Modeling Power System Restoration

Feng Qiu [1]

A joint work with Jianhui Wang[1], Peijie Li [2]
and Jianzhong Tong[3]

[1]Energy Systems Division
Argonne National Laboratory

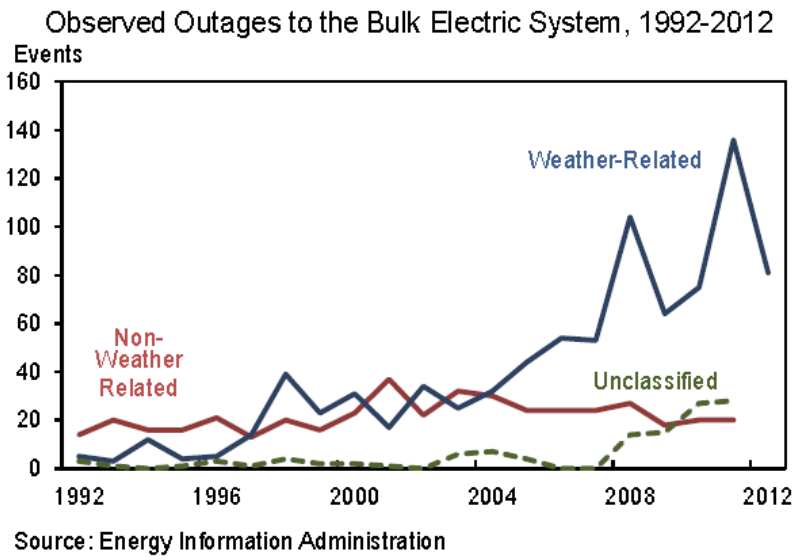
[2]Department of Electric Engineering
Guangxi University

[3]PJM

Resilience Week 2016
August 18, 2016

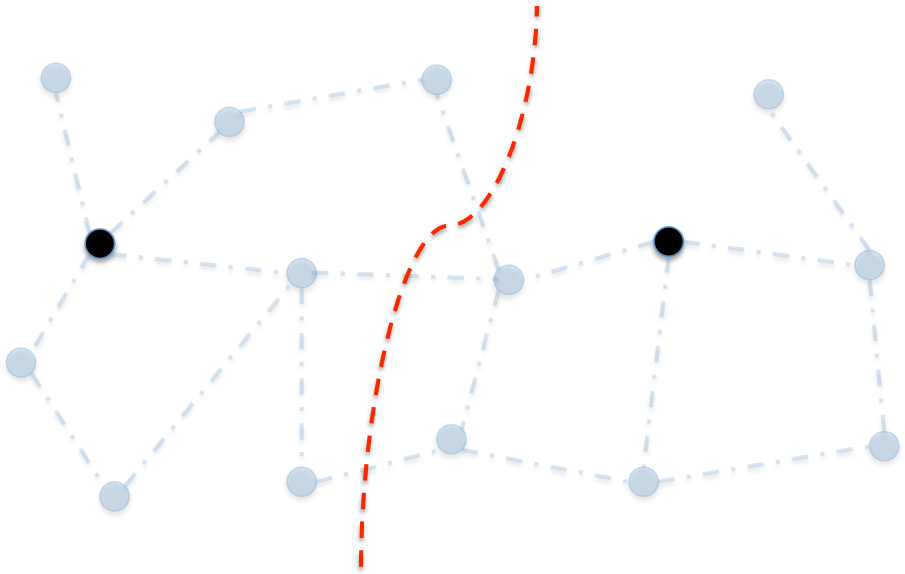
Outages and Blackouts

- Power outages have become more and more frequent



- Hurricane Sandy: 7.5 million customers without power [Che et. al. 14']
- Huge cost: $25-$70 billion a year [congressional research service, 12']
- The longer the blackouts are, the more costly the damages will be
- Focus on **transmission and generation recovery**

Build-up Restoration Strategy



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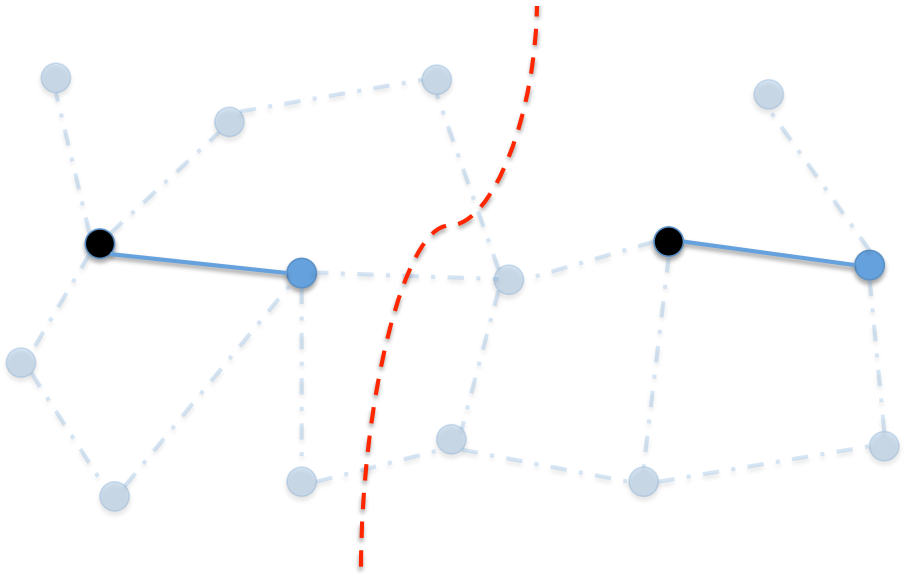
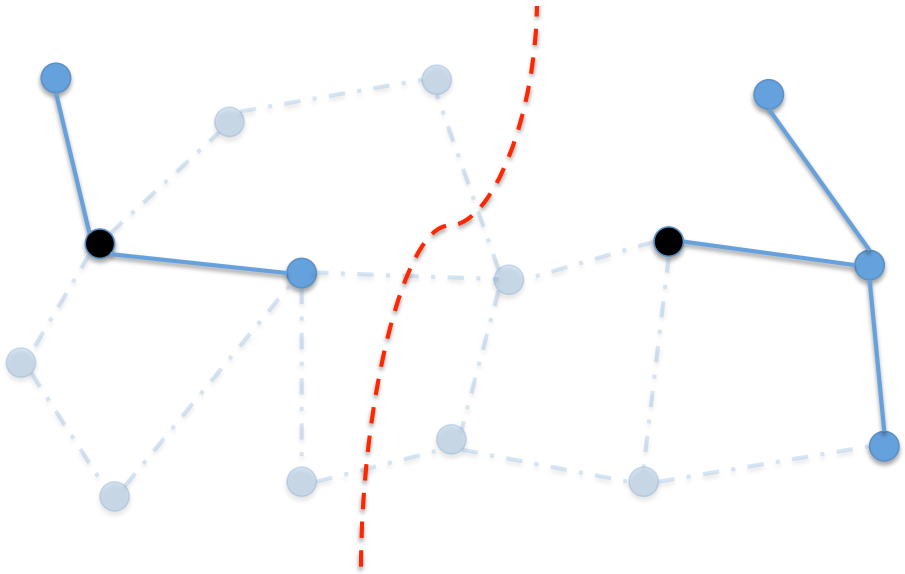


- Always starts from BS units
- Parallel recovery
- Two steps conceptually: sectionalization/partition and start-up sequencing
- How quickly each subsystem is restored relies heavily on how the system is sectionalized

Build-up Restoration Strategy



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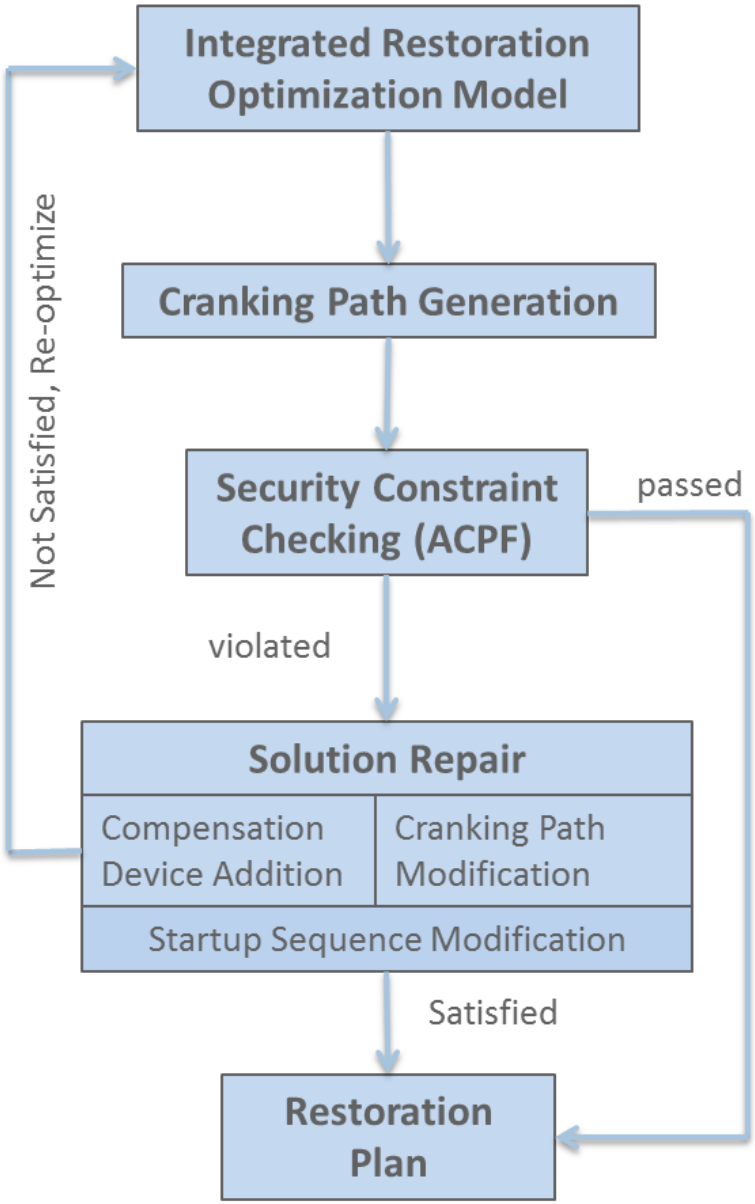
Modeling Challenges

- Highly nonlinear and combinatorial process
  - Non-convex and discontinues generation capacity curves
  - Non-linear stability constraints at multiple operating points
- Multiple decisions
  - Islanding (graph partition), start-up sequencing (scheduling), transmission path search (topology optimization), load pickup (lot-sizing) .....
- Compromise between optimality and tractability
  - Linearization generation capacity curves
  - Separation of linearity from nonlinearity: optimization (linear constraints) and then validation (nonlinear constraints)
  - Prioritize optimization modules
    - First and foremost: integrated sectionalization and sequencing

Integrated Restoration Planning Framework

- Integrated restoration optimization model produce an initial parallel recovery plan
- Cranking path module finds transmission path to energize to crank a generator
- Security constraint checking module checks transmission limit and voltage stability
- Three options to fix a restoration plan
  - Add compensation devices (for voltage violation)
  - Switch to another cranking path so that transmission or voltage violation is eliminated; it may track back and change previous transmission paths
  - Remove the current sequencing result and resolve the sequencing problem in this section to find the next best sequencing solution
- If a restoration plan cannot be repaired (or with an unsatisfied quality), remove current plan from solution space and resolve the integrated restoration optimization model



Sectionalization/Partition

- Mathematical description
  - N all buses; $I \subseteq N$ buses with a NBS; $J \subseteq N$ buses with a BS; L transmission lines
  - Given a graph $G(N, L)$ (L is the set of all arcs) and mutually disjoint nonempty sets $J_1, \ldots, J_m \subseteq N$
  - Partition G into mutually vertex-disjoint connected subgraphs $G_1, \ldots, G_m$ of G such that $J_i \subseteq V_{G_i}$ for $1 \leq i \leq m$
- Sectionalization is $\mathcal{NP}$-complete
  - 2-DISJOINT CONNECTED SUBGRAPHS [Hof et al., 09']
- Simplification
  - $|J_i| = 1$ for all $1 \leq i \leq m$
  - Each section consists of only one BS unit

Start-up Sequencing

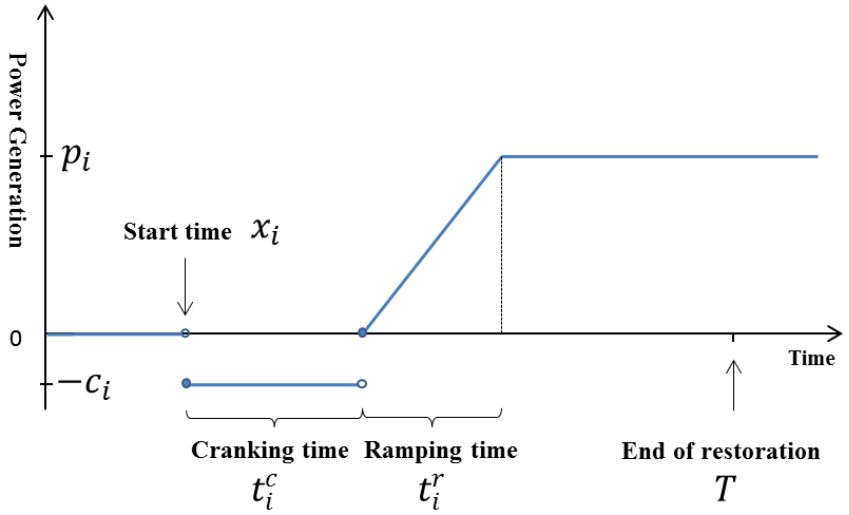


Figure: Generation capability curve of a NBS

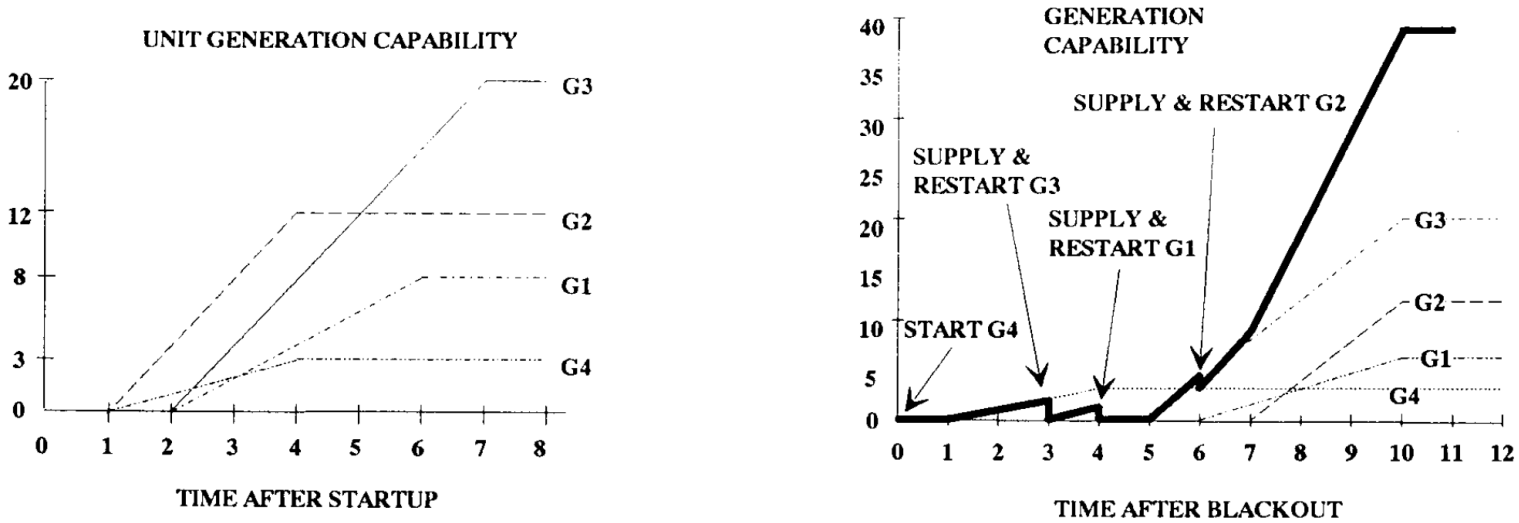


Figure: A Start-up Example with 4 NBS[1]

[1] Liu, Chu, and Holen 93'

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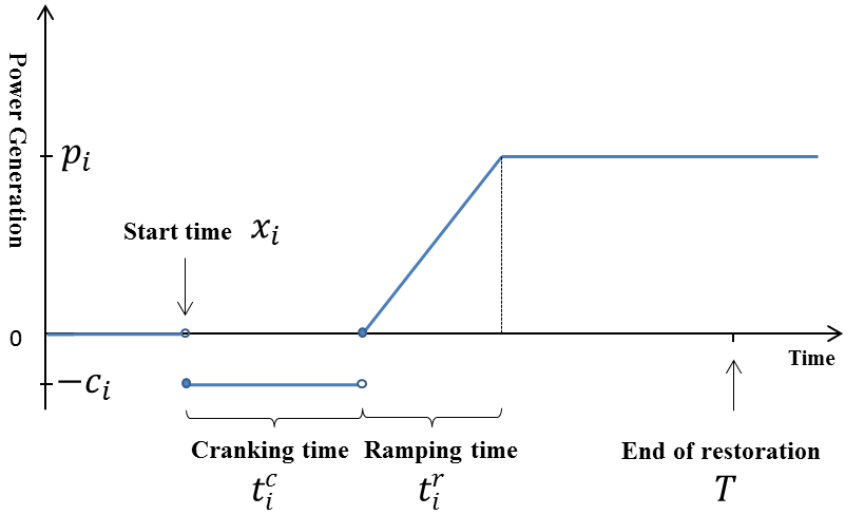

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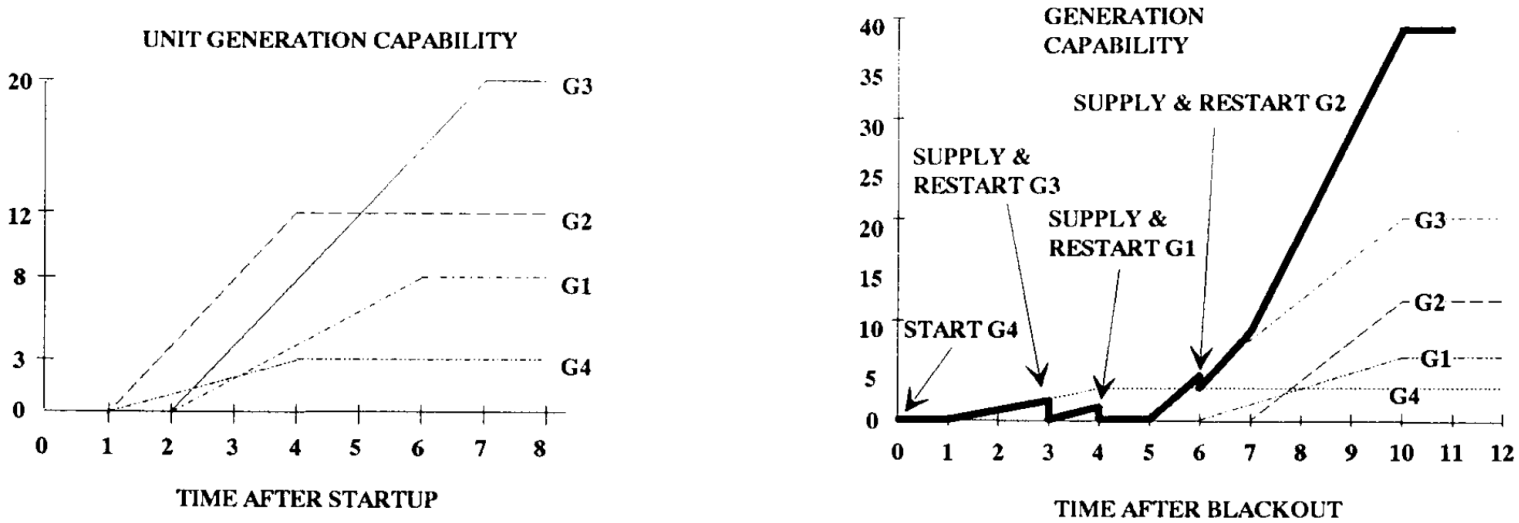

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Case Study

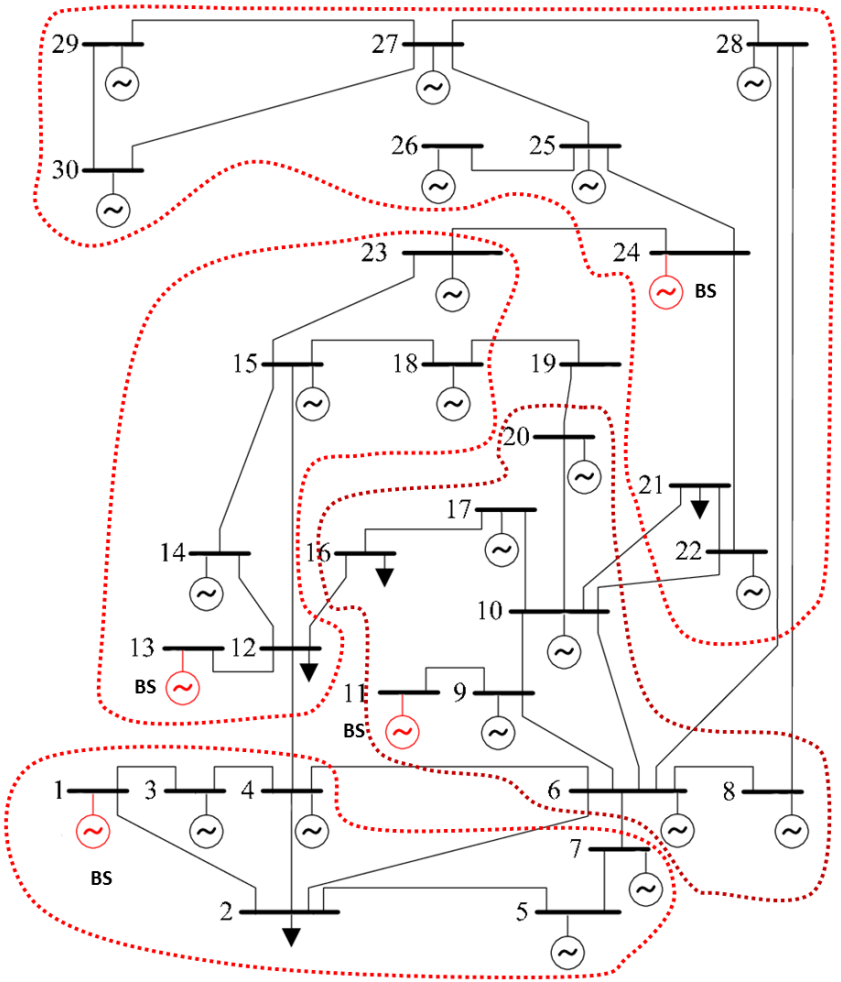
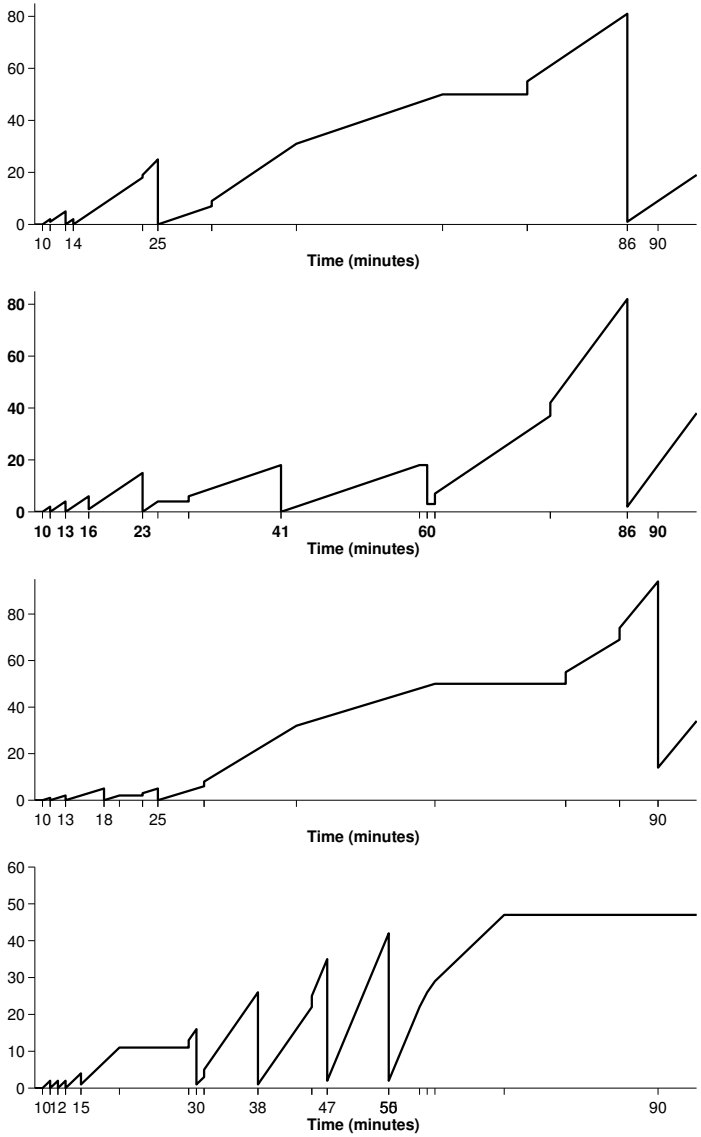


Figure: Sectionalization



Restoration Plan Refinement

- An IEEE-118-Bus System
  - Given a start-up sequence produced by MIP model, a sequence of ACOPFs are solved to ensure voltage stability

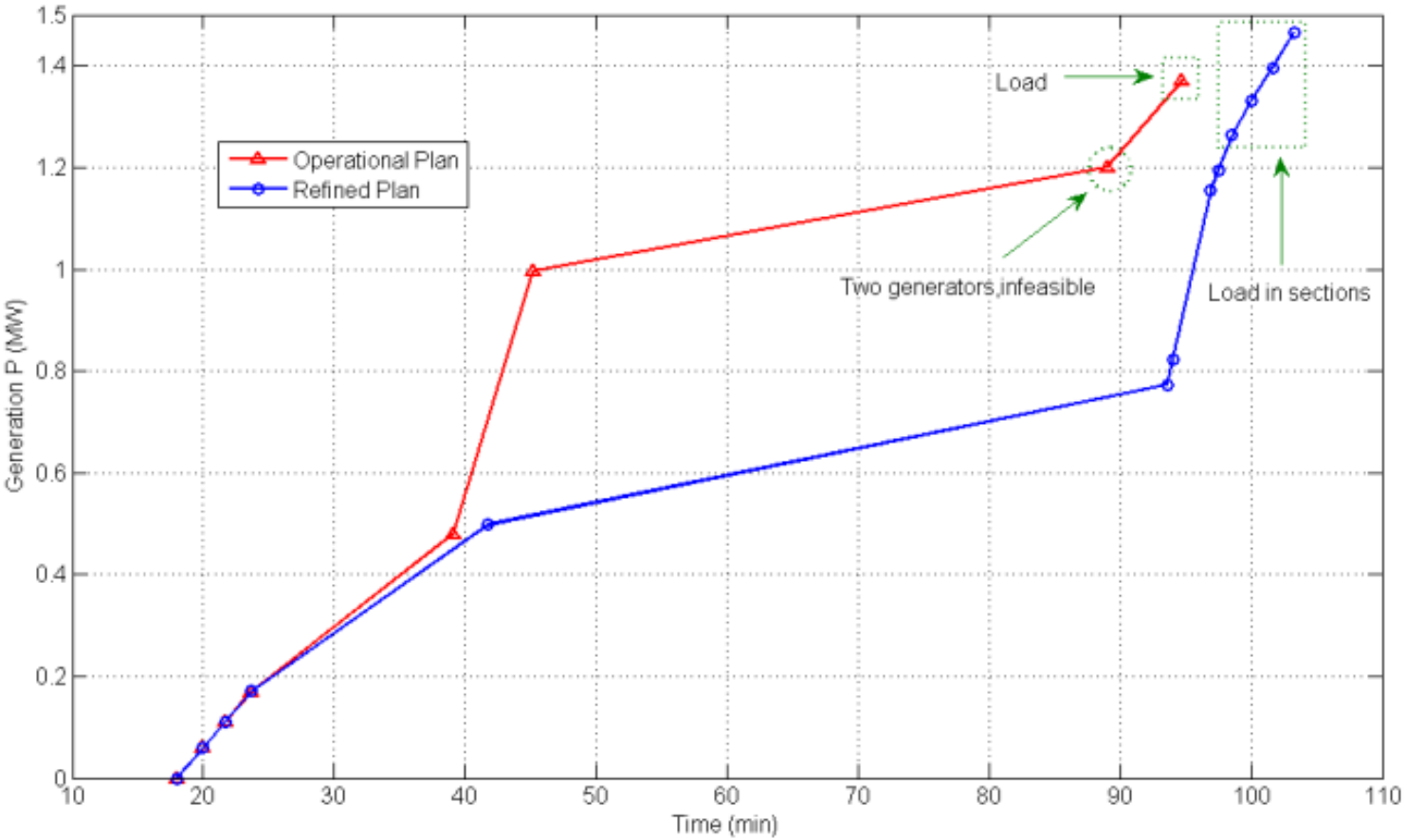


Figure: Operational Plan V.S. Refined Plan

Black-Start Resource Procurement

- Independent System Operators (ISOs) identify and contract resources with BS capability and establishes financial agreements with them to provide this obligatory service
- To meet the system restoration requirement, questions to be answered:
  - Existing black start generators are enough?
  - If not, where and how many new black start capacities are required?
- A black-start resource procurement pan:
  - Given a restoration requirement, i.e., time limit, procure a set of BS resources that has the minimal cost and satisfy the requirement
  - Procurement plan must be analyzed together with restoration plan

Case Study

- Restoration time limit = 50 minutes
- Optimal procurement plan: BS resources at buses 13 and 24

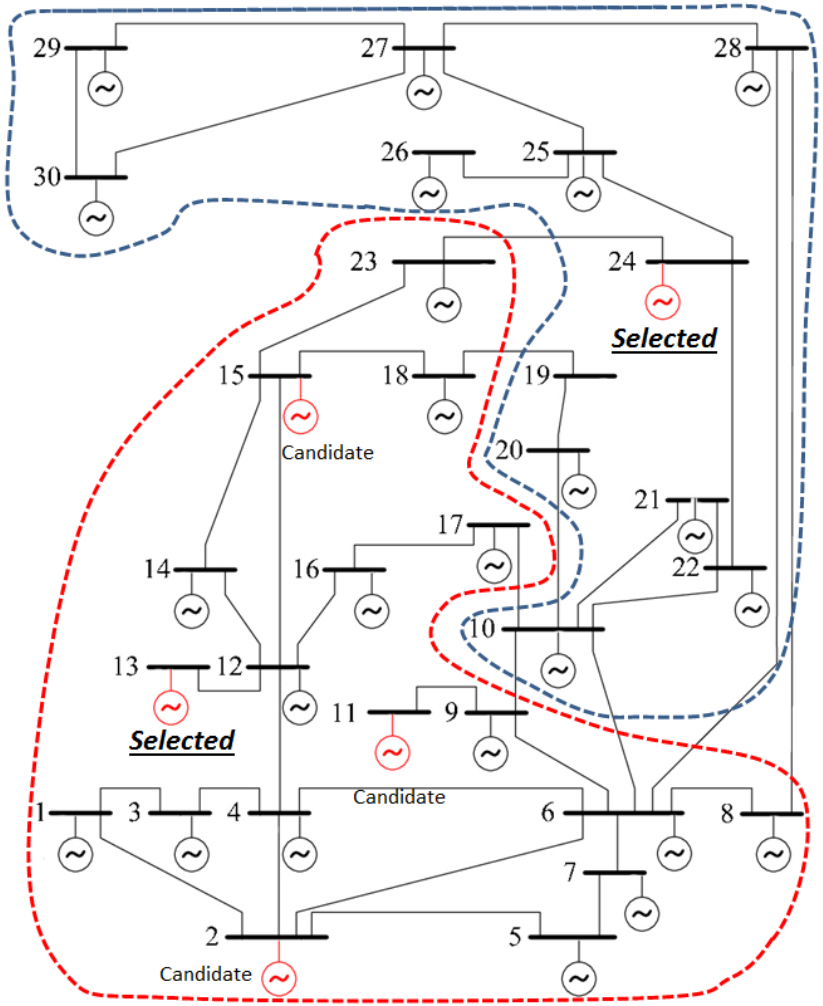


Figure: Islanding With Two Procured BS Units

Thank you!

Comments?