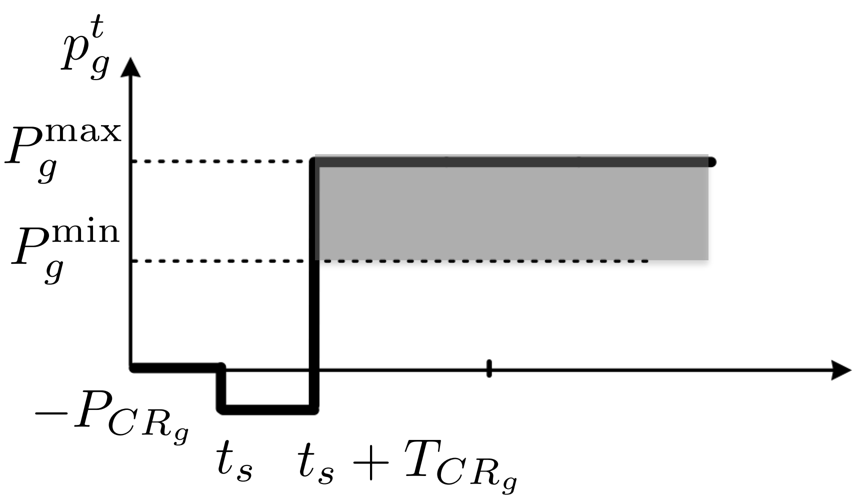


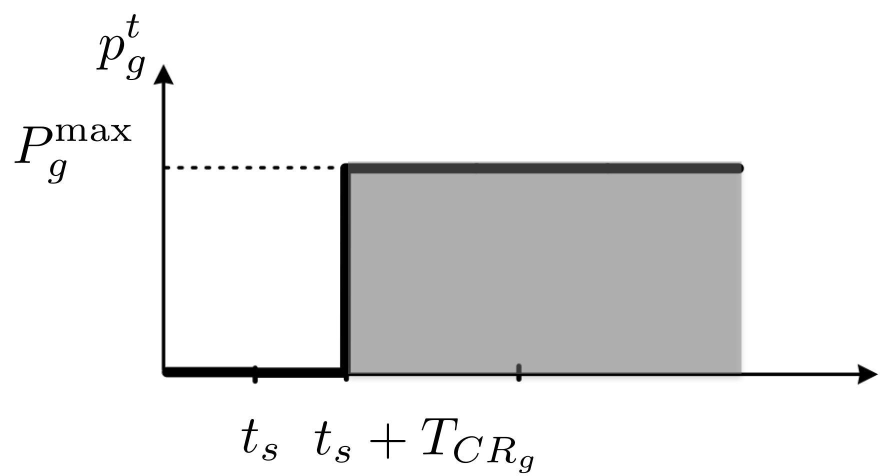
Outline

- Power System Resilience: Motivation and Definition
- Black Start and Restoration: Planning and Reality
- Optimal Black Start Allocation: Modeling and Solution Approach
- **Optimal Black Start Allocation: Reformulations (simplified model)**
- Extension: Stochastic Black Start Allocation
- Extension: Power System Restoration
- Conclusions

A simplified model for BSA

- The previous model is still very complex to handle models of industrial size.
- Major simplifications to solve large scale instances to get black start suggestions and start the planning process:
  - Transportation model for active power and aggregate constraint for reactive power
  - Ramping constraint relaxed in generator startup curves





A simplified model for BSA

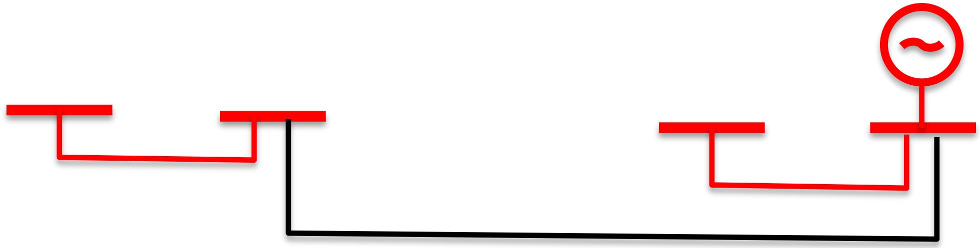
- Such simplifications are common in the literature for BSA, due to the difficulty of tackling the full problem. More detail is introduced in subsequent steps of restoration planning.
- The model accommodates for major considerations:
    - selecting BS units with suitable start-up characteristics
    - well positioned on the underlying graph of the power system
    - energized generators are connected to load centers that could ensure the technical minima during restoration
    - respecting a predefined allocation budget
- The results of this section are covered mainly in [18] (and some in [17])

[17] Patsakis, G., Rajan, D., Aravena, I., & Oren, S. (2019). Strong Mixed-Integer Formulations for Power System Islanding and Restoration. *IEEE Transactions on Power Systems*, *34*(6), 4880-4888.

[18] Patsakis, G., Rajan, D., Aravena, I., & Oren, S. (2020). Formulations and Valid Inequalities for Optimal Black Start Allocation in Power Systems. Optimization Online.

Island Energization Constraints

- Why are they valid? (implied by exact power flows)
- Red = Energized (on), Black = De-energized (off)



- The island created has no physical meaning. The two nodes and line are marked as energized, even though there is no path to any source of energy

Island Energization Constraints

- Usual Formulation

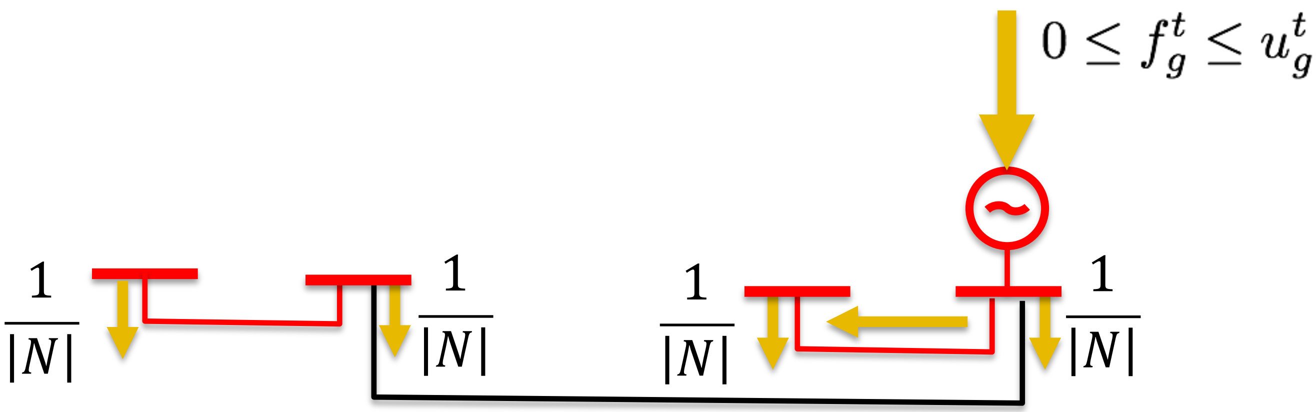
$$\exists f_g, f_{ij}: \quad \begin{aligned} 0 \le f_g \le u_g, \forall g \in G \\ -u_{ij} \le f_{ij} \le u_{ij}, \forall ij \in E \\ \textstyle\sum_{(ji)\in \mathrm{E}} f_{ji} - \sum_{(ij)\in \mathrm{E}} f_{ij} + \sum_{g\in G(i)} f_g = \frac{1}{|N|} u_i,\ \forall i \in N \end{aligned} \quad \mathbf{(F_1)}$$

- This way to impose connectivity appears in literature for power system restoration and optimal islanding [9], [19], [20]

[9] F. Qiu, J. Wang, C. Chen, J. Tong, Optimal black start resource allocation, IEEE Transactions on Power Systems 31 (3) (2016) 2493–2494.
[19] T. Ding, K. Sun, C. Huang, Z. Bie, F. Li, Mixed-integer linear programming- based splitting strategies for power system islanding operation considering 40 network connectivity, IEEE Systems Journal.
[20] N. Fan, D. Izraelevitz, F. Pan, P. M. Pardalos, J. Wang, A mixed integer programming approach for optimal power grid intentional islanding, Energy Systems 3 (1) (2012) 77–93.

Island Energization Constraints

- How to impose them?



- Assume that every energized node must act as a sink of 1/|N| amount of network flow
- This flow can only be generated by energized generators
- It can only move through energized lines

$$-u_{ij}^t \leq f_{ij}^t \leq u_{ij}^t$$

Island Energization Constraints

- Usual Formulation

$$\exists f_g, f_{ij}: \quad \begin{aligned} & 0 \leq f_g \leq u_g, \forall g \in G \\ & -u_{ij} \leq f_{ij} \leq u_{ij}, \forall ij \in E \\ & \textstyle\sum_{(ji)\in \mathrm{E}} f_{ji} - \sum_{(ij)\in \mathrm{E}} f_{ij} + \sum_{g\in G(i)} f_g = \frac{1}{|N|} u_i,\ \forall i \in N \end{aligned} \quad \mathbf{(F_1)}$$

- This way to impose connectivity appears in literature for power system restoration and optimal islanding [9], [19], [20]
- Goal: Reformulate these constraints (referred to as Island Energization constraints)
- One alternative: multi-commodity flow, i.e. create a set of flow equations for every node $\mathbf{(F_2)}$

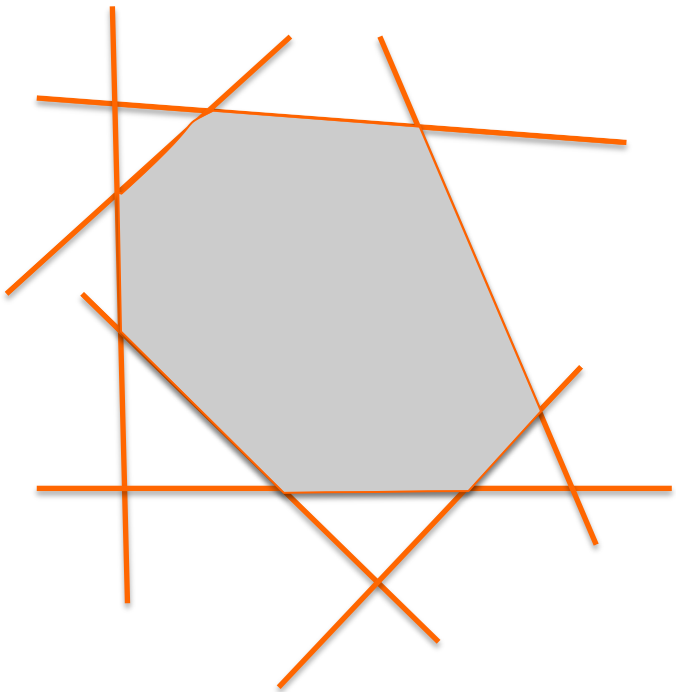
[9] F. Qiu, J. Wang, C. Chen, J. Tong, Optimal black start resource allocation, IEEE Transactions on Power Systems 31 (3) (2016) 2493–2494.
[19] T. Ding, K. Sun, C. Huang, Z. Bie, F. Li, Mixed-integer linear programming- based splitting strategies for power system islanding operation considering
40 network connectivity, IEEE Systems Journal.
[20] N. Fan, D. Izraelevitz, F. Pan, P. M. Pardalos, J. Wang, A mixed integer programming approach for optimal power grid intentional islanding, Energy Systems 3 (1) (2012) 77–93.

Optimal Black Start Allocation: Reformulations

- While formulating a problem as a mixed integer linear program might often be easy, the way to model the problem is important
  - Size of formulation (number of variables and constraints)
  - Strength of the formulation
- The process involves:
  - Identifying subset of constraints or substructure
  - Finding an alternative formulation to impose the same requirement
  - Evaluating the change in performance for the original problem

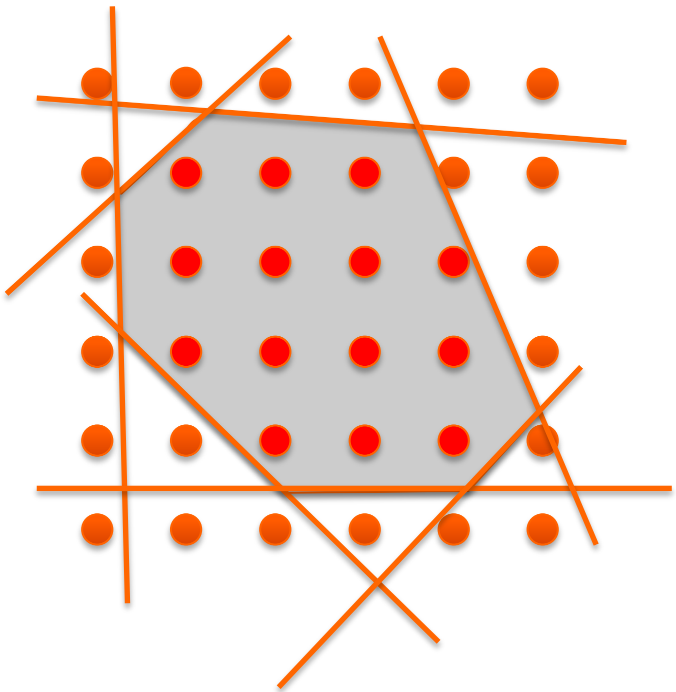
Reformulation Strength

- The feasible region for $\boldsymbol{Ax} \leq \boldsymbol{b}, \boldsymbol{x} \in \mathbb{R}^2$ looks like:



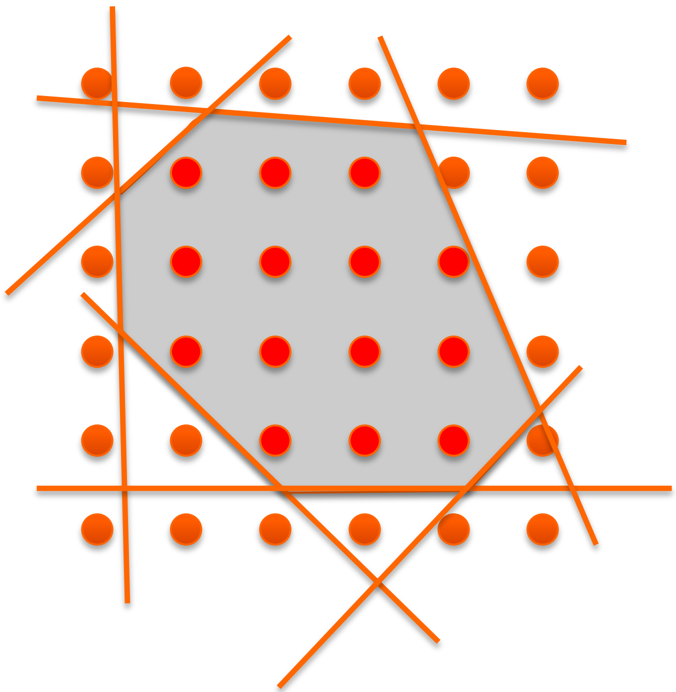
A Tighter Reformulation

- If we restrict $\boldsymbol{x} \in \mathbb{Z}^2$, the feasible region is the (integer) points in red:



A Tighter Reformulation

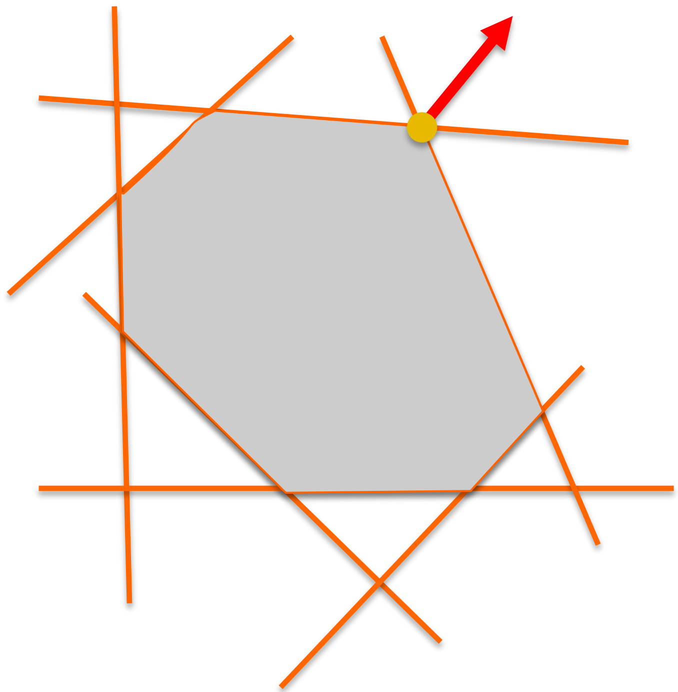
- If we restrict $\boldsymbol{x} \in \mathbb{Z}^2$, the feasible region is the (integer) points in red:



- Now assume the goal is to maximize an objective: $\boldsymbol{c}^T\boldsymbol{x}$

A Tighter Reformulation

- The MIP solver will initially ignore integrality, and solve the LP relaxation (gives UB)

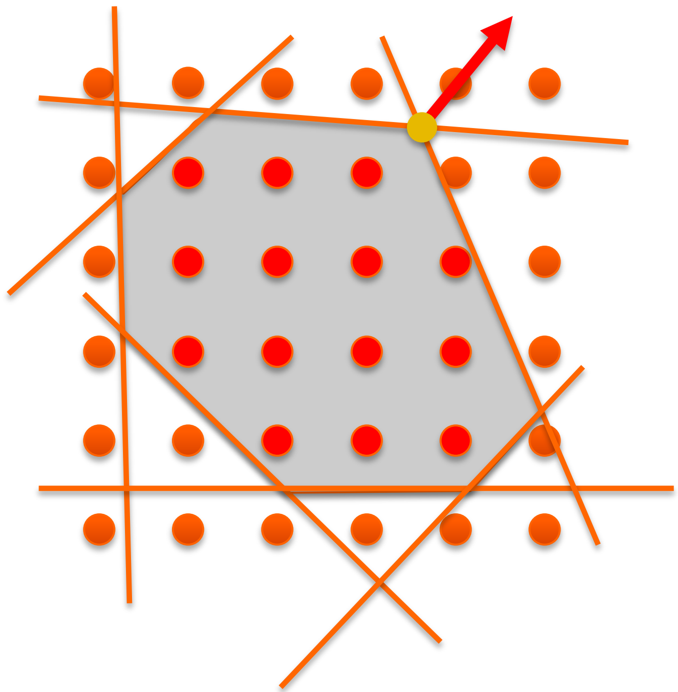


- Now assume the goal is to maximize an objective:

$$c^T x$$

A Tighter Reformulation

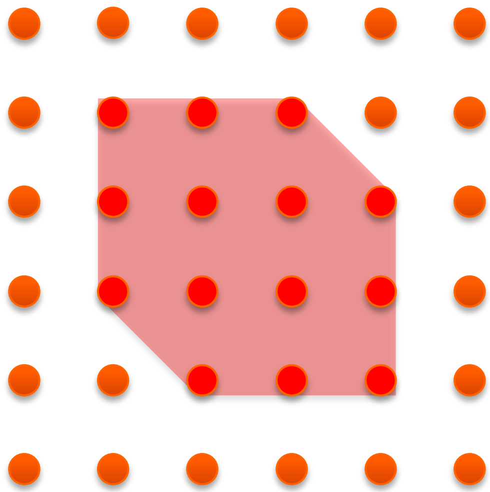
- The MIP solver will initially ignore integrality, and solve the LP relaxation (gives UB)



- Now assume the goal is to maximize an objective:
  $\boldsymbol{c}^T \boldsymbol{x}$

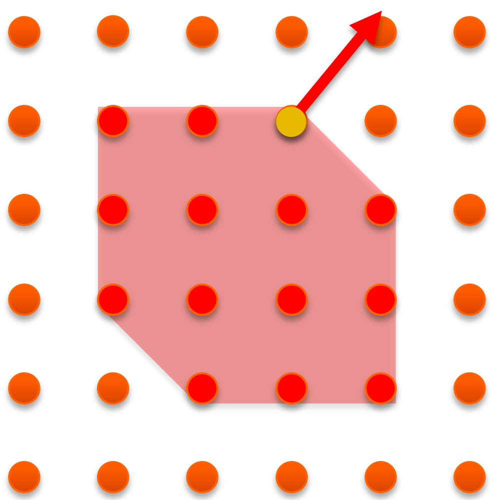
A Tighter Reformulation

- What if we started with a set of equations $\widehat{\boldsymbol{A}}\boldsymbol{x} \leq \widehat{\boldsymbol{b}}$ for the following region instead?



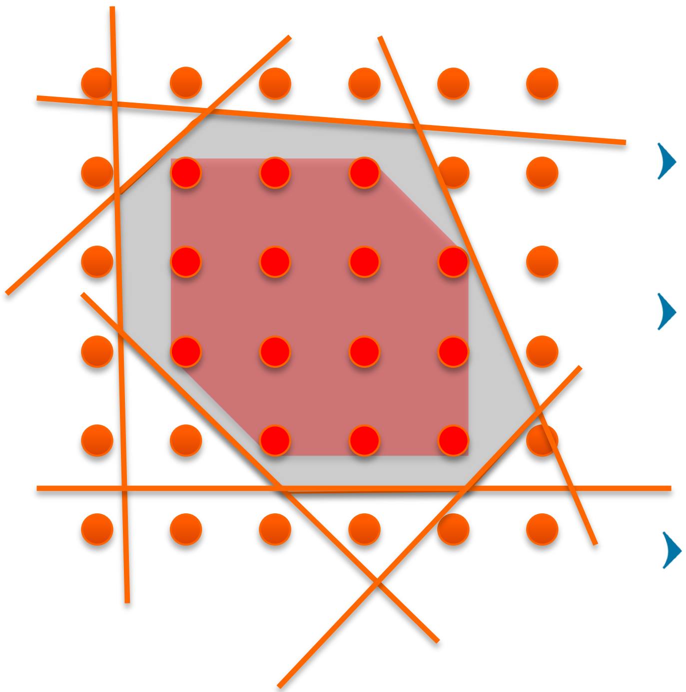
A Tighter Reformulation

- What if we started with a set of equations $\hat{\boldsymbol{A}}\boldsymbol{x} \leq \hat{\boldsymbol{b}}$ for the following region instead?



A Tighter Reformulation

- What if we started with a set of equations $\widehat{\boldsymbol{A}}\boldsymbol{x} \leq \widehat{\boldsymbol{b}}$ for the following region instead?



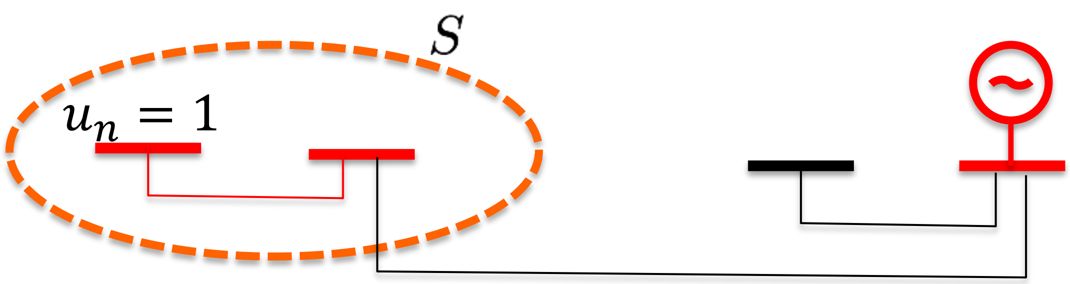
- All the integer points are **the same**
- The feasible region of the continuous relaxation is smaller!
- We call that a tighter (stronger) formulation

Type I Constraints

- Consider the (exponential in size) formulation **(F3)**:

$$\sum_{(ij)\in\delta(S)} u_{ij} + \sum_{i\in S}\sum_{g\in G(i)} u_g \geq u_n, \forall n \in S, \forall\, S \subseteq N:$$

Type I Constraints



Formulation Comparison

(F1), (F2) and (F3) define the same feasible region for the variables u_i, u_{ij}, u_g restricted to binary

Optimizing over the Island Energization feasible region is NP-hard (reduction from rooted maximum weight connected subgraph problem)

(F3) is strictly stronger than (F1) and (F2) is as strong as (F3)

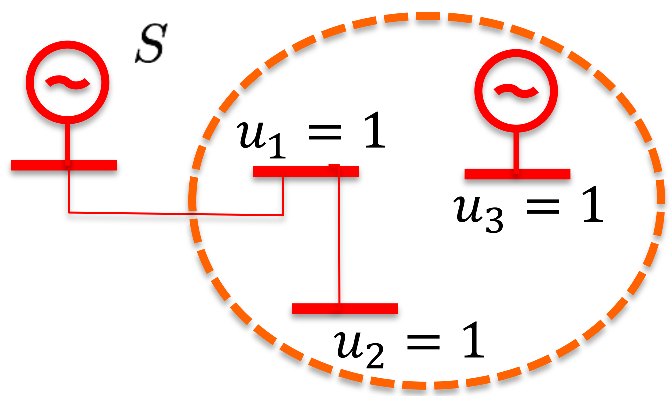
(F3) is separable in polynomial time

Type II Constraints

- Consider the following inequalities:

$$\sum_{i,j\in S} u_{ij} + \sum_{(ij)\in\delta(S)} u_{ij} + \sum_{i\in S}\sum_{g\in G(i)} u_g \geq \sum_{i\in S} u_i,\ \forall\, S \subseteq N:$$

Type II Constraints



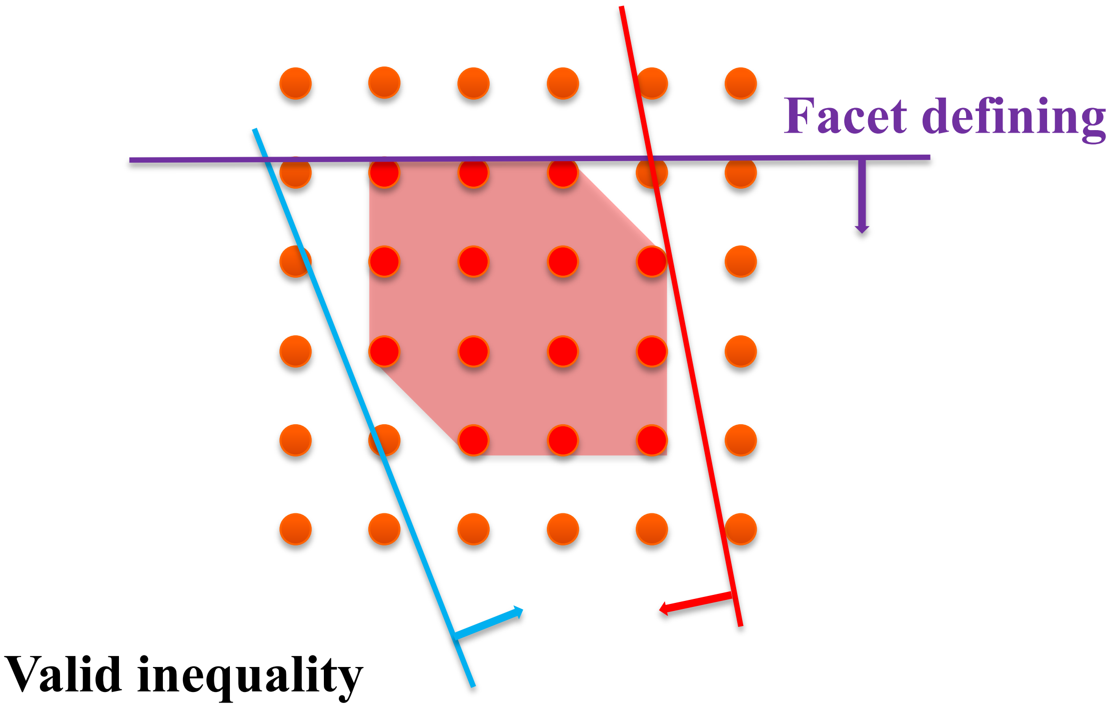
Type II Constraints

Type II constraints are valid

Type II constraints are neither stronger nor weaker than Type I constraints

Type II constraints are separable in polynomial time

A polyhedral study



A polyhedral study

- Also, assuming a complete graph and a generator on every node:

The integer hull defined by the Island Energization constraints is a full dimensional polyhedron

Type I constraints define facets of the integer hull for $|S| = 1$ and $S = N$

Type II constraints define facets of the integer hull for $S = N$

Power Model Reformulation

- To further eliminate problem variables, we reformulate a set of constraints corresponding to:
  - Generator lower and upper capability
  - Transportation model for active flows
  - Power balance constraints
  - Load shed model

Simulations to near optimality

(A) F1
(B) F2
(C) Type I integer
(D) Type I&II integer
(E) Type I&II integer callback and power model reformulation

Gurobi Termination:
2000s time limit
1% optimality gap

Default parameters

Optimal BSA	Gap [%]	Upper Bound	Lower Bound	Time [s]
IEEE-39				
(A)	Optimal	2221.04	2199.15	2.6
(B)	Optimal	2210.59	2199.15	10
(C)	Optimal	2199.15	2199.15	3.9
(D)	Optimal	2199.15	2199.15	3.2
(E)	Optimal	2206.75	2199.15	1.7
IEEE-118				
(A)	Optimal	5066.87	5018.69	50
(B)	24.9	5101.76	4084.56	2000
(C)	Optimal	5062.64	5018.16	47
(D)	Optimal	5051.41	5019.56	55
(E)	Optimal	5053.76	5018.56	120
WECC-225				
(A)	Optimal	16598.51	16574.62	96
(B)*	–	16696.60	0	2000
(C)	Optimal	16604.51	16444.93	58
(D)	Optimal	16610.33	16516.27	71
(E)	Optimal	16610.56	16510.42	53

Simulations to near optimality

(A) F1
(B) F2
(C) Type I integer
(D) Type I&II integer
(E) Type I&II integer callback and power model reformulation

Gurobi Termination:
2000s time limit
1% optimality gap

Default parameters

Optimal BSA	Gap [%]	Upper Bound	Lower Bound	Time [s]
Illinois-200				
(A)	Optimal	6480.59	6460.99	147
(B)	–	6517.80	0	2000
(C)	Optimal	6494.89	6460.99	53
(D)	Optimal	6510.60	6446.90	42
(E)	Optimal	6494.54	6460.79	44
IEEE-300				
(A)	8.69	12916.52	11883.79	2000
(B)*	–	16989.79	0	2000
(C)	3.98	12807.97	12317.66	2000
(D)	2.02	12773.35	12520.20	2000
(E)	1.18	12684.21	12536.08	2000
South Carolina-500				
(A)	156.47	13987.39	5453.70	2000
(B)*	–	19009.15	0	2000
(C)	8.55	14262.80	13138.36	2000
(D)	4.35	13778.61	13203.37	2000
(E)	5.22	13782.59	13098.70	2000

Quality of Upper Bound

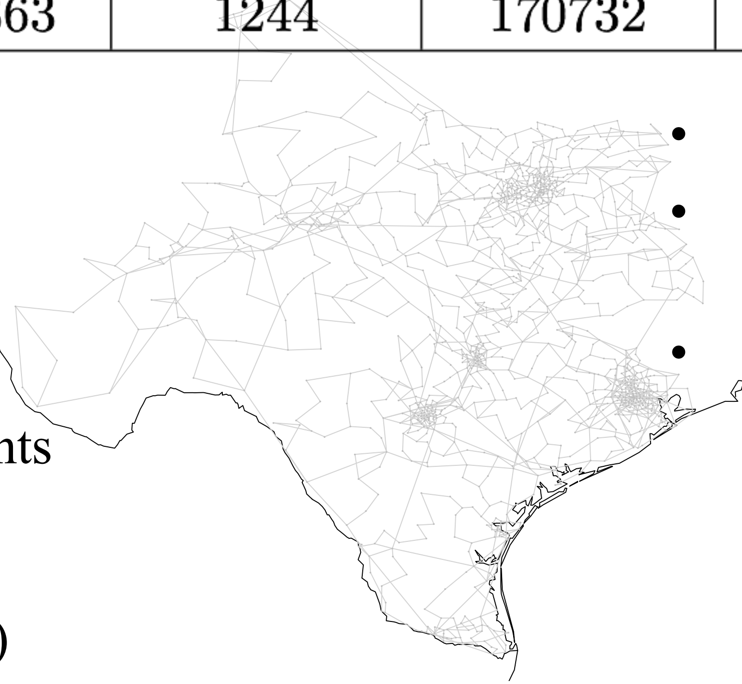
BSA Root	F_1 [%]	F_3 (Type I) [%]	F_1 & Type II [%]	F_3 & Type II [%]	Best Bound
IEEE-39	21.75	15.59	15.35	15.35	2199.15
IEEE-118	6.57	1.89	1.41	1.23	5051.41
Illinois-200	8.45	3.37	2.43	2.43	6480.59
WECC-225	4.13*	1.48	1.47	1.47	16598.51
IEEE-300	16.19	6.47	4.85	4.81	12684.21
South Carolina-500	16.99	4.19	1.07	0.95	13778.61

- Columns 2-5 are percentages above the best upper bound found from branch and bound (column 6)
- Formulation difference in strength has an impact to the full problem
- Formulation F_1 has is significantly worse than the strengthened versions
- Type II cuts seem to help only in the two largest instances
- * indicates numerical warnings and suboptimal termination

Texas

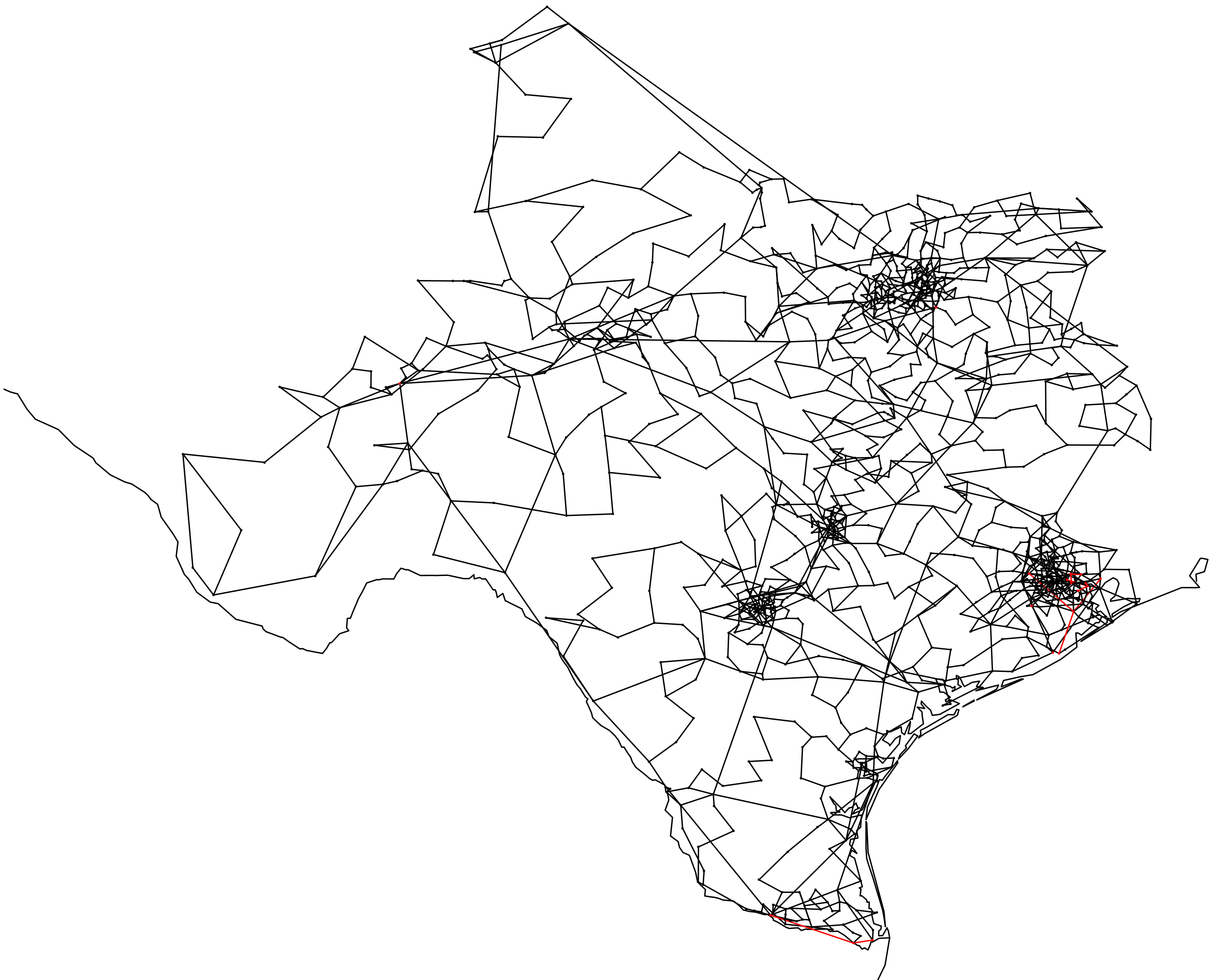
BSA Implementation	UB after root	Time after root [s]	UB at time limit	LB at time limit	Gap at time limit
(A)	178224	4597	178224	164112	8.59%
(C)	175366	5475	173712	164112	5.84%
(D)	171874	11371	171874	164112	4.72%
(E)	171863	1244	170732	164112	4.03%

- 2000 buses
  3206 branches
  544 generators
  40 time steps
- 1 830 671 constraints
  779 178 variables
  (274 064 binary)
  for formulation (A)



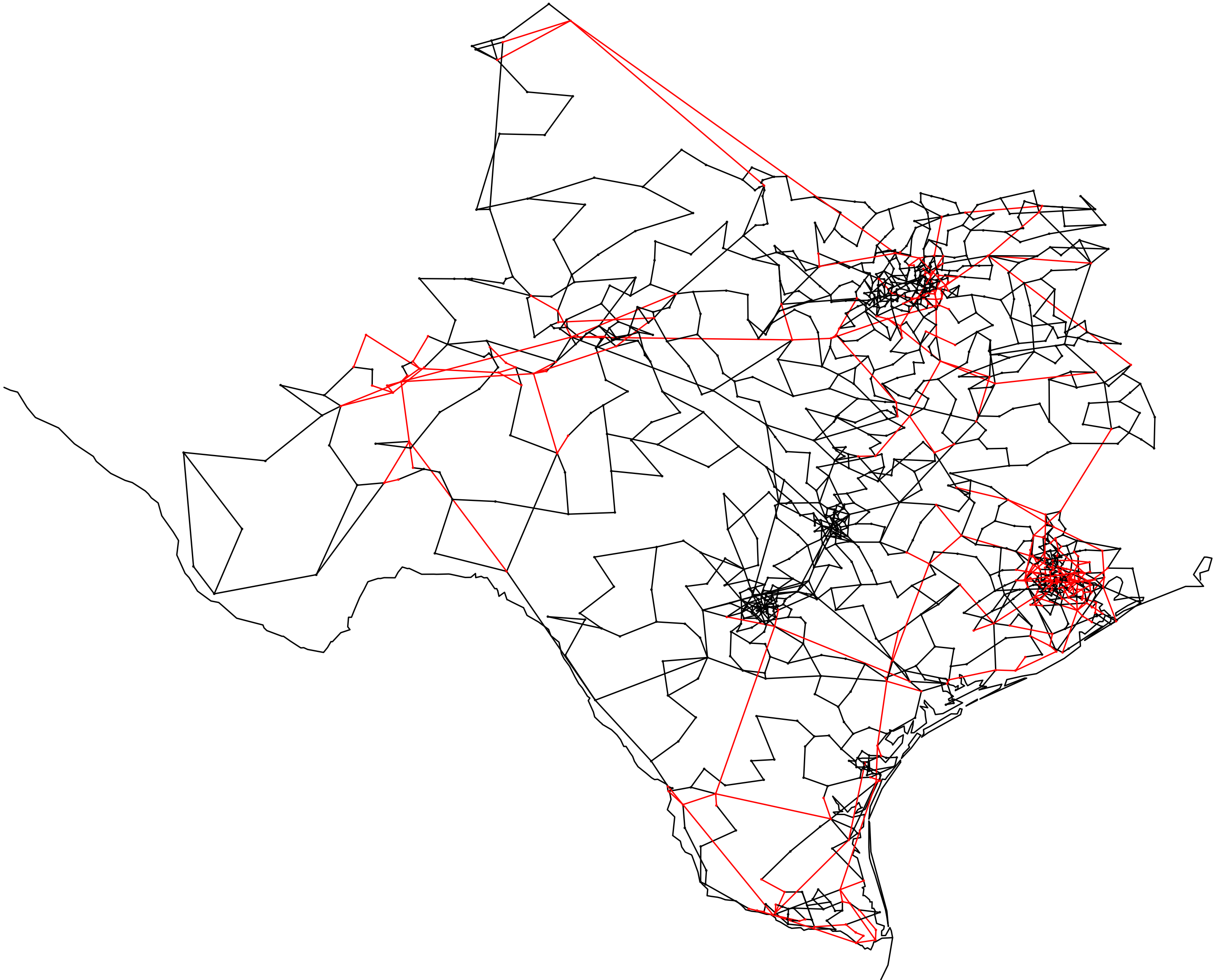
- Heuristic for LB
- Gurobi Termination
  20 000 time limit
- Heuristics parameter: 0.3
  Custom Branching Priority
  Lazy Constraints
  Method: 3

T = 2

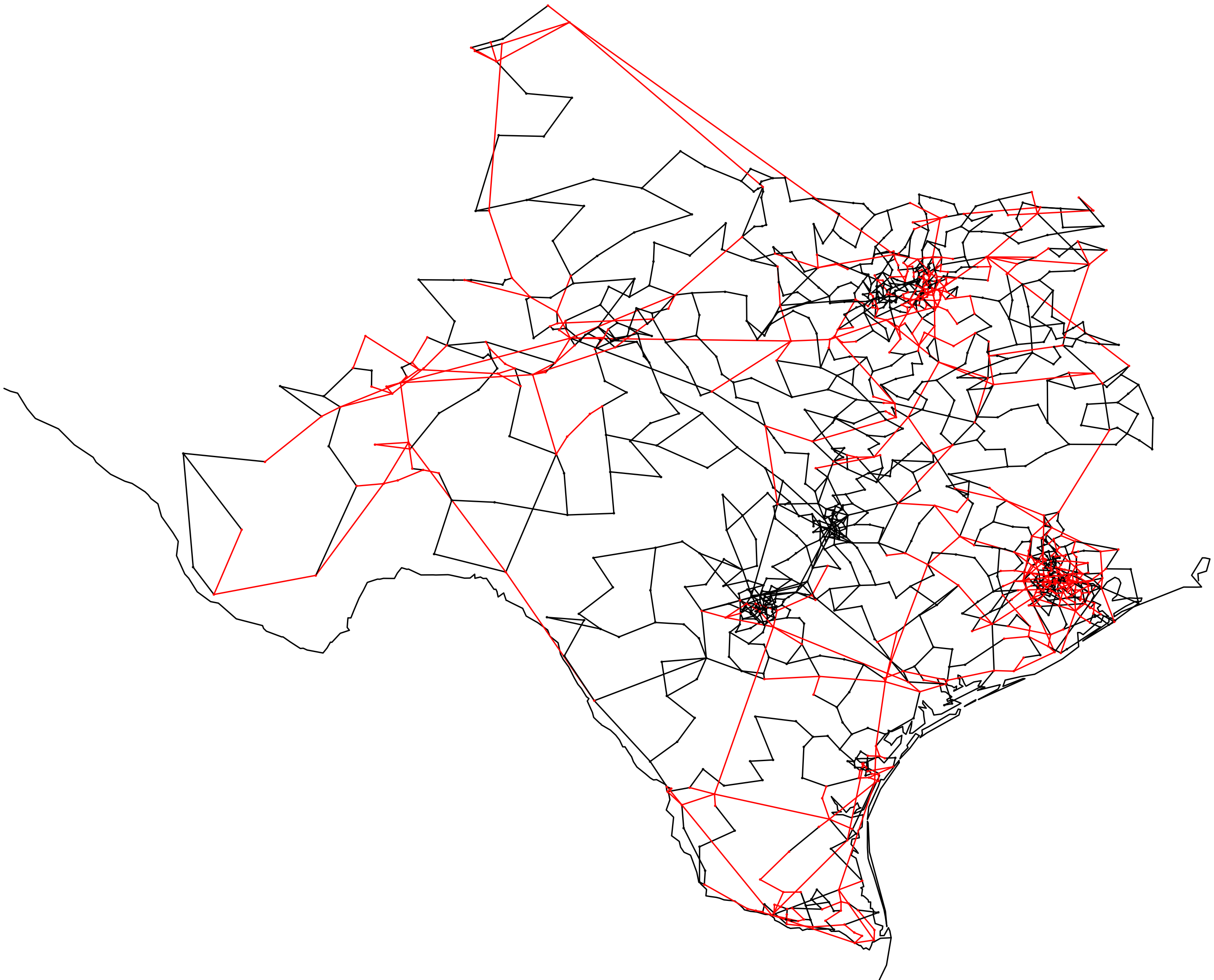


T = 3

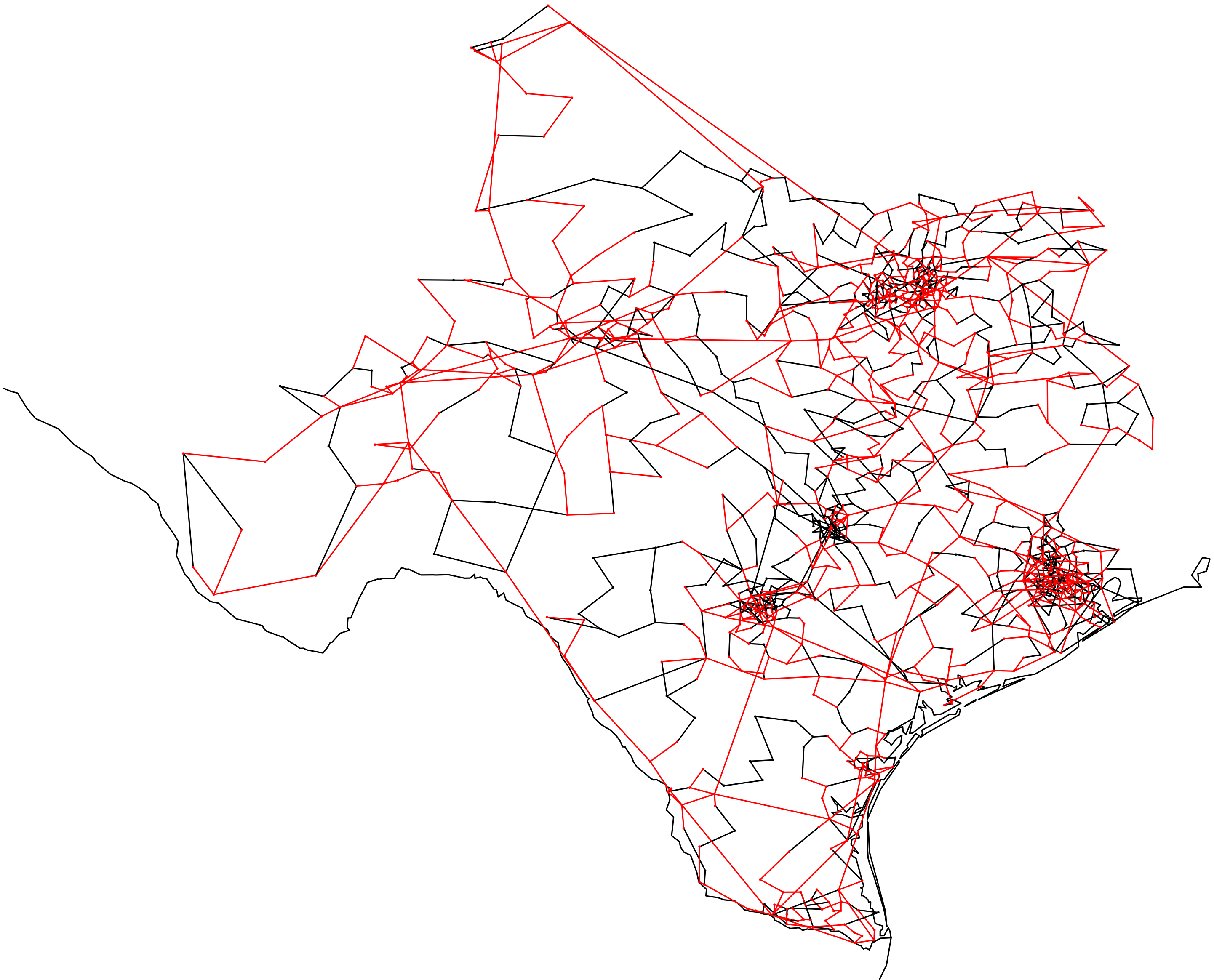
T = 7



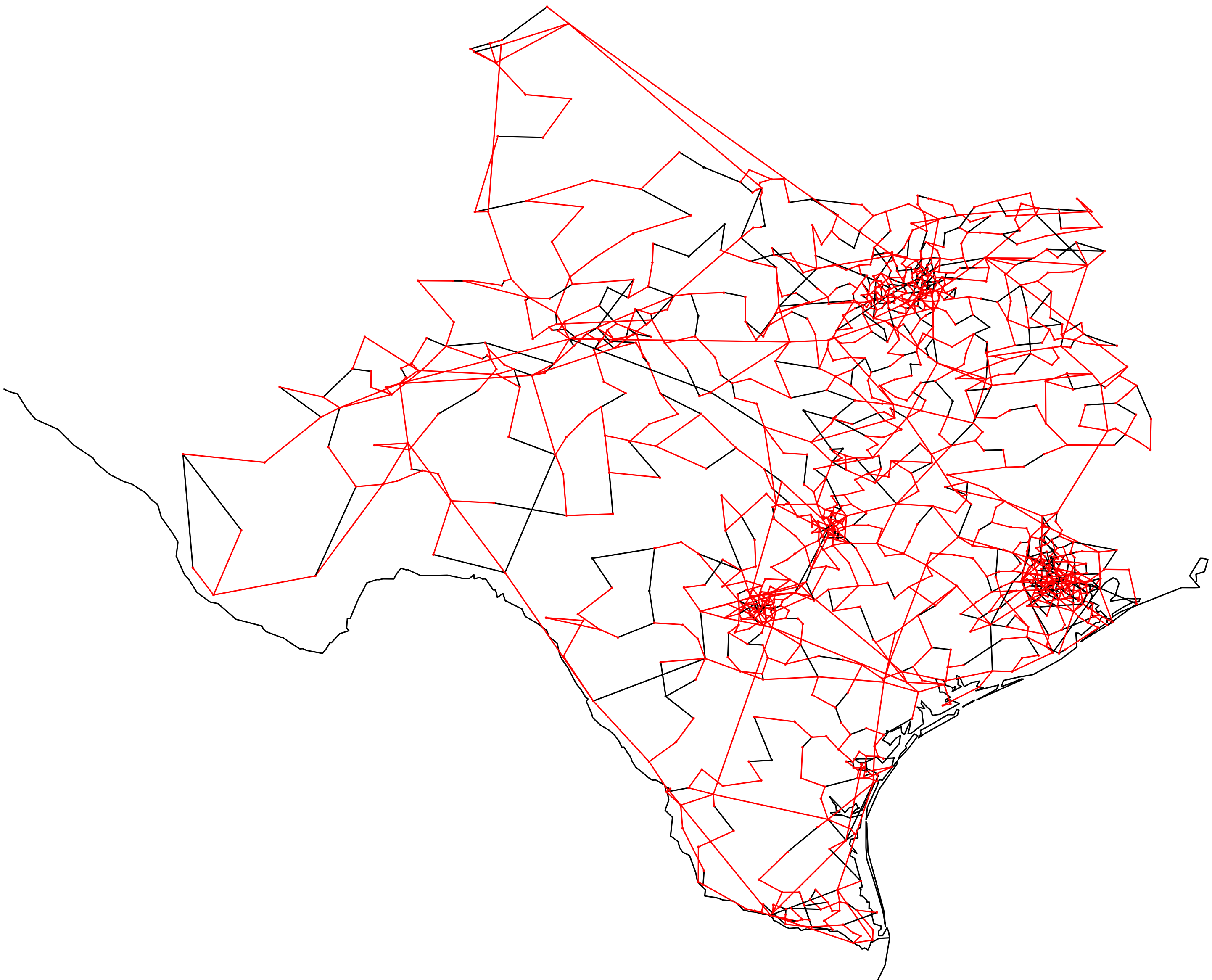
T = 10



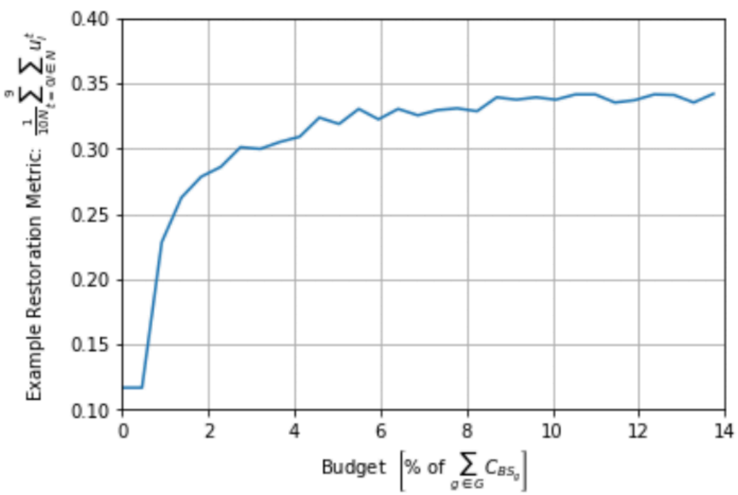
T = 15



T = 20



A use case



- Plot a restoration metric as a function of the budget for allocation (WECC). Budget is measured as a percentage of the cost to allocate all units.
- Note:
  - There is a 157% improvement in the metric by investing 2.74% of the total cost
  - Investing more than 4% does not seem to yield a substantial additional improvement

Important reminders

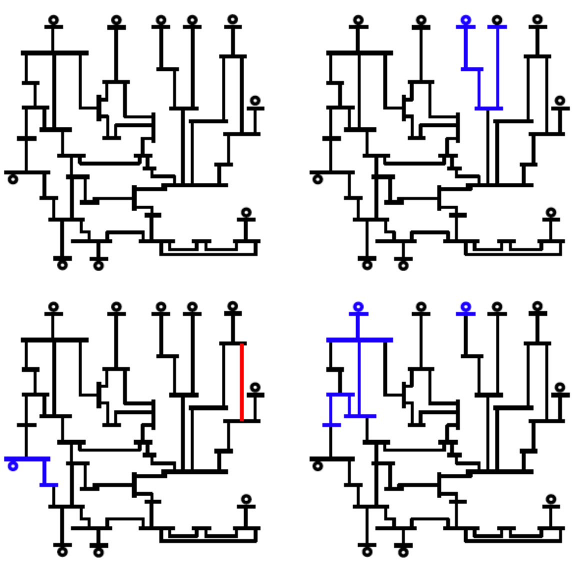
- The simplified model is not guaranteed to provide feasible restoration sequences – it is only meant as the first step of the planning process for black start.
- The computational benefits for the MIP may not be realized if a different model is used (add/remove constraints) or if a different objective is used for the problem.

Outline

- Power System Resilience: Motivation and Definition
- Black Start and Restoration: Planning and Reality
- Optimal Black Start Allocation: Modeling and Solution Approach
- Optimal Black Start Allocation: Reformulations (simplified model)
- **Extension: Stochastic Black Start Allocation**
- Extension: Power System Restoration
- Conclusions

Accommodating for uncertainty

- We care about an optimal allocation over a set of **outage scenarios**
- Scenarios can include:
  - Partial/total outages of the power system
  - Unavailability of lines, generators, or buses

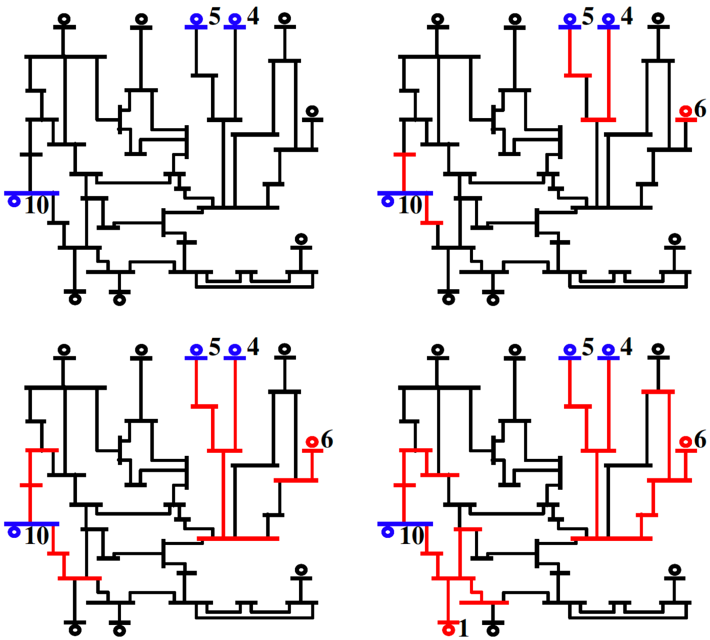


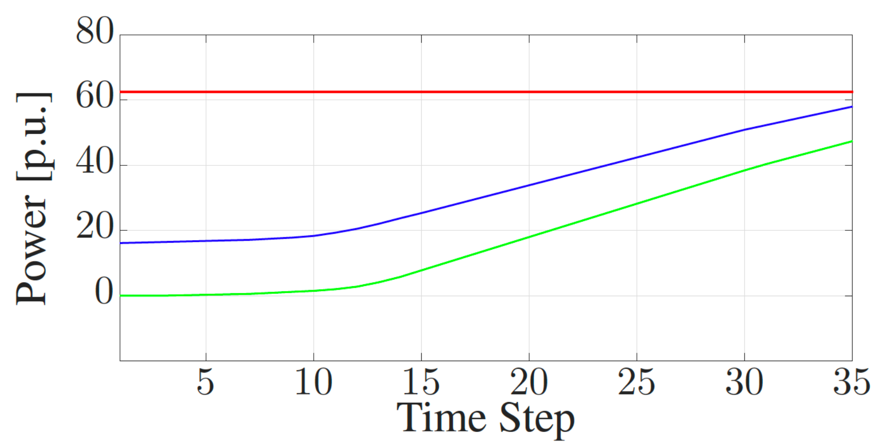
- Scenarios can be generated based on expert knowledge of the power system/past outage data/research studies

A small example

Example: IEEE-39 (39 buses, 10 generators, and 34 branches):

The decomposition algorithm was parallelized in 6 nodes with 2 jobs per node (Lawrence Livermore National Laboratory Cab Cluster)





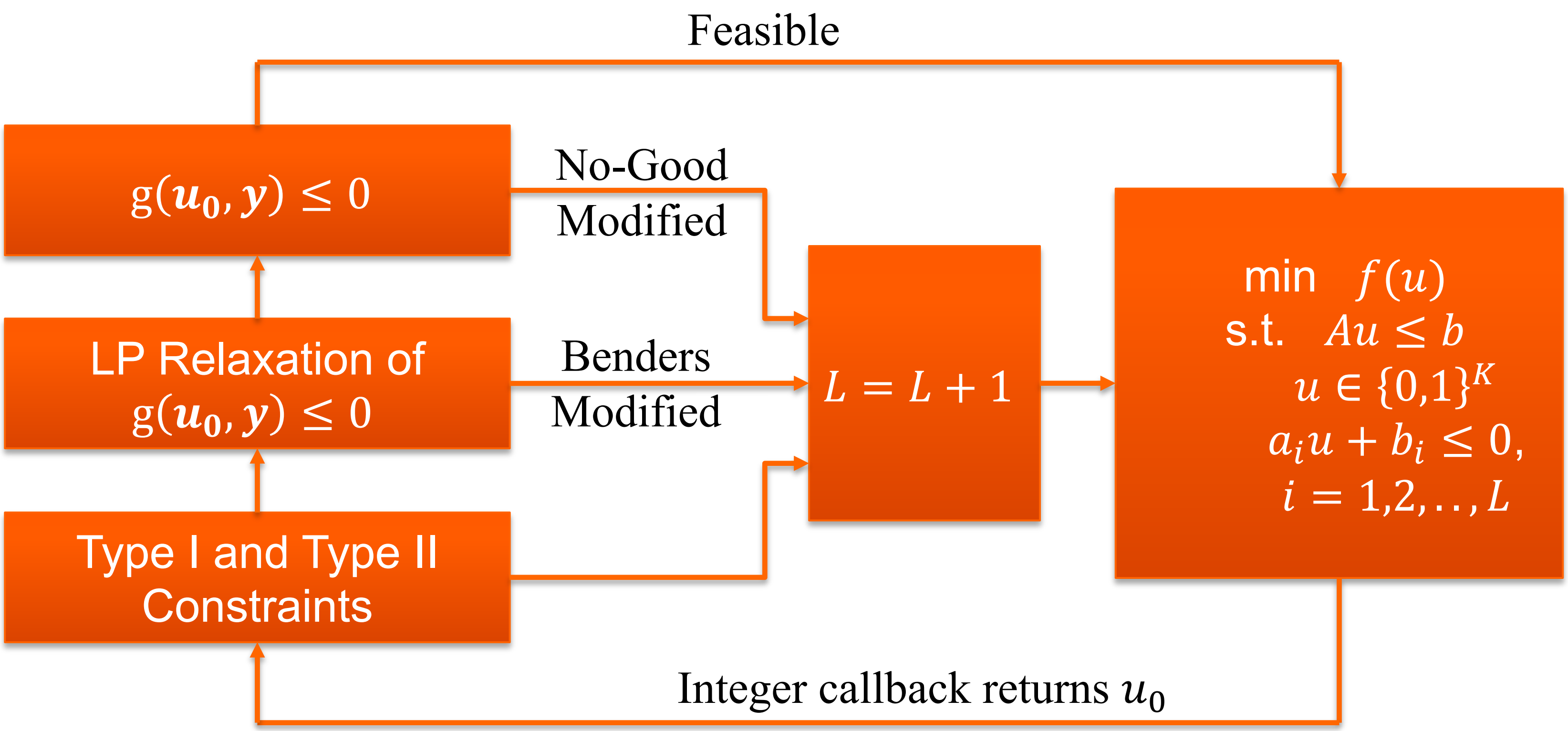
[21] Patsakis, Georgios, Ignacio Aravena, and Deepak Rajan. "A Stochastic Program for Black Start Allocation." Proceedings of the 52nd Hawaii International Conference on System Sciences. 2019.

Outline

- Power System Resilience: Motivation and Definition
- Black Start and Restoration: Planning and Reality
- Optimal Black Start Allocation: Modeling and Solution Approach
- Optimal Black Start Allocation: Reformulations (simplified model)
- Extension: Stochastic Black Start Allocation
- **Extension: Power System Restoration**
- Conclusions

Power System Restoration

- Given a binary restoration plan $\boldsymbol{u}$, a feasibility problem $\mathrm{g}(\boldsymbol{u},\boldsymbol{y}) \leq 0$ with respect to a mixed integer $\boldsymbol{y}$ is solved to determine if the plan $\boldsymbol{u}$ is feasible.



[22] Aravena, I., Rajan, D., Patsakis, G., Oren, S., and Rios, J., "A scalable mixed-integer decomposition approach for optimal power system restoration", available at Optimization Online

Outline

- Power System Resilience: Motivation and Definition
- Black Start and Restoration: Planning and Reality
- Optimal Black Start Allocation: Modeling and Solution Approach
- Optimal Black Start Allocation: Reformulations (simplified model)
- Extension: Stochastic Black Start Allocation
- Extension: Power System Restoration
- **Conclusions**

Conclusions

- This talk focused on models and computational techniques for black start allocation.
- This is only one step in a multi-stage planning and execution process that requires many different levels of expertise.
- Specialized techniques can enable solving the resulting large-scale MIPs:
    - Customized heuristics
    - Stronger formulations
    - Decomposition algorithms

Questions?

Georgios Patsakis

(gpatsakis@berkeley.edu)