Safety-Assured Collaborative Load Management in Smart Grids

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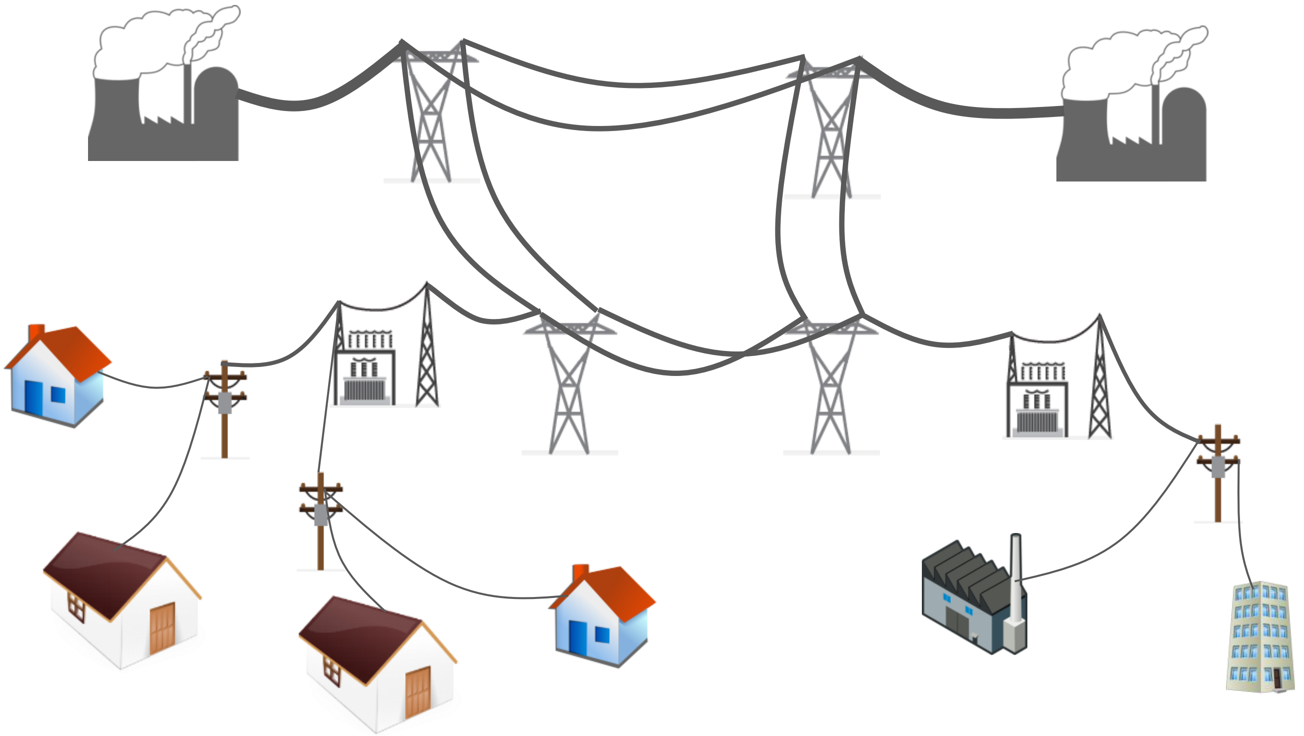
Overloaded Grid is Unsafe



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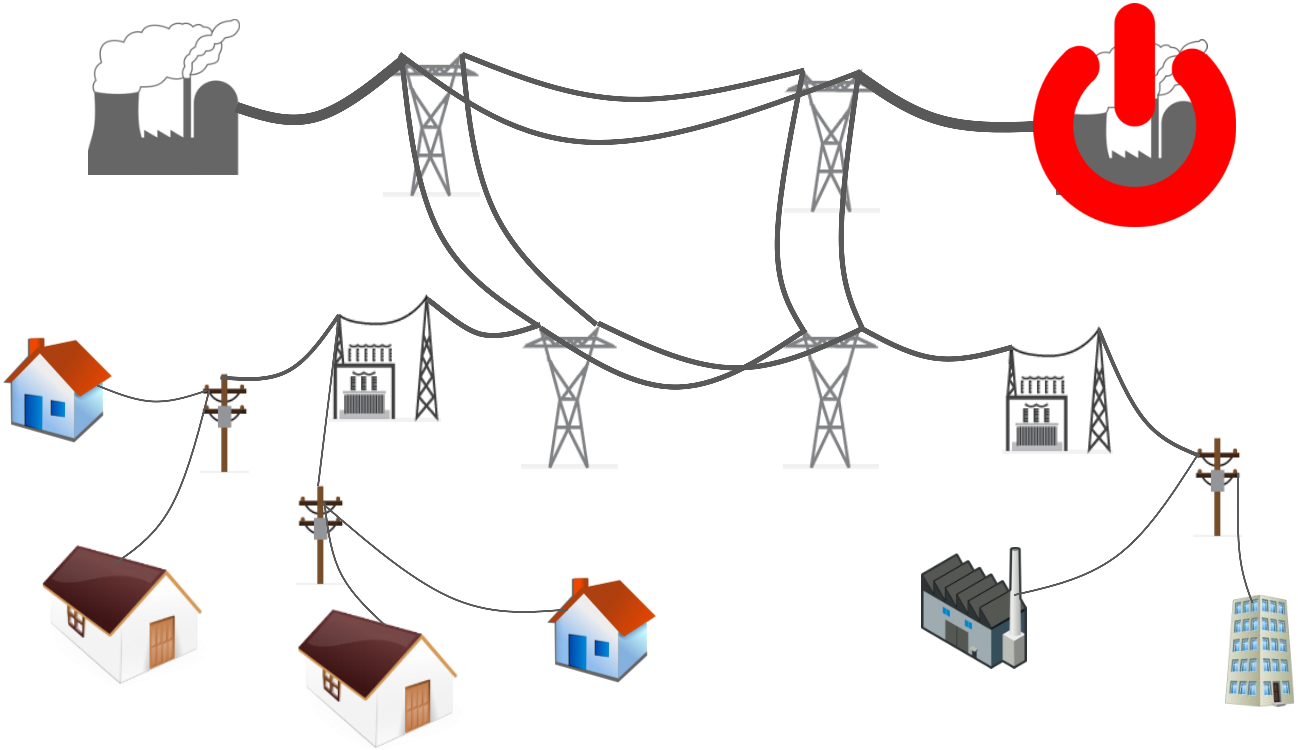

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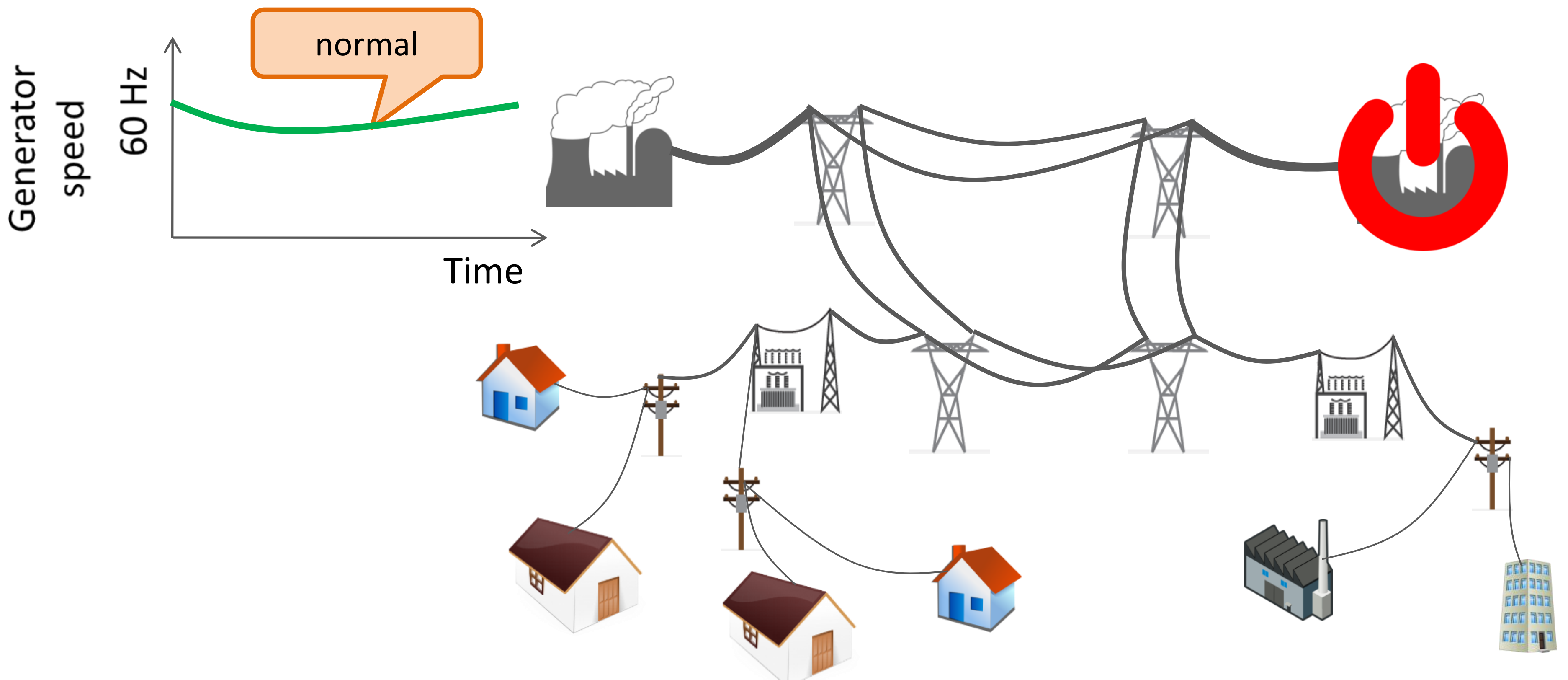

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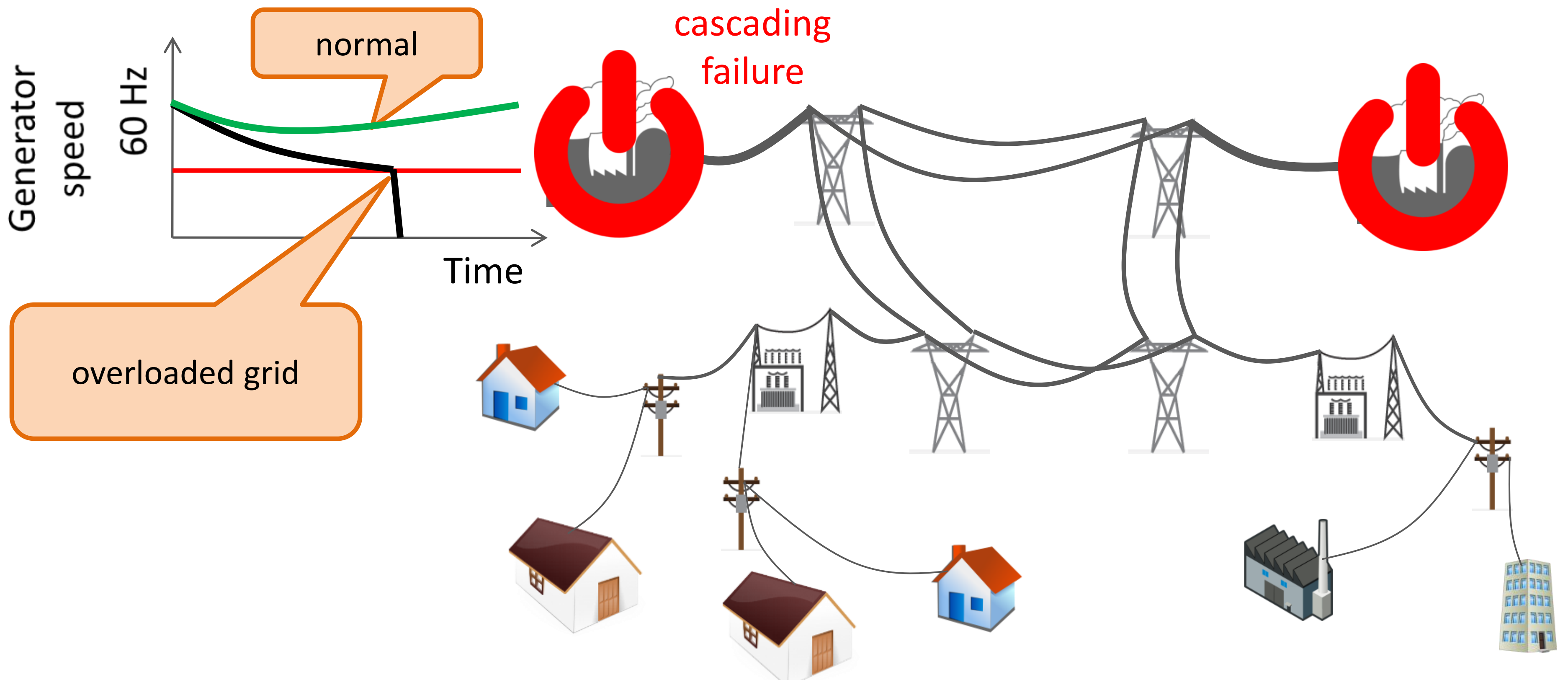

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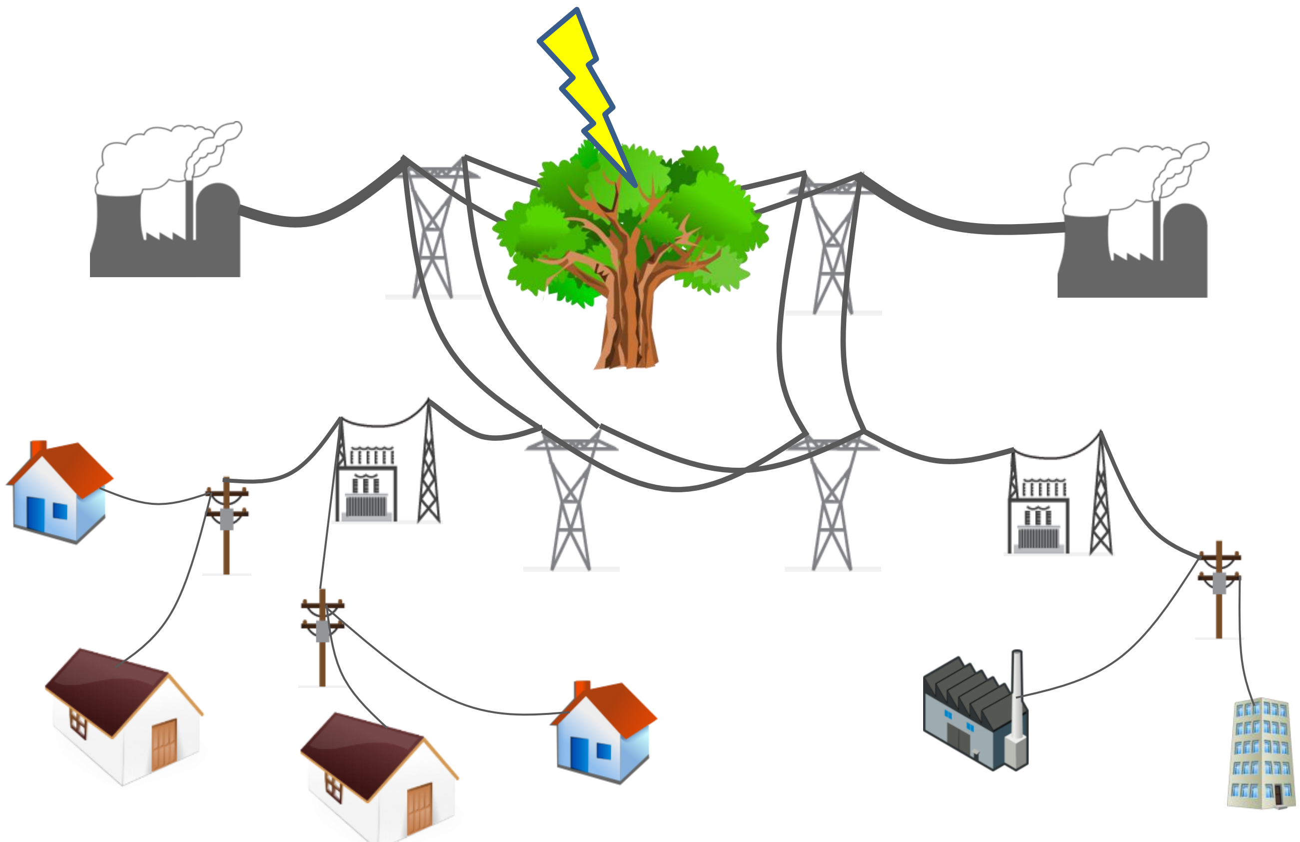
- Transmission line short circuit
  - Hits by overgrown trees (2003 Northeast Blackout)



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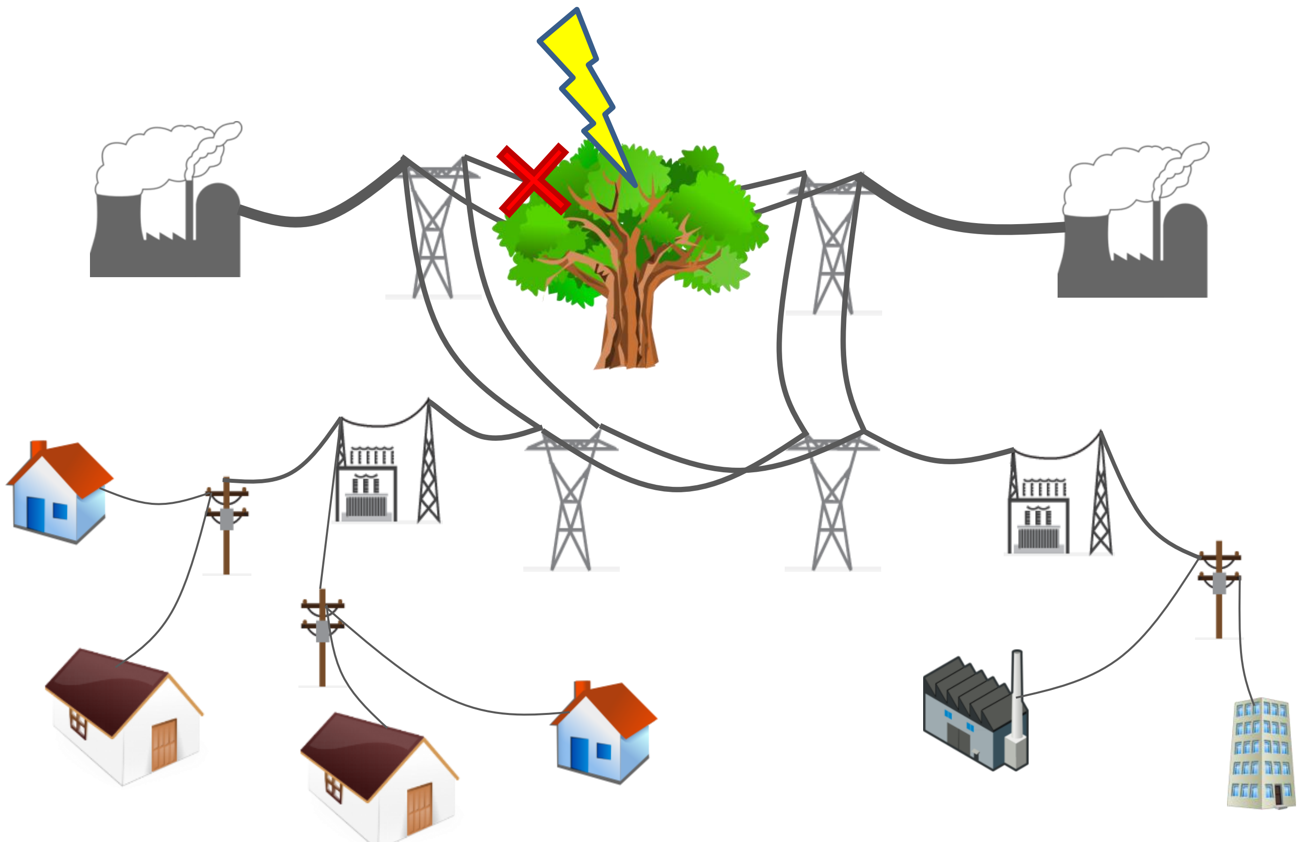

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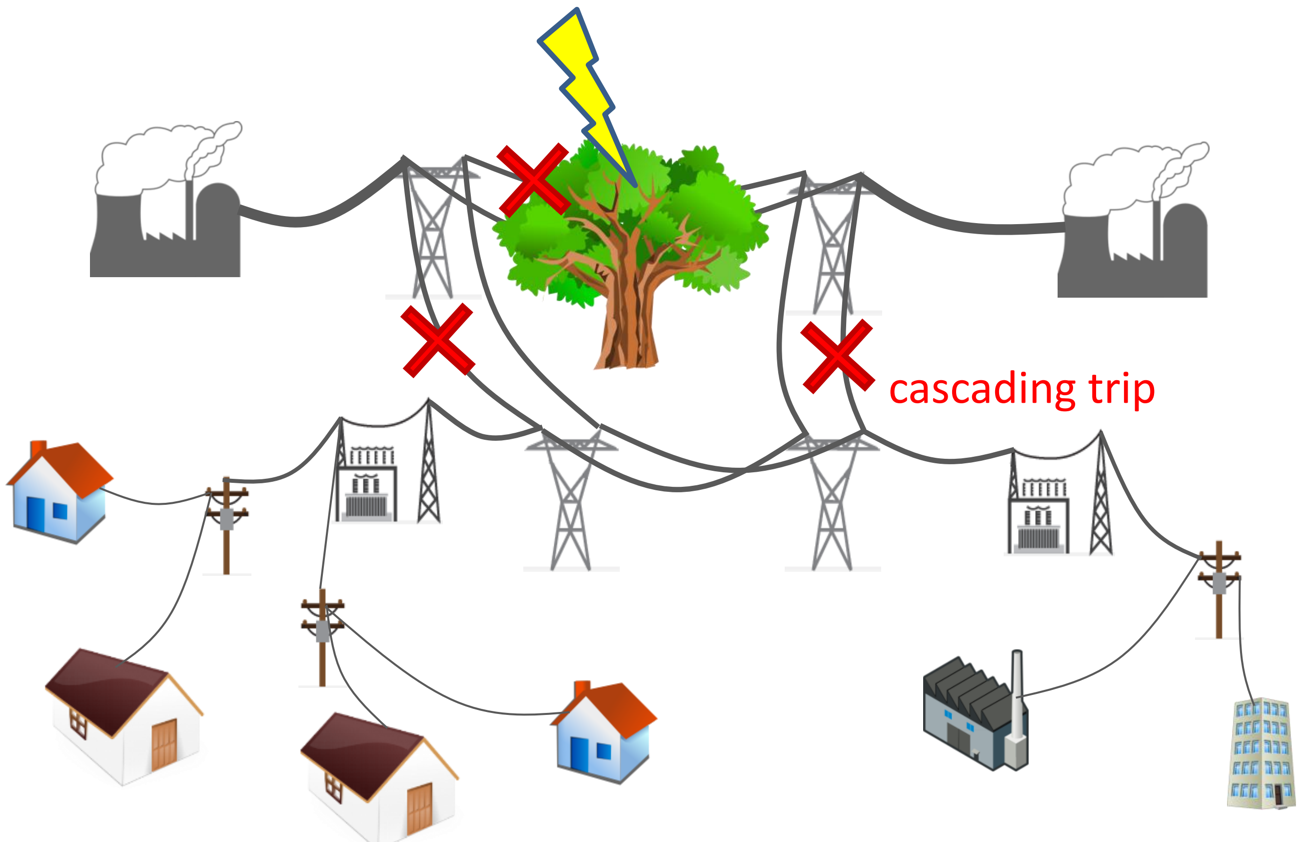
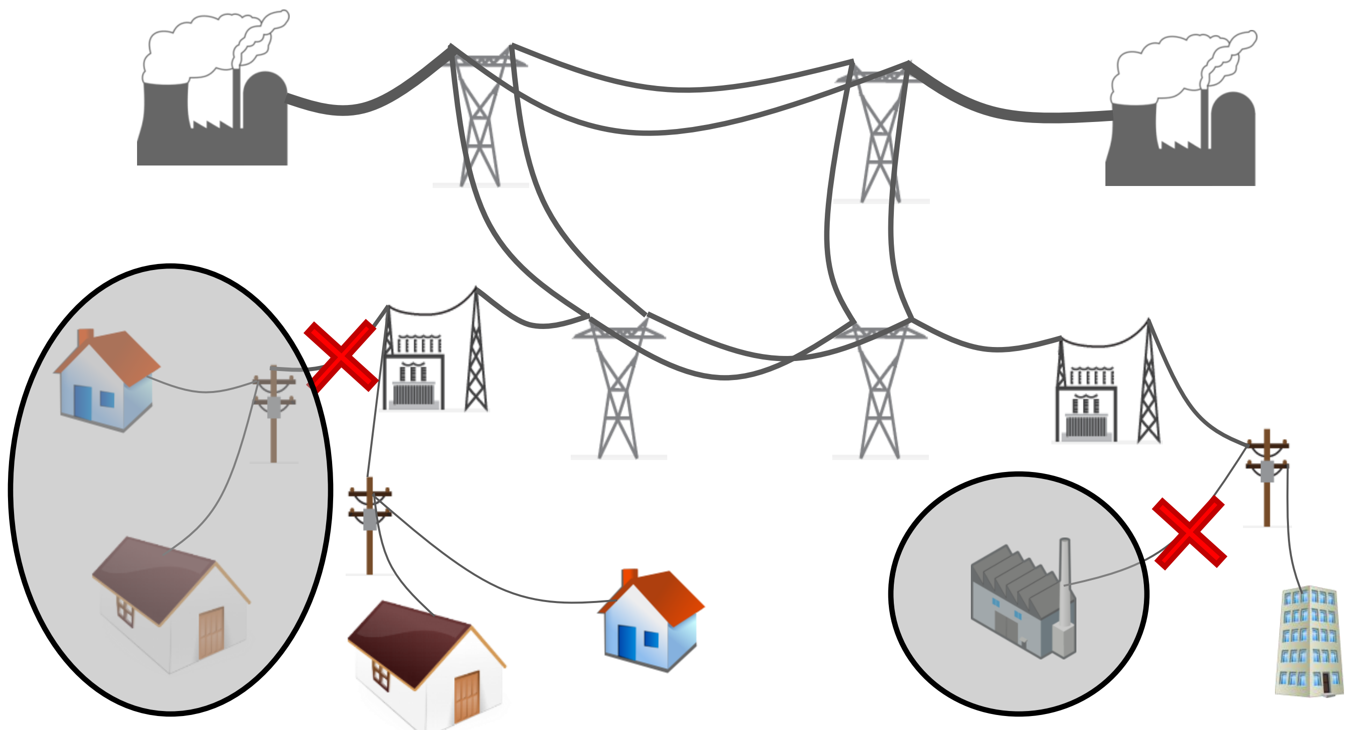
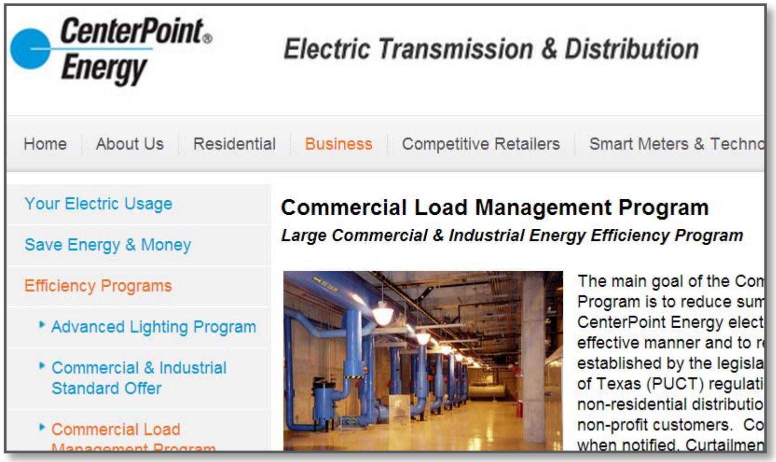


Existing Solution: Load Shedding

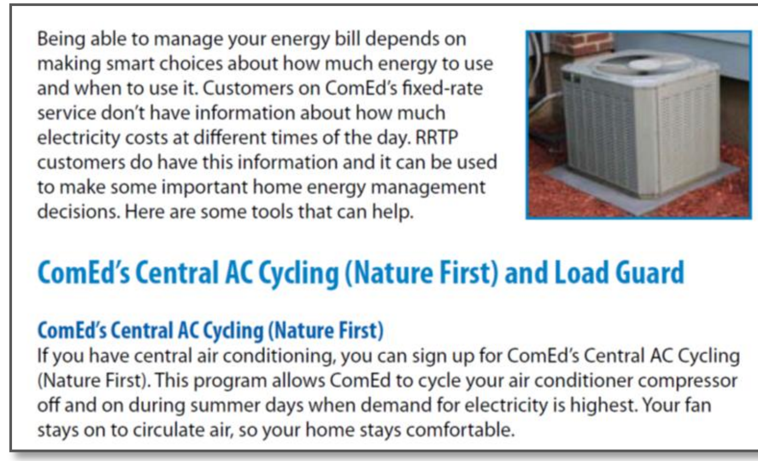
- Disconnect some loads
  - When demand surges or failure detected
  - Resilient to (remaining) credible contingencies
- Unfair, uncomfortable



New Opportunity: Load Curtailment



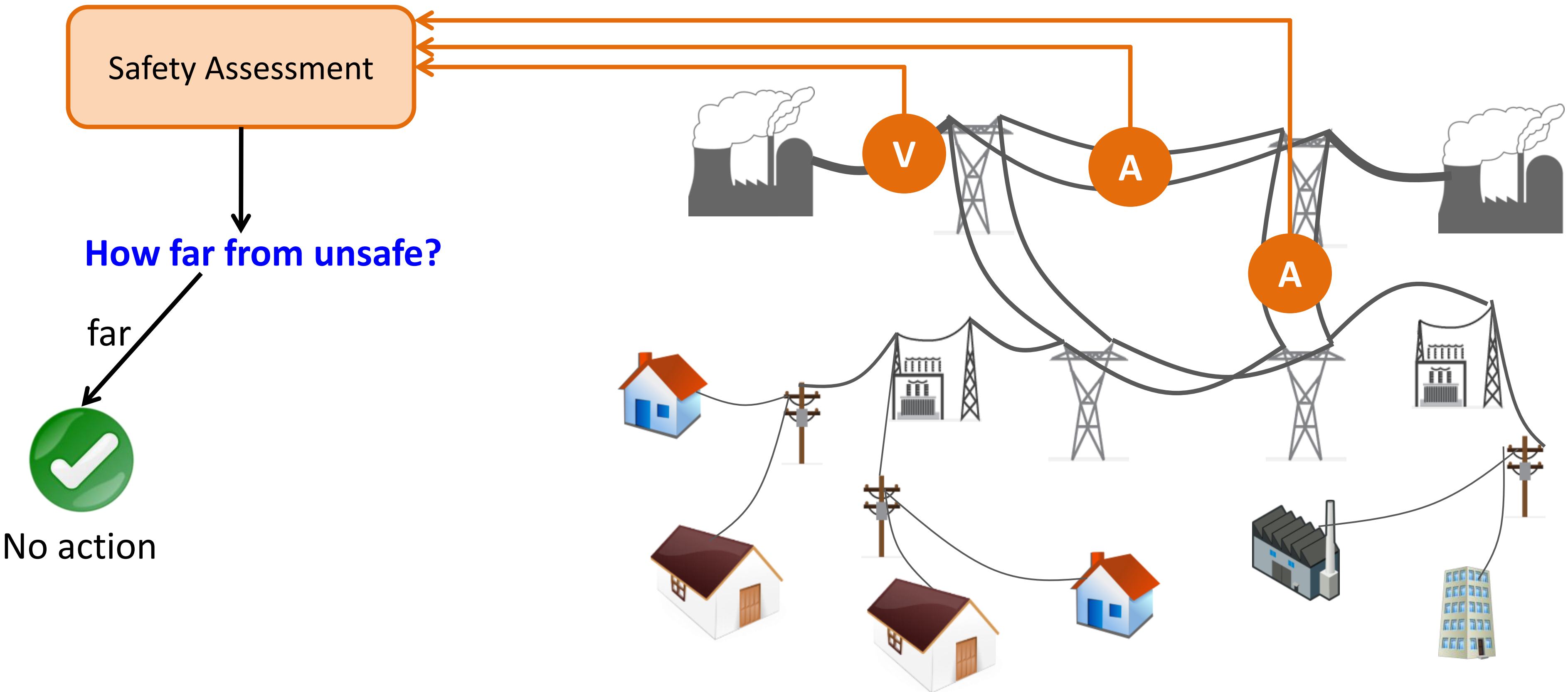
Large commercial and industrial curtailment programs [CenterPoint Energy]



Residential air conditioner moderated by real-time electricity price [ComEd Illinois]

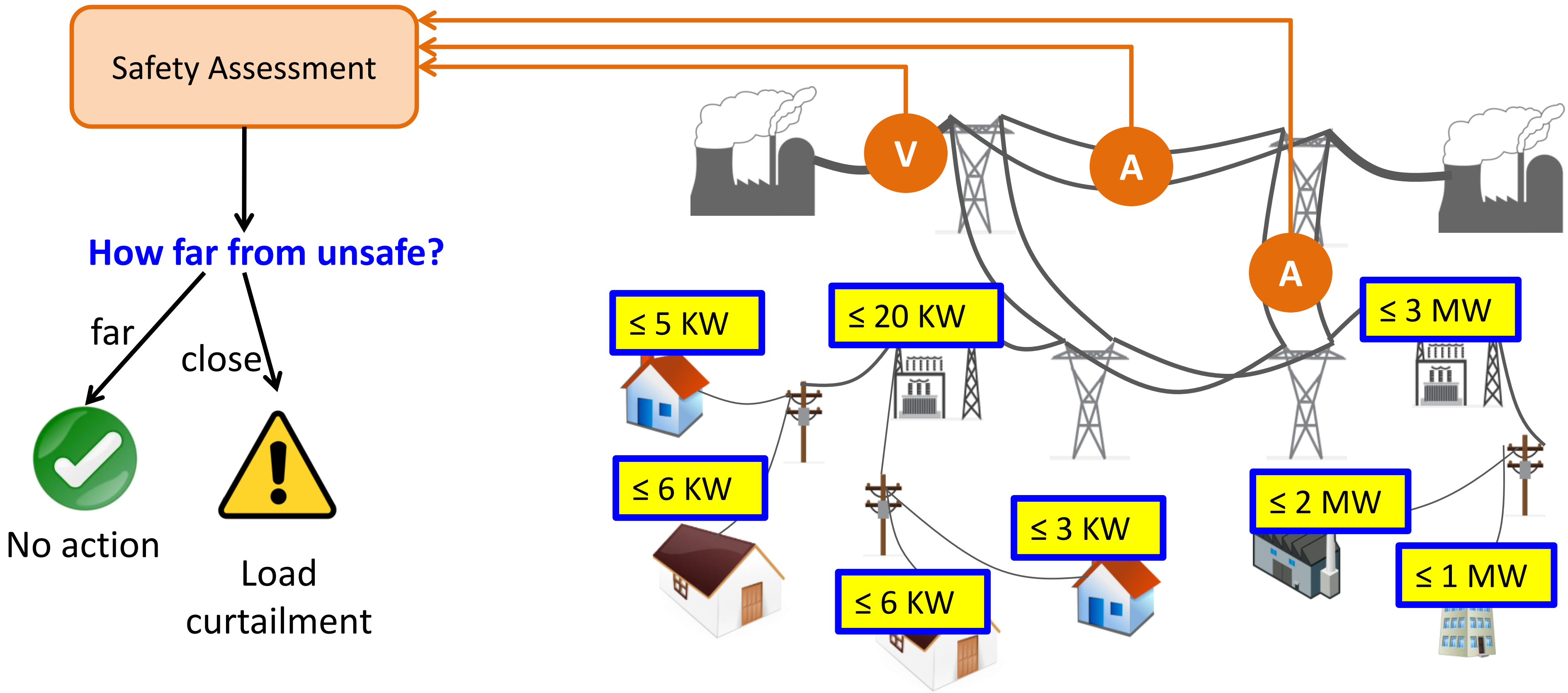
- Collaborative load curtailment
  - Fair, less painful
  - Untrustworthy (human factors, huge # of edge devices)
- Handle overload using curtailment with safety assurance?

Approach Overview



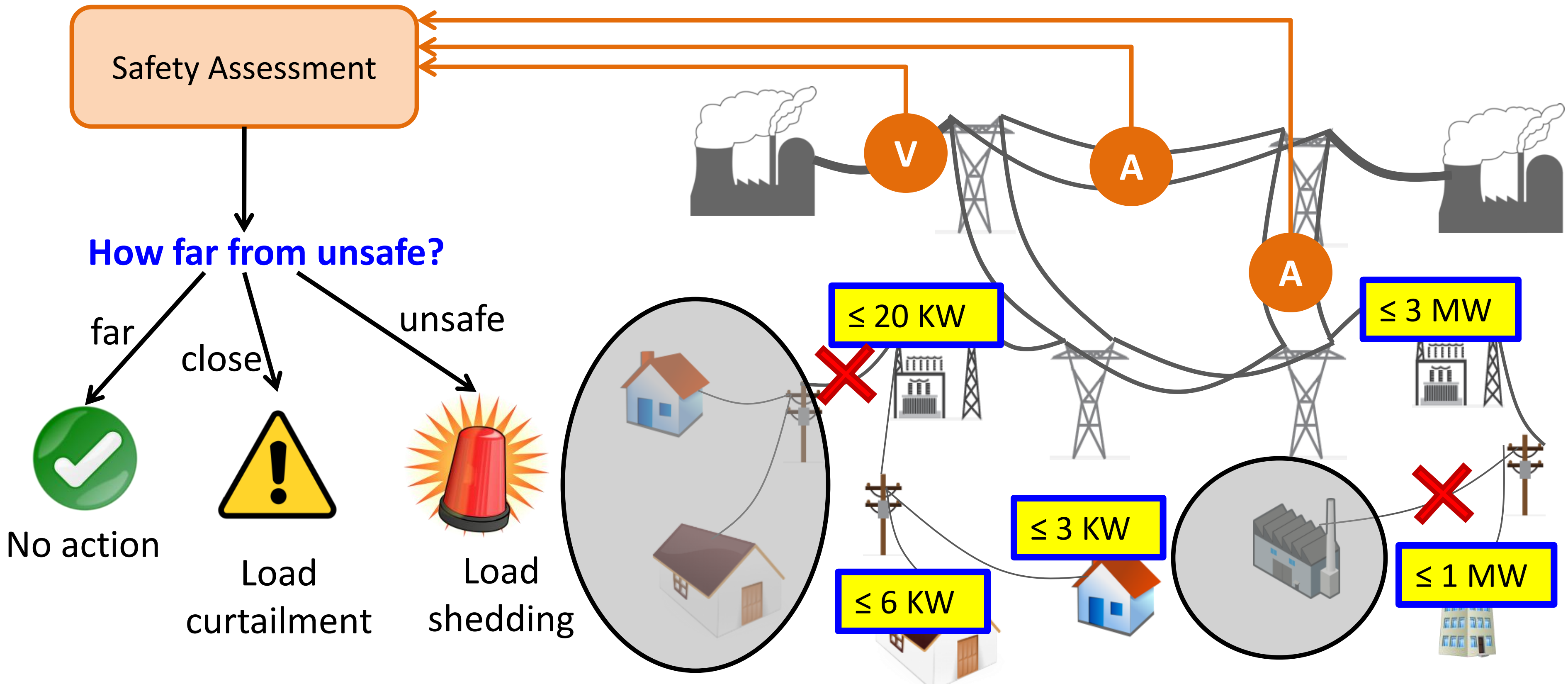
Approach Overview

- Close to unsafe
  - Load curtailment



Approach Overview

- Close to unsafe
  - Load curtailment
- Already unsafe
  - Load shedding



Challenges

- Existing grid safety assessment tools
  - Time-domain simulators [PowerWorld]
    Slow!
  - Learning-based classifiers [Sun 2007, Amjady 2007]
    "Safe" or "unsafe" for triggering shedding

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  - Too late to trigger curtailment if already unsafe
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- Curtailment needs time to take effect
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  - Predictive assessment needed
- Safety: non-linear
  - Curtailment scheduling repeatedly invokes assessment
  - Rapid assessment needed

Outline

- Motivation, Approach Overview
- **Rapid and Predictive Grid Safety Assessment**
- Predictive Curtailment Scheduling
- Simulations

Background of Safety Assessment

- Grid is safe if **safety condition** is met when **contingency** happens
  - Safety condition
    Example: All generators' speed within (55 Hz, 62 Hz)
  - Contingency
    Example 1: Most overloaded line trips
    Example 2: Any single line trips

- Safety depends on grid state
  - Load (dominating)

Background of Safety Assessment

- Grid is safe if **safety condition** is met when **contingency** happens
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  - Contingency
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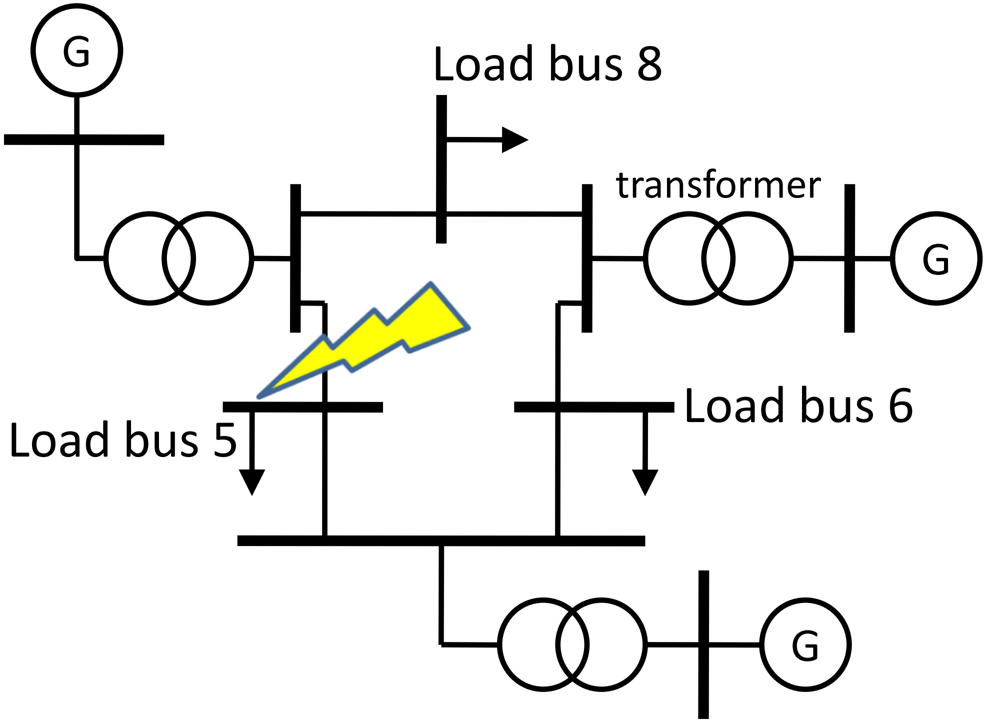
Basic requirement: Tolerate loss of any single line

- Safety depends on grid state
  - Load (dominating)

An Example



IEEE 9-bus system

- Safety assessment
  - Contingency: short circuit on a line

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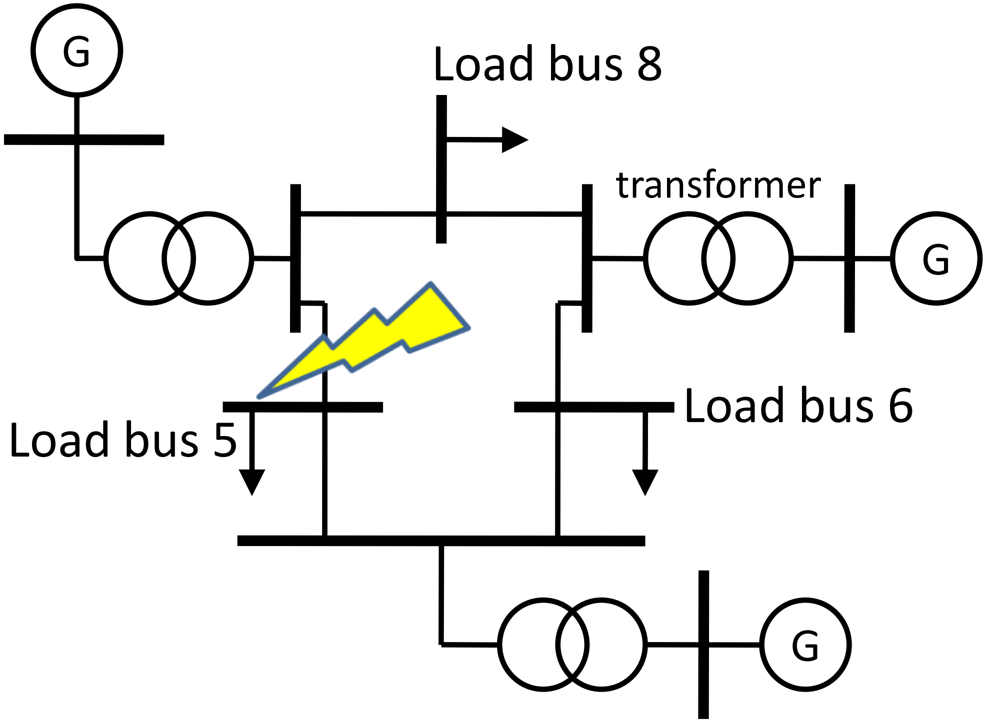

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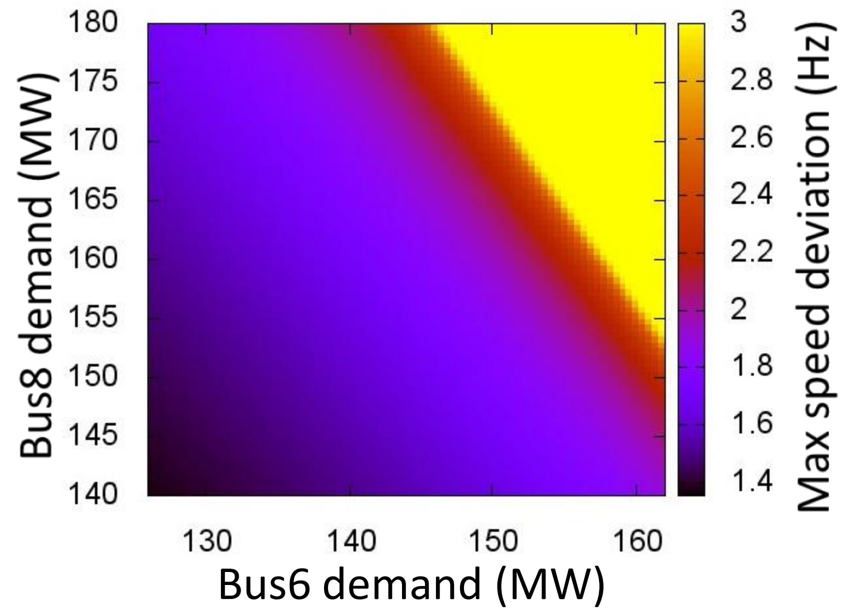

Time-domain simulation result
(Bus5 demand fixed)

- Safety assessment
  - Contingency: short circuit on a line

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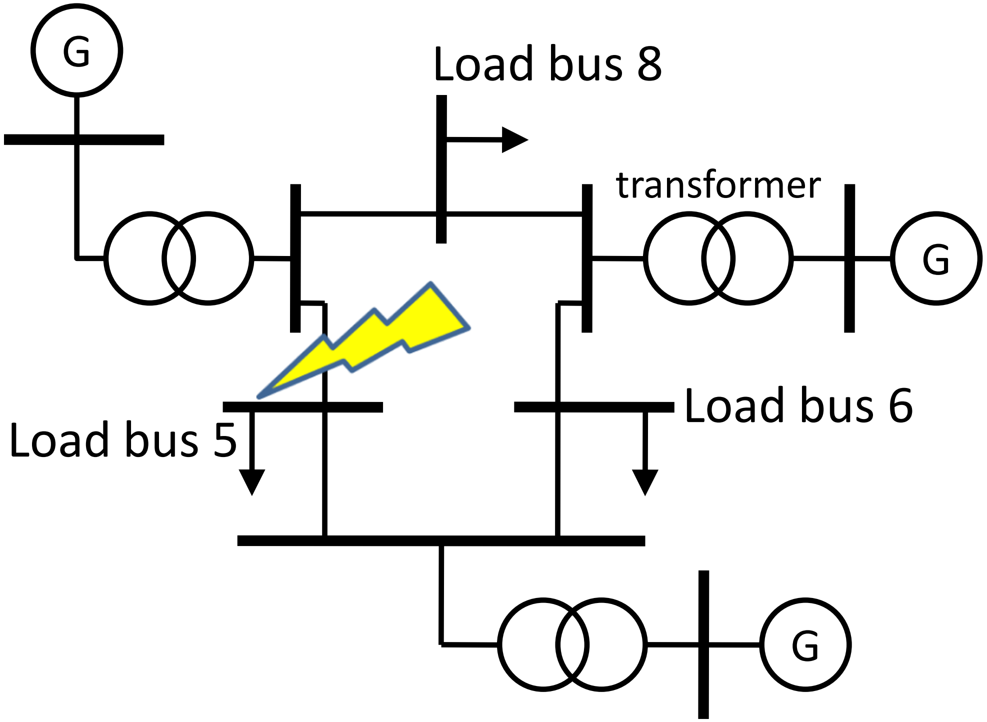

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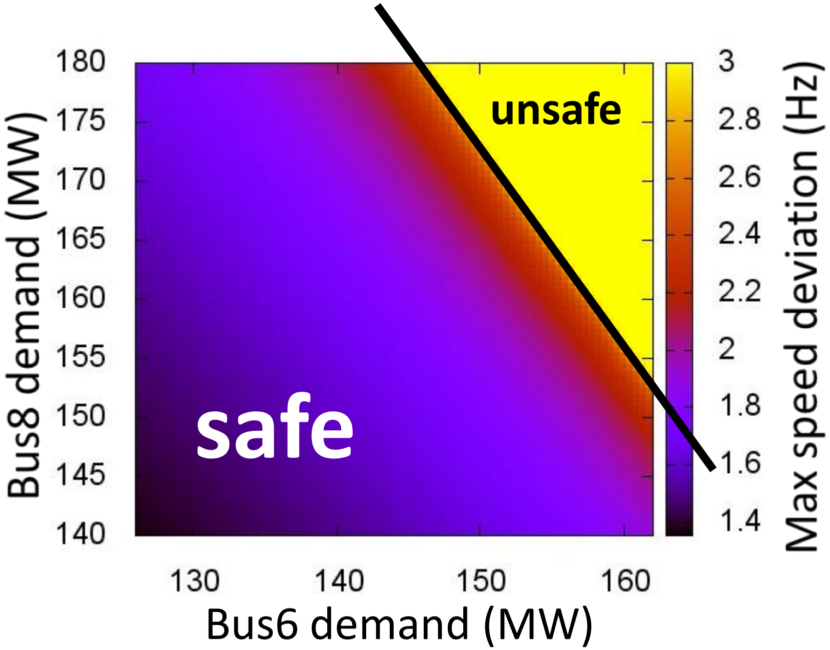

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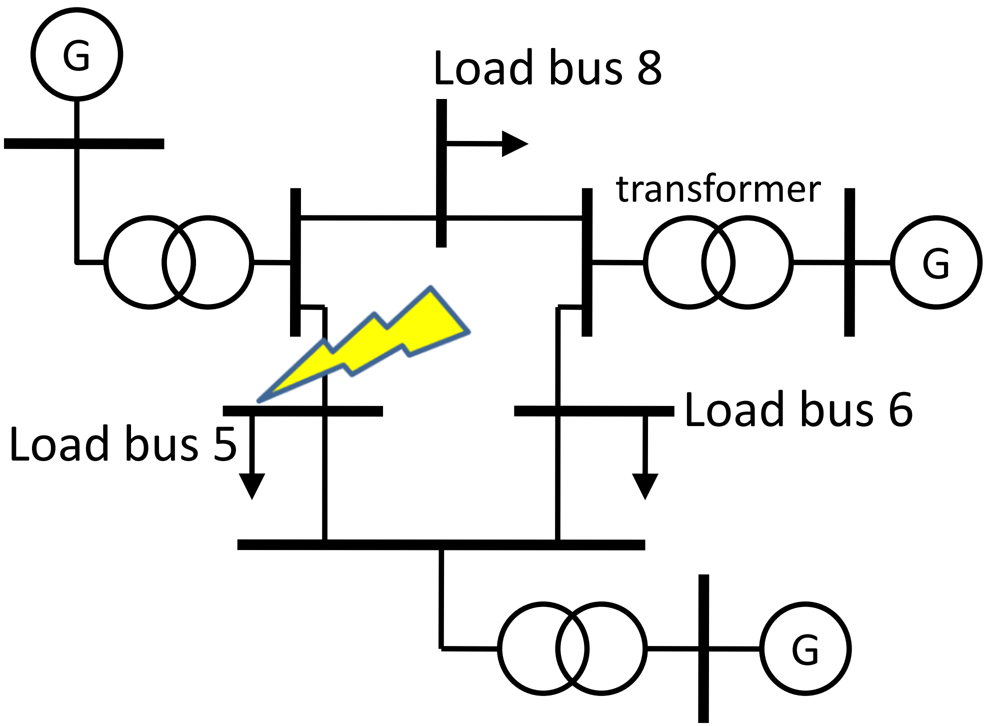

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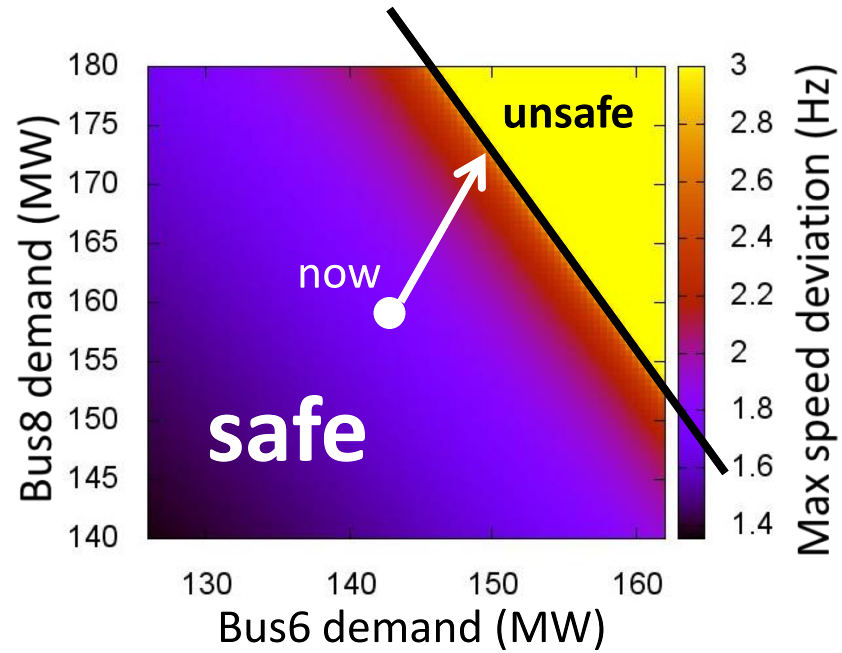

Time-domain simulation result
(Bus5 demand fixed)

- Safety assessment
  - Contingency: short circuit on a line
  - Safety condition: speed dev < 3 Hz
- A grid becomes unsafe if demands increase
  - How much time from now?

Time to Being Unsafe (TTBU)

- TTBU is minimum time t
  grid with demand $\mathbf{D} + \mathbf{\Delta}(t)$ is unsafe

vector of buses' demands

max demand increment over time period t

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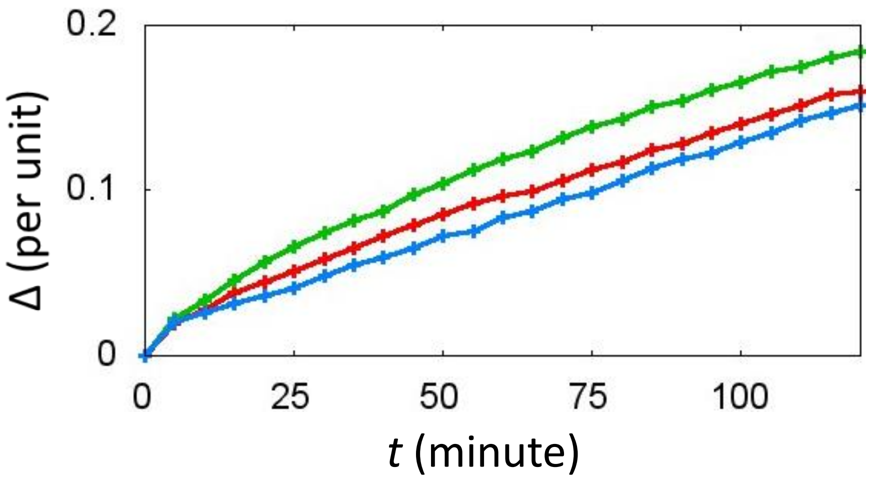

Δ(*t*) for 3 load buses
learned from New York ISO load data June-July, 2012

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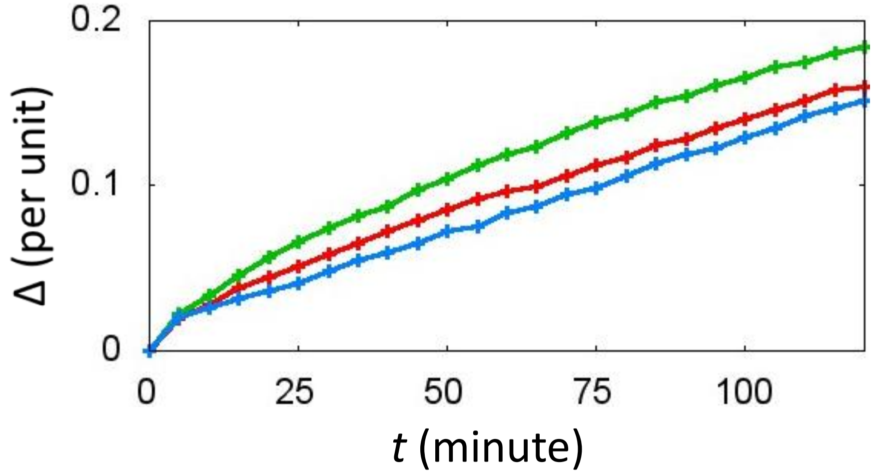

$\Delta(t)$ for 3 load buses
learned from New York ISO load data June-July, 2012

- Predictive but compute-intensive safety metric
  - Run PowerWorld for each t
    15 secs for 37-bus system on 4core @ 2.8GHz

ELM-Based Assessment

- Extreme Learning Machine [Huang 2006]
  - Neural network with one hidden layer

- Training data set {<demand vector, TTBU>}
  - Demand history
  - TTBU from offline time-domain simulations

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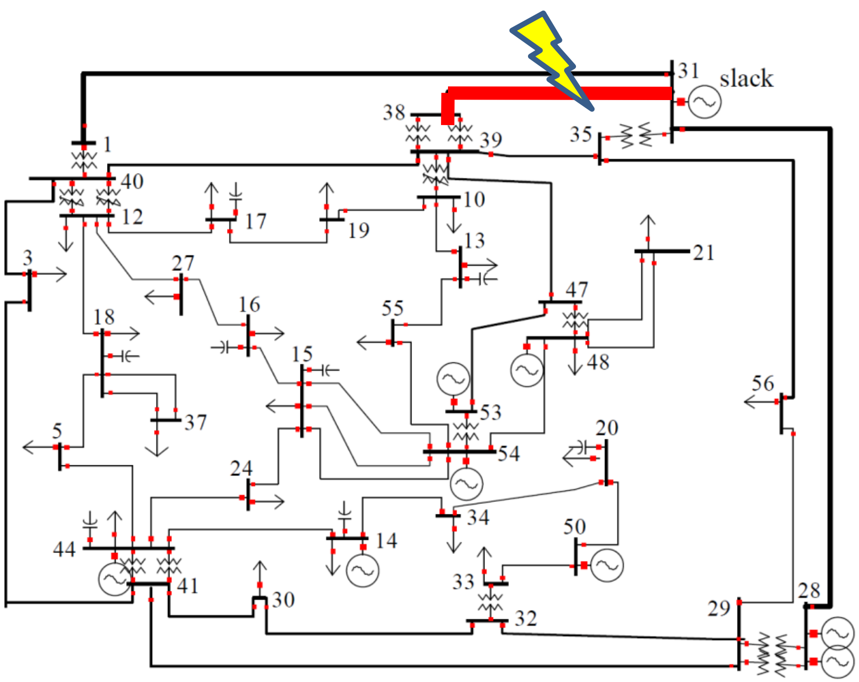
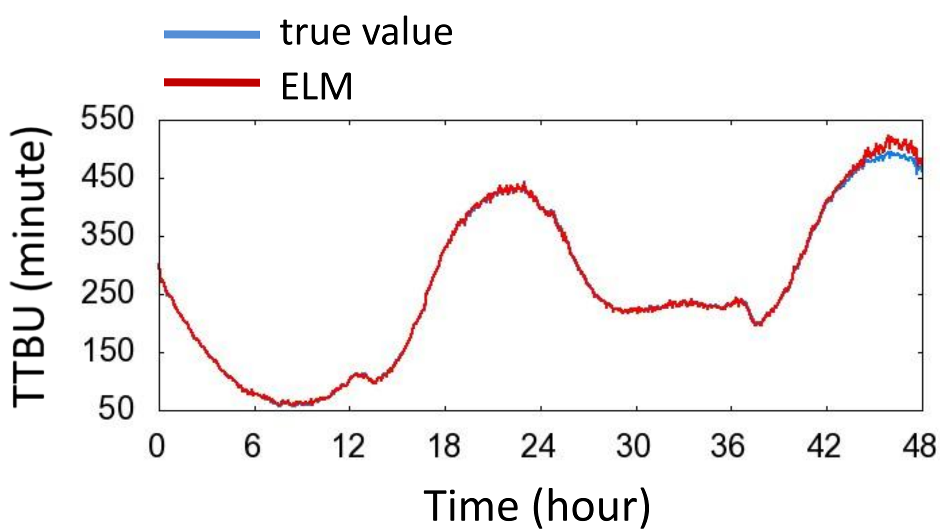


37-bus system



avg err = 0.9%

10^5x speed-up

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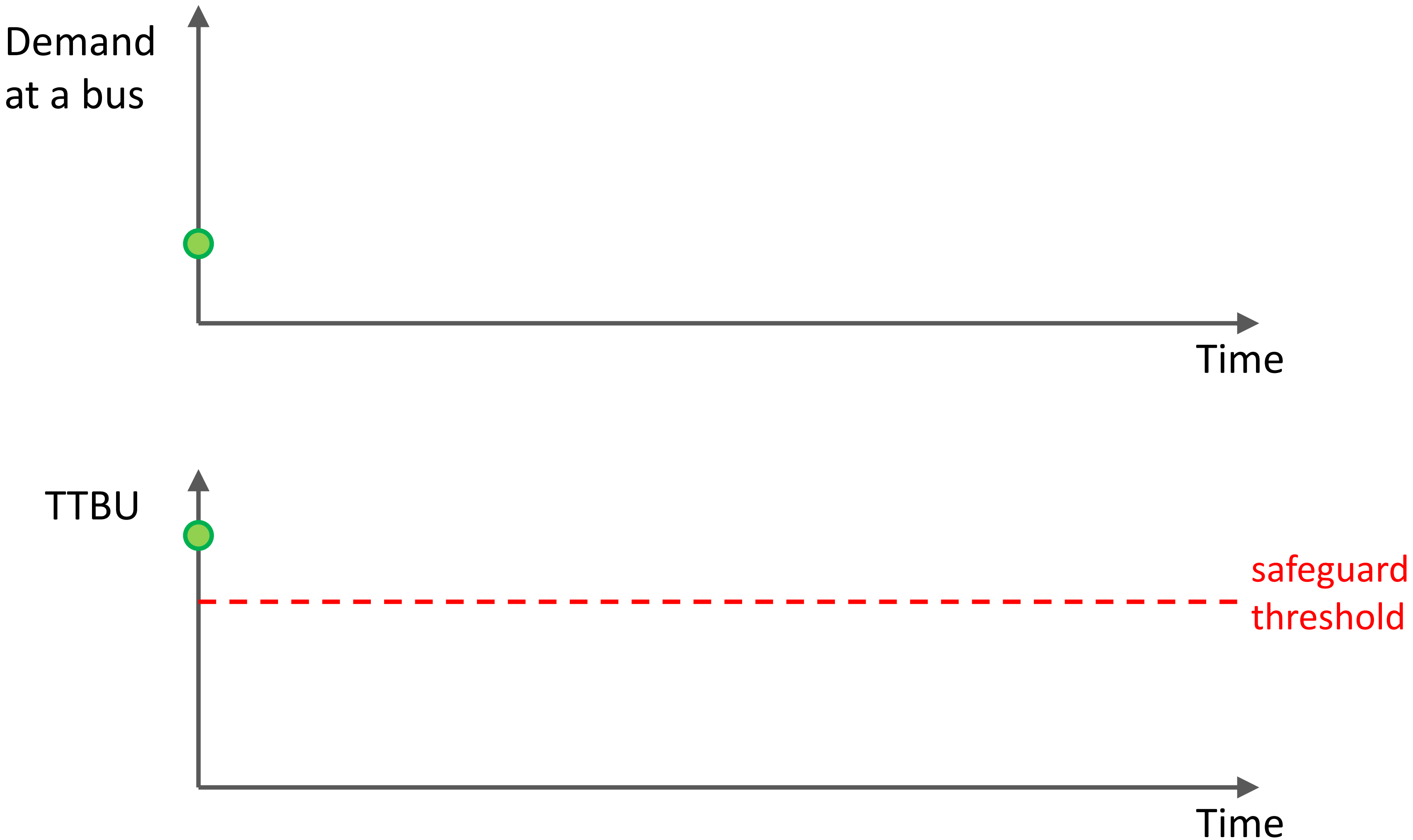

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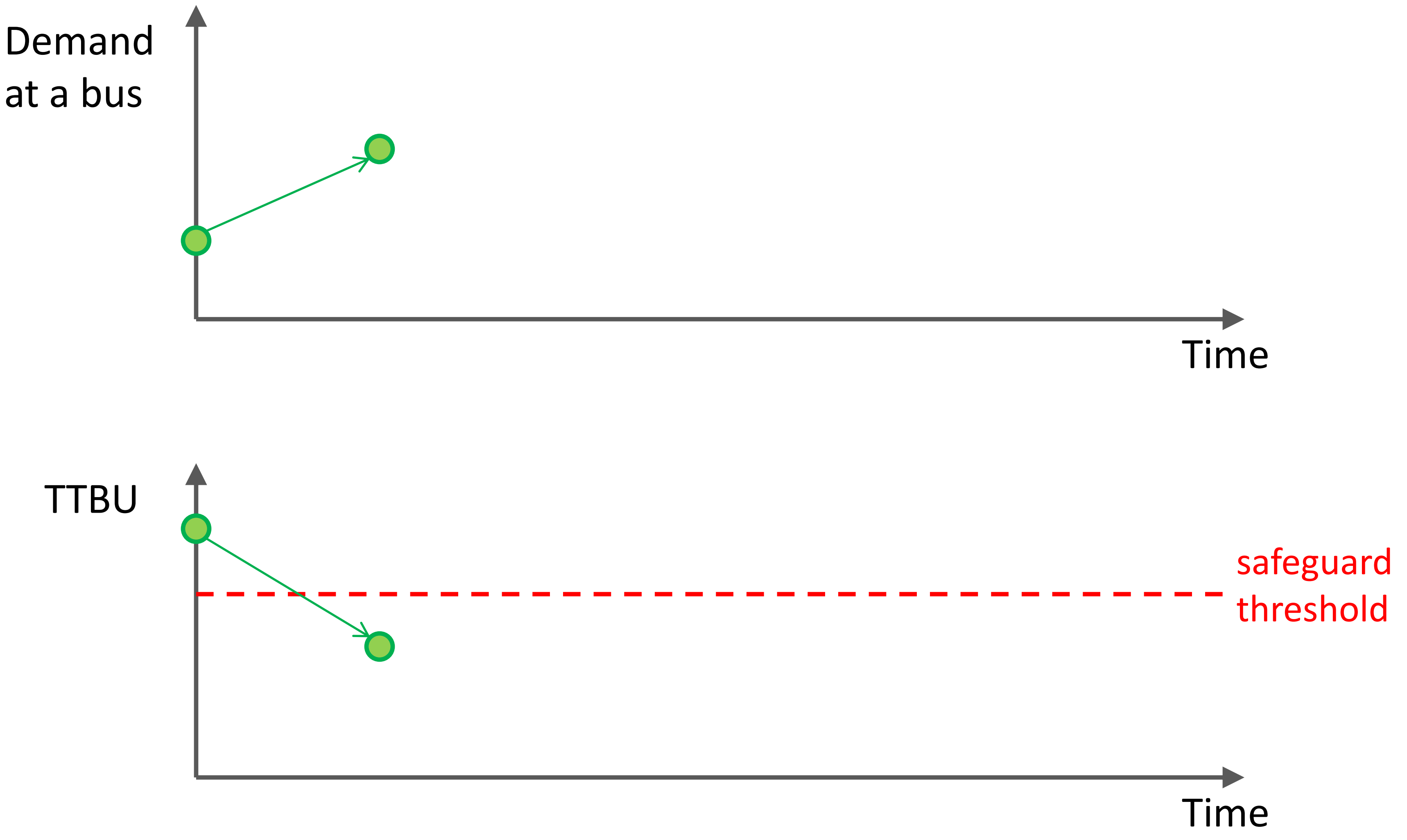

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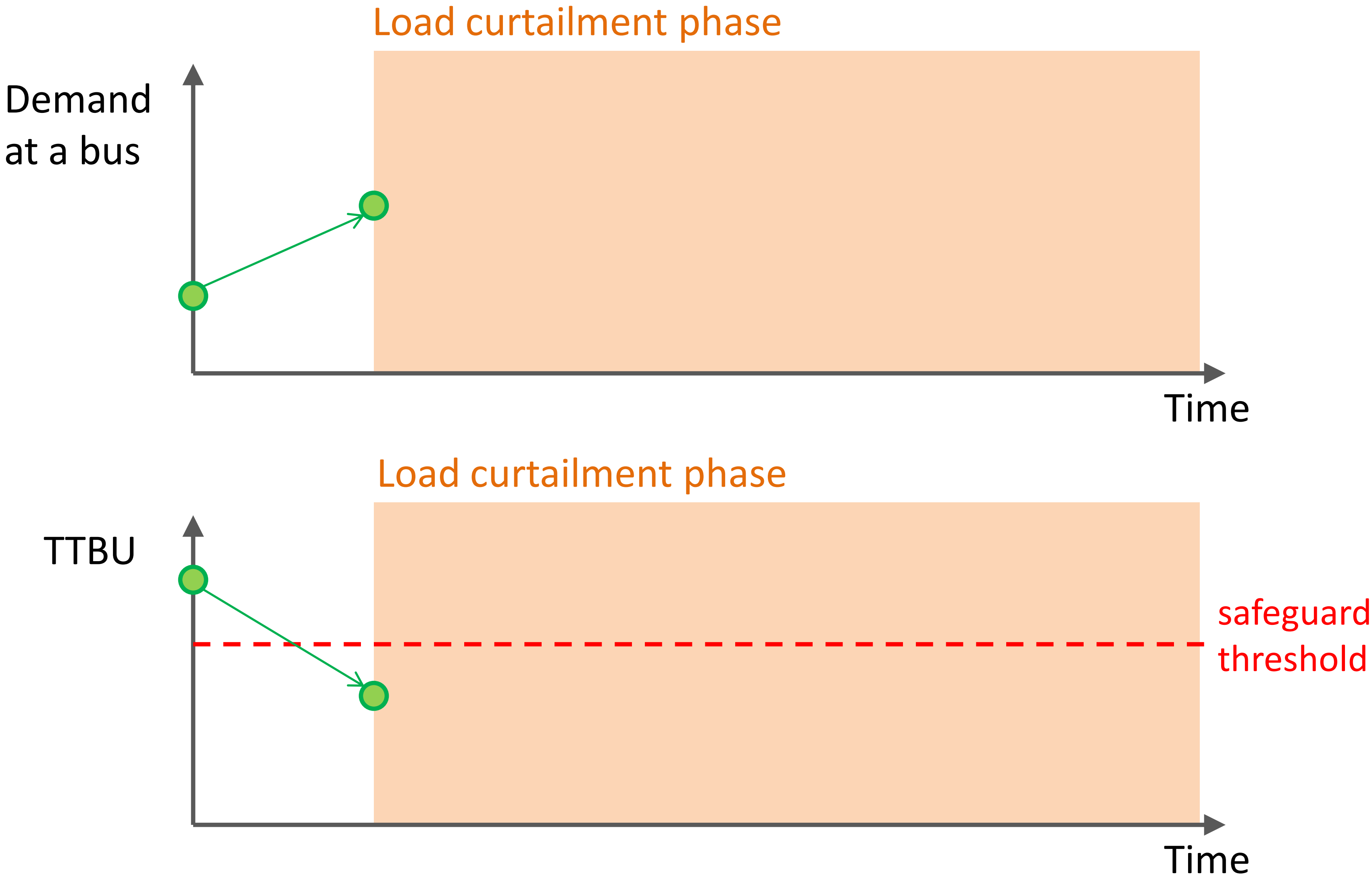

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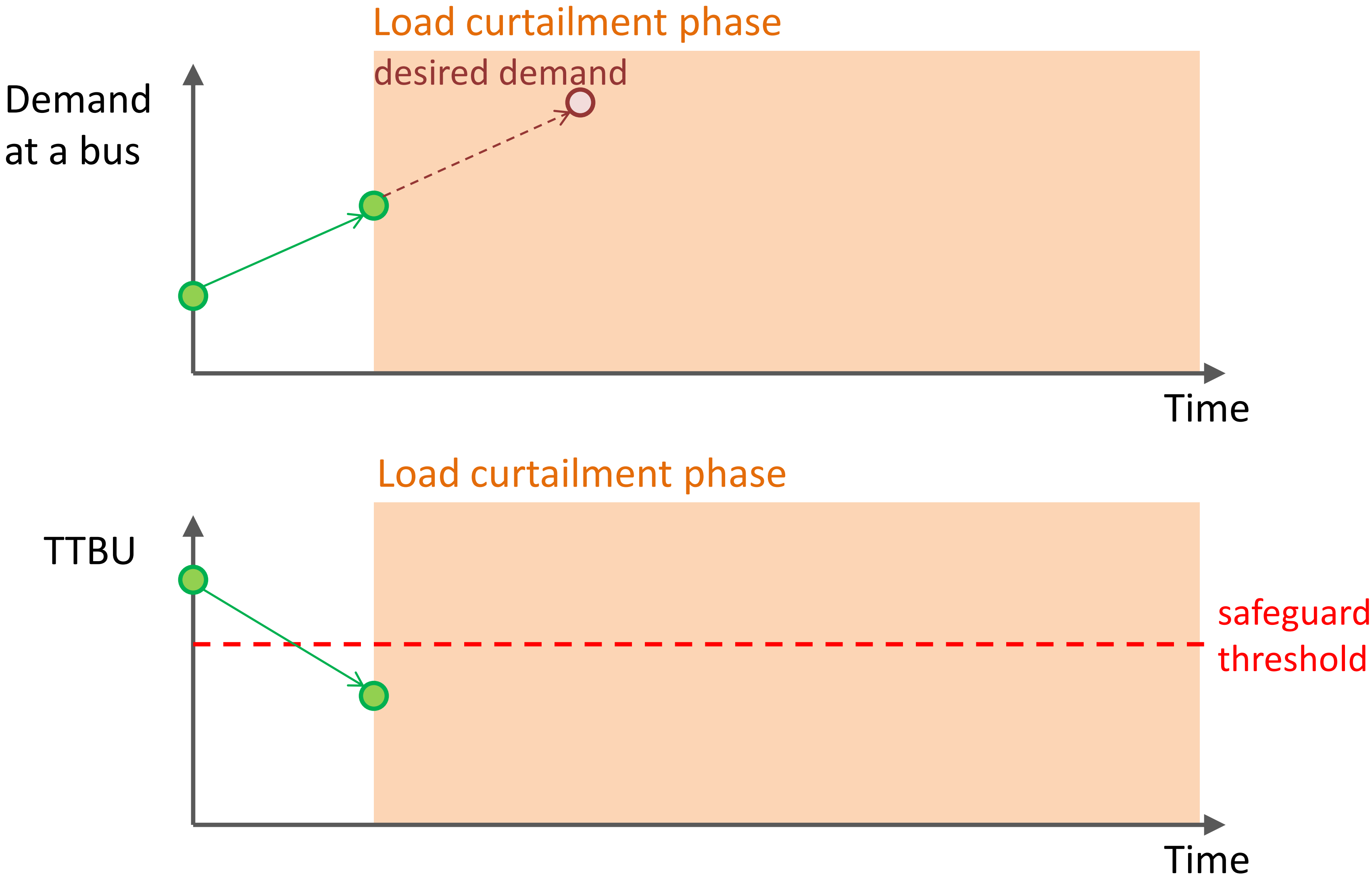

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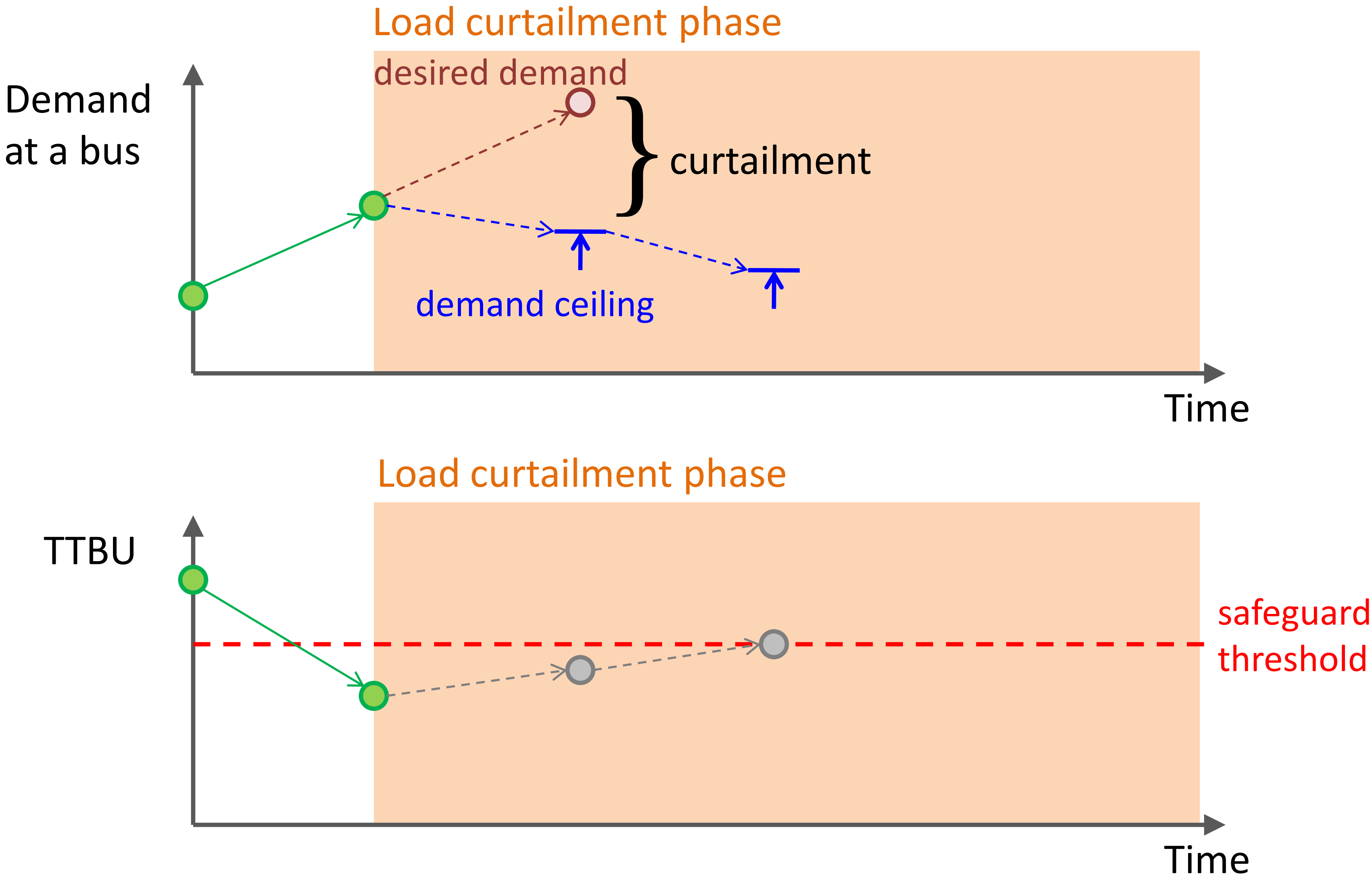

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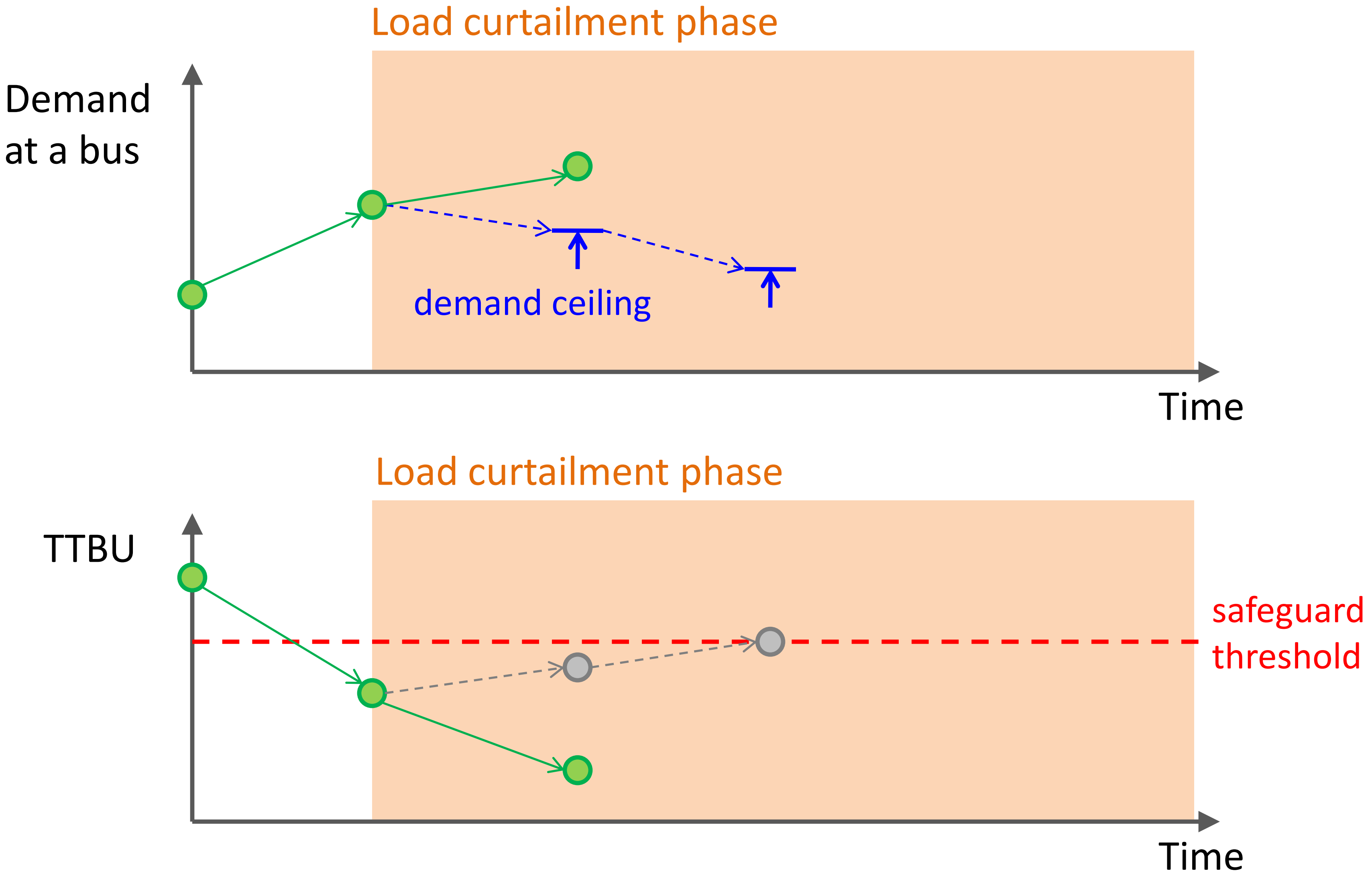

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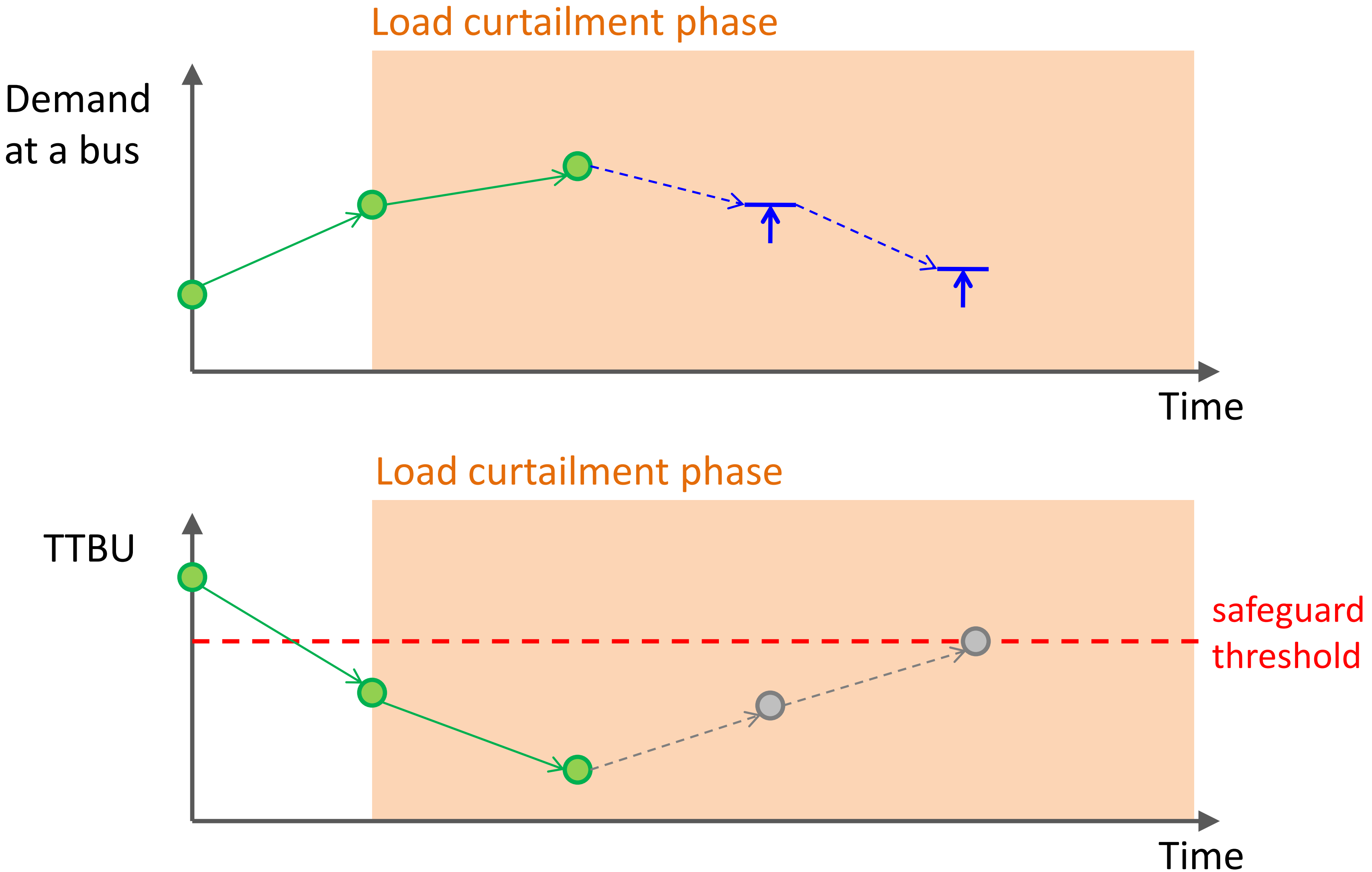

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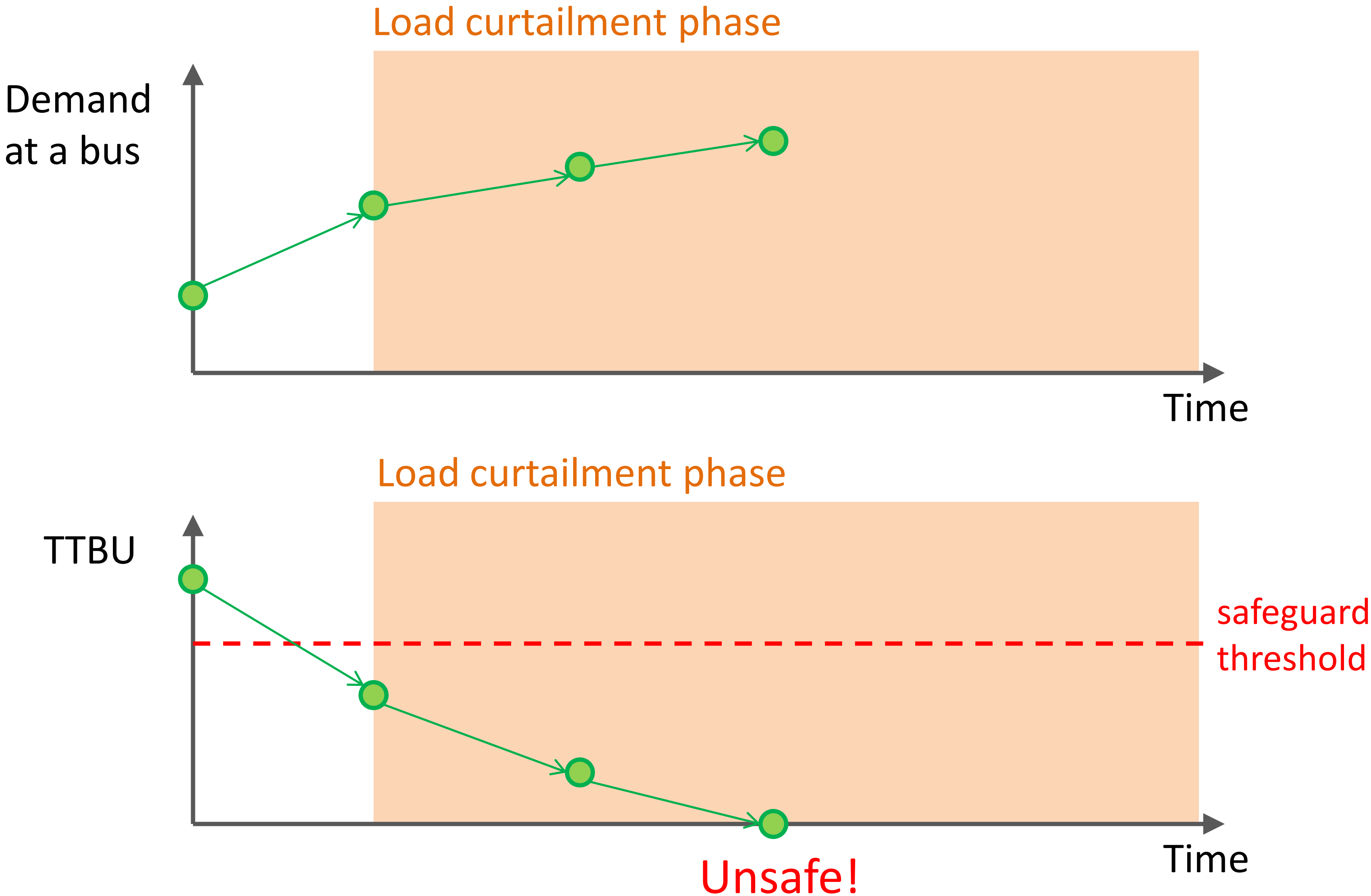

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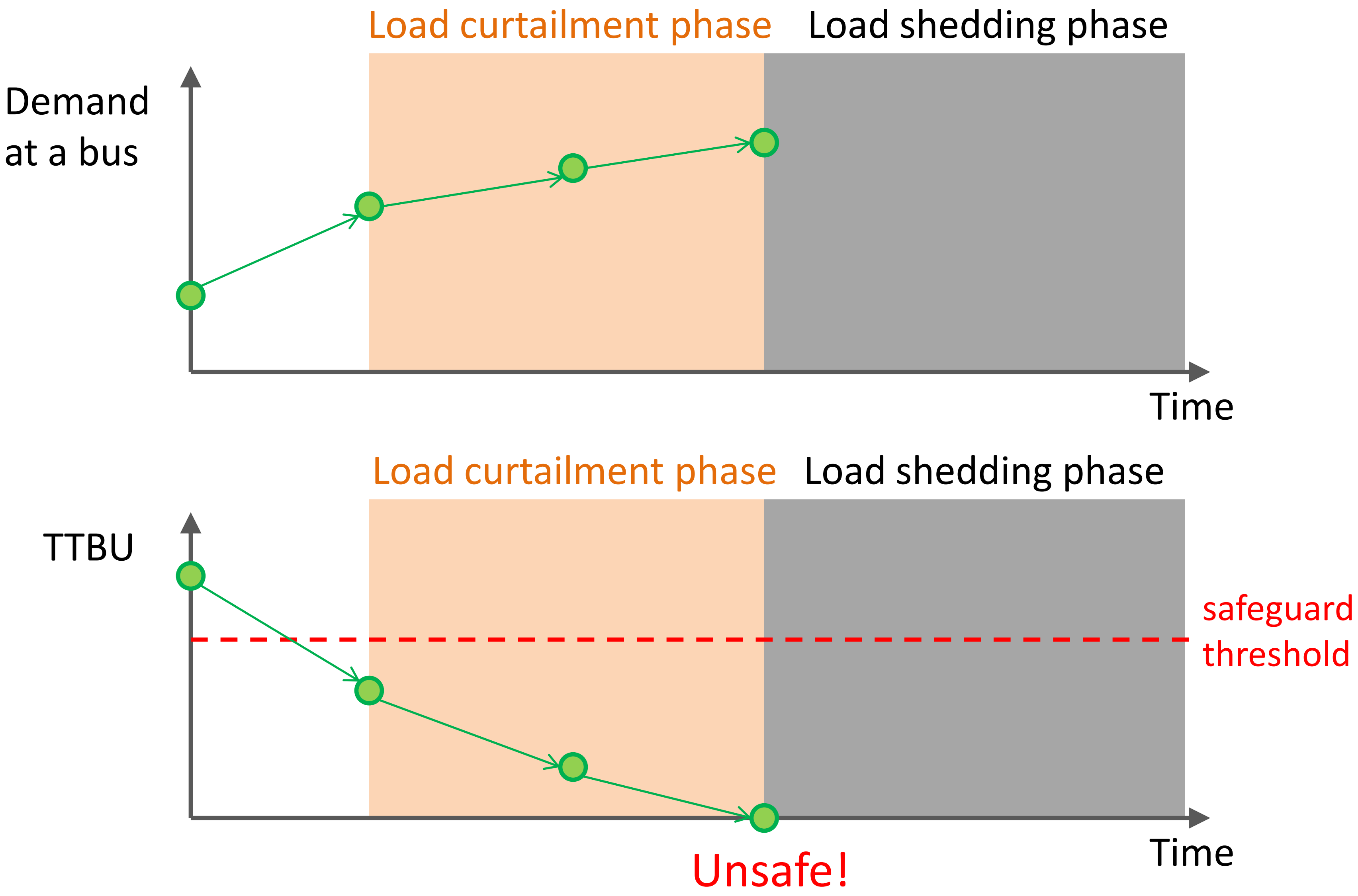

Demand Prediction Model

- Strong temporal correlation
  - One-step prediction

$$\hat{d}_1 = f(d_0, d_{-1}, \cdots, d_{-R+1})$$

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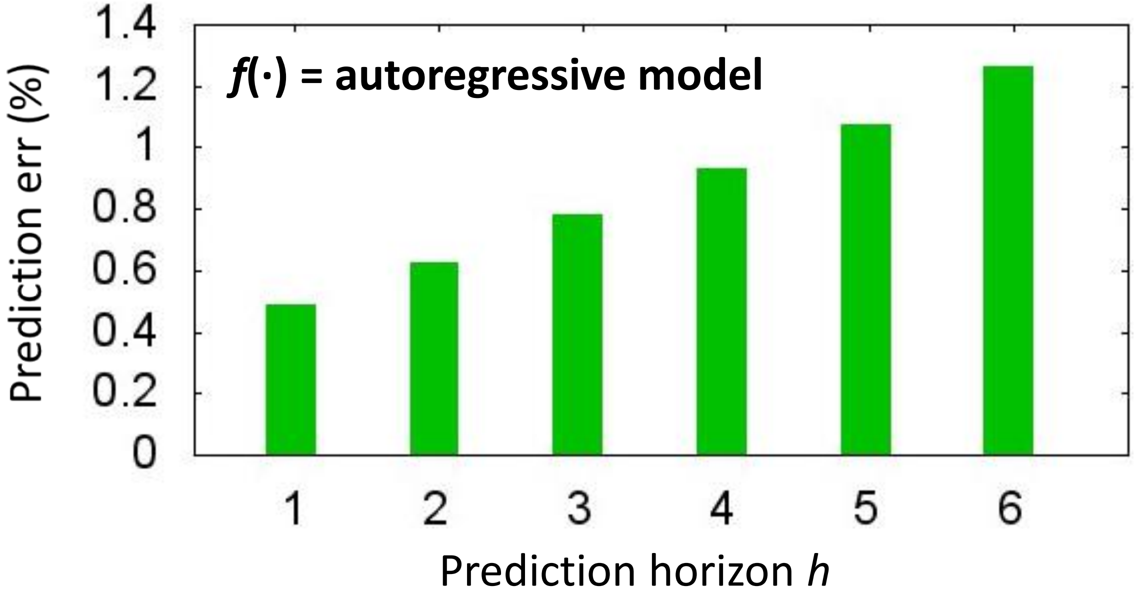

New York ISO data
Cycle = 10 min
R = 12

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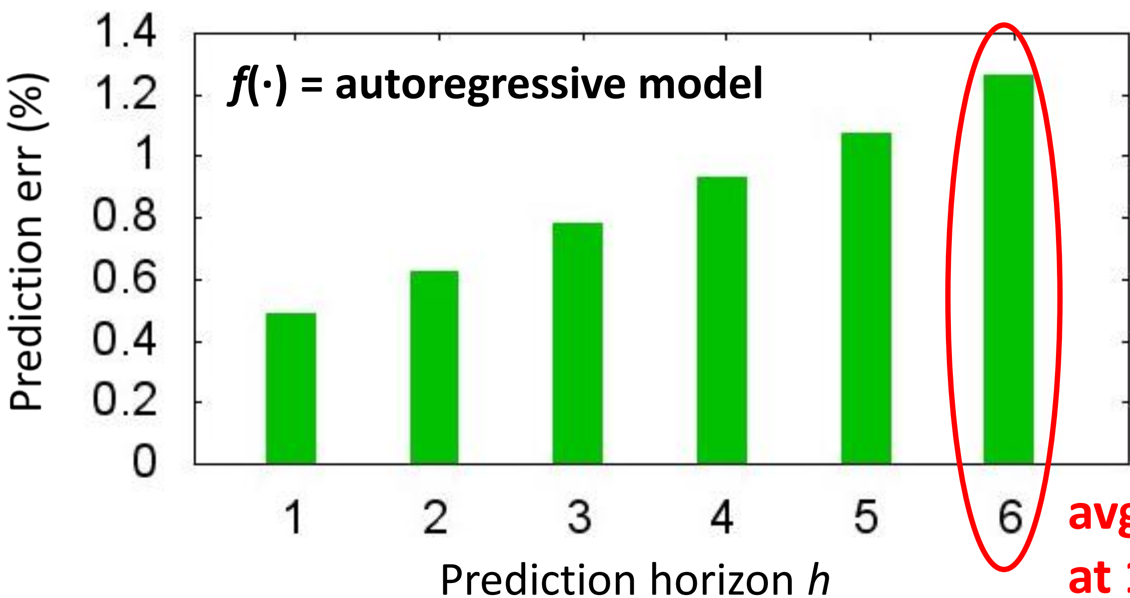

New York ISO data
Cycle = 10 min
R = 12

avg err = 1.3%
at 1 hour horizon

Curtailment Scheduling

- Find curtailments $\{x_1, x_2, \ldots, x_H\}$

min. $$\sum_{h=1}^{H} |\mathbf{TTBU}_h - \mathbf{safeguard}|$$

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Predicted TTBU at horizon *h*

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ELM

Demand ceiling at horizon *h*

$$\boxed{\hat{d}_h} = f(\hat{d}_{h-1}, \cdots, \hat{d}_1, d_0, \cdots, d_{-R+h}) - x_h$$

Predicted demand at horizon *h*

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Predicted demand at horizon *h*

s.t. $$\sigma(x_1, x_2, \cdots, x_H) \le \sigma_0$$

Curtailments variation

Curtailment Scheduling

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$$\boldsymbol{\sigma = \max_{h=1}^{H} | x_h - x_{h-1} |}$$

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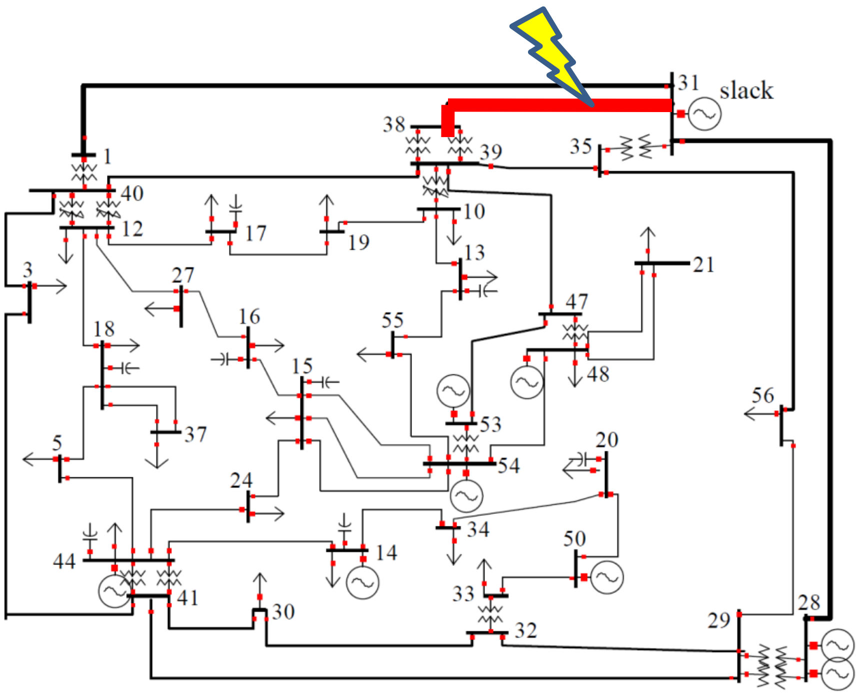
optional

Simulation Settings



37-bus system

Contingency:
Short circuit on a backbone line

Safety condition:
Generators' speed within (55 Hz, 62 Hz)

Demand:
Synthesized from New York ISO load data

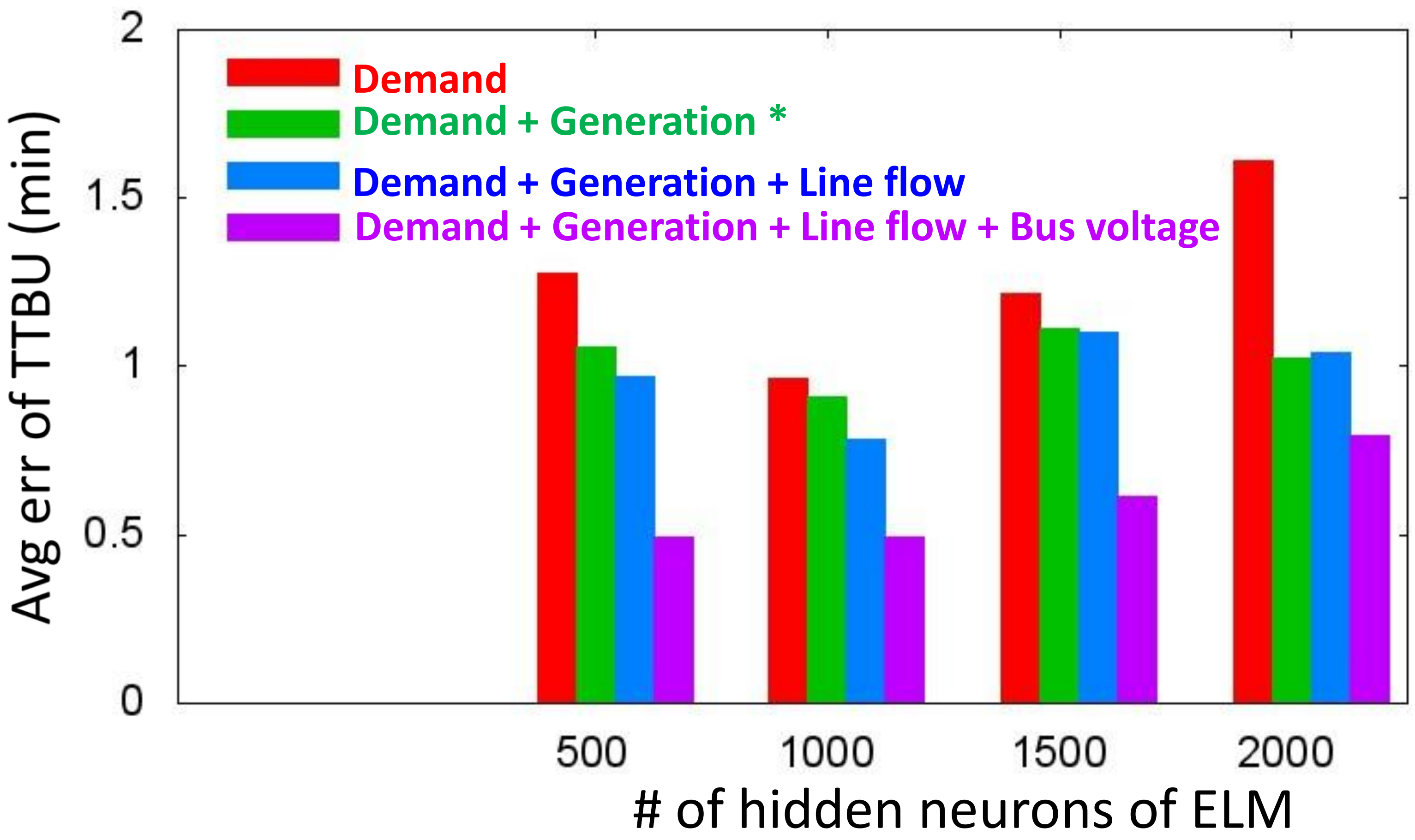
Cycle len = 10 min, σ_0 = 0.02 p.u.

- Commitment $\xi \in [0, 1]$

actual demand = ξ × demand ceiling + (1 – ξ) × desired demand

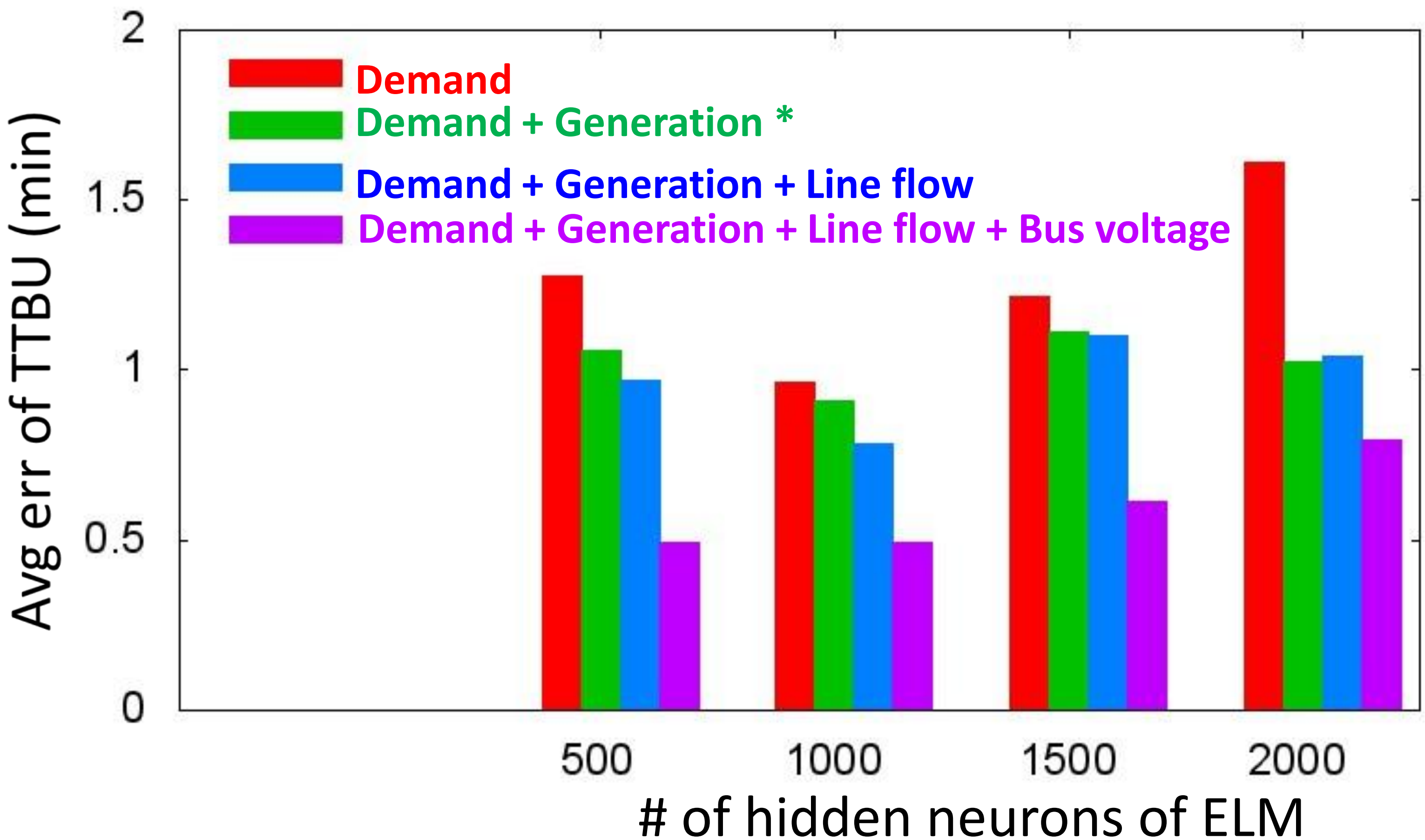
(desired demand: data traces)

Alternative Designs of ELM



* Generation follows demand by economic dispatch

Alternative Designs of ELM



- More state data improves accuracy slightly
  - Need more sensors
  - Estimating them from demands incur overhead

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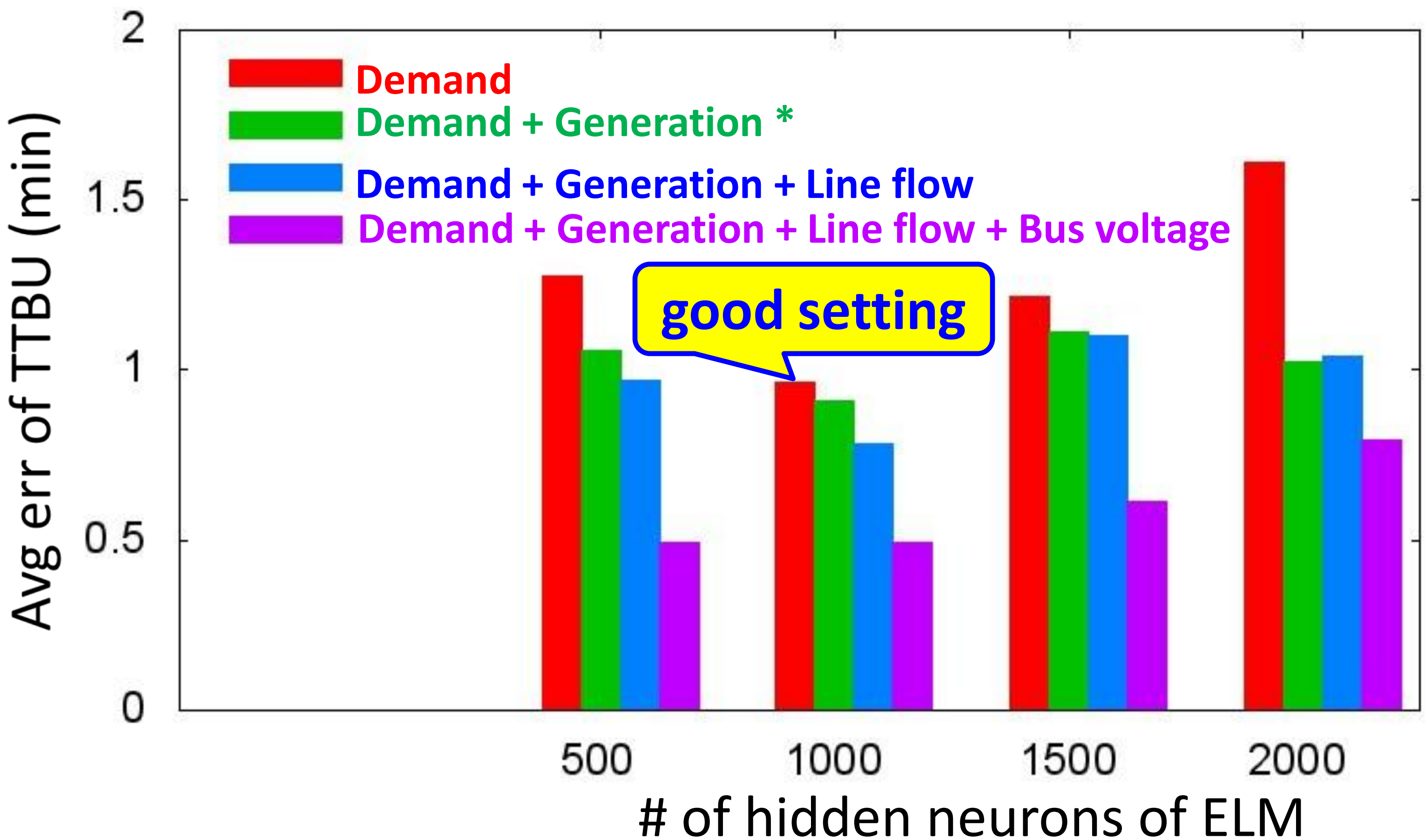

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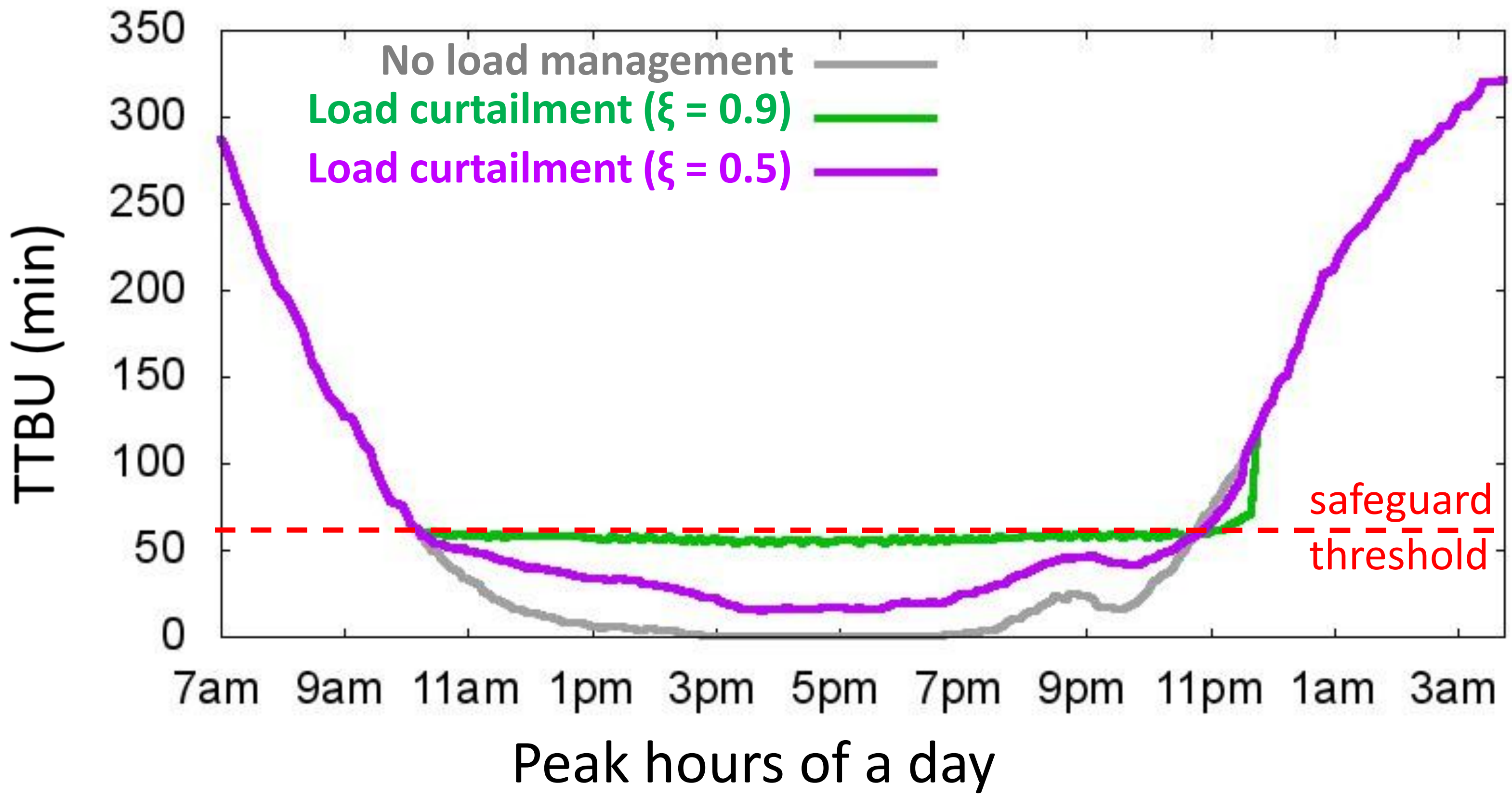
Impact of Commitment



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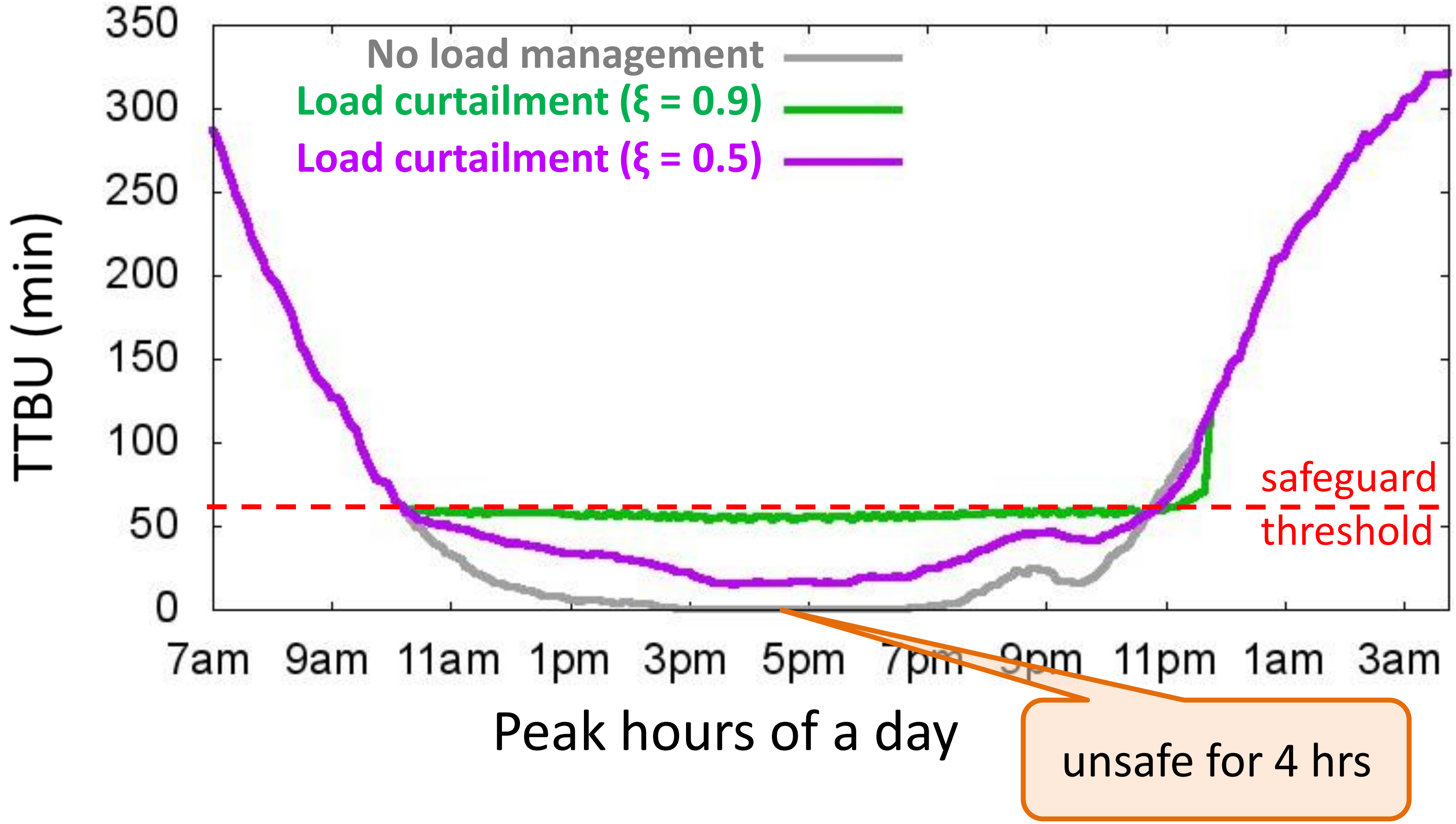

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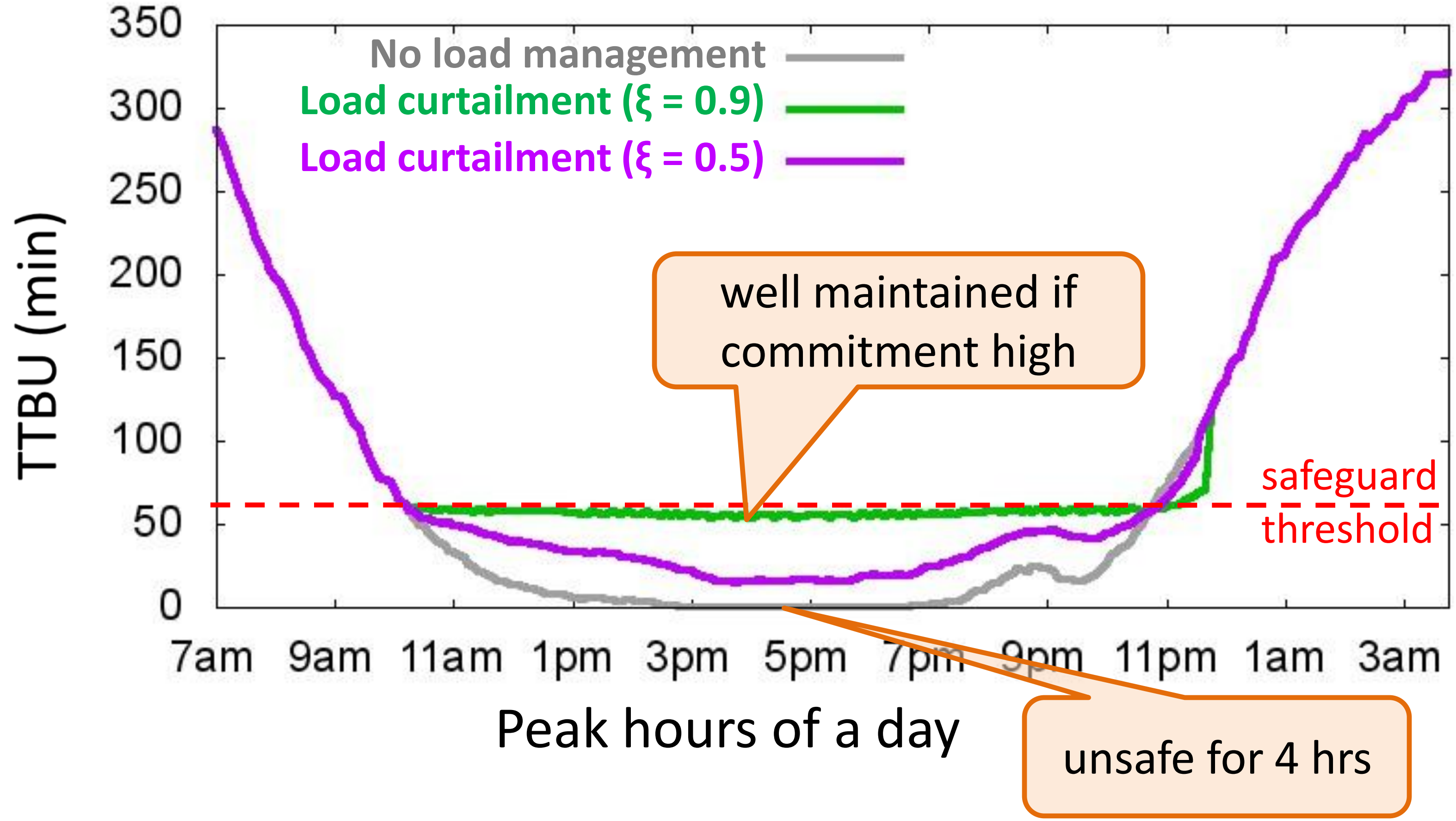

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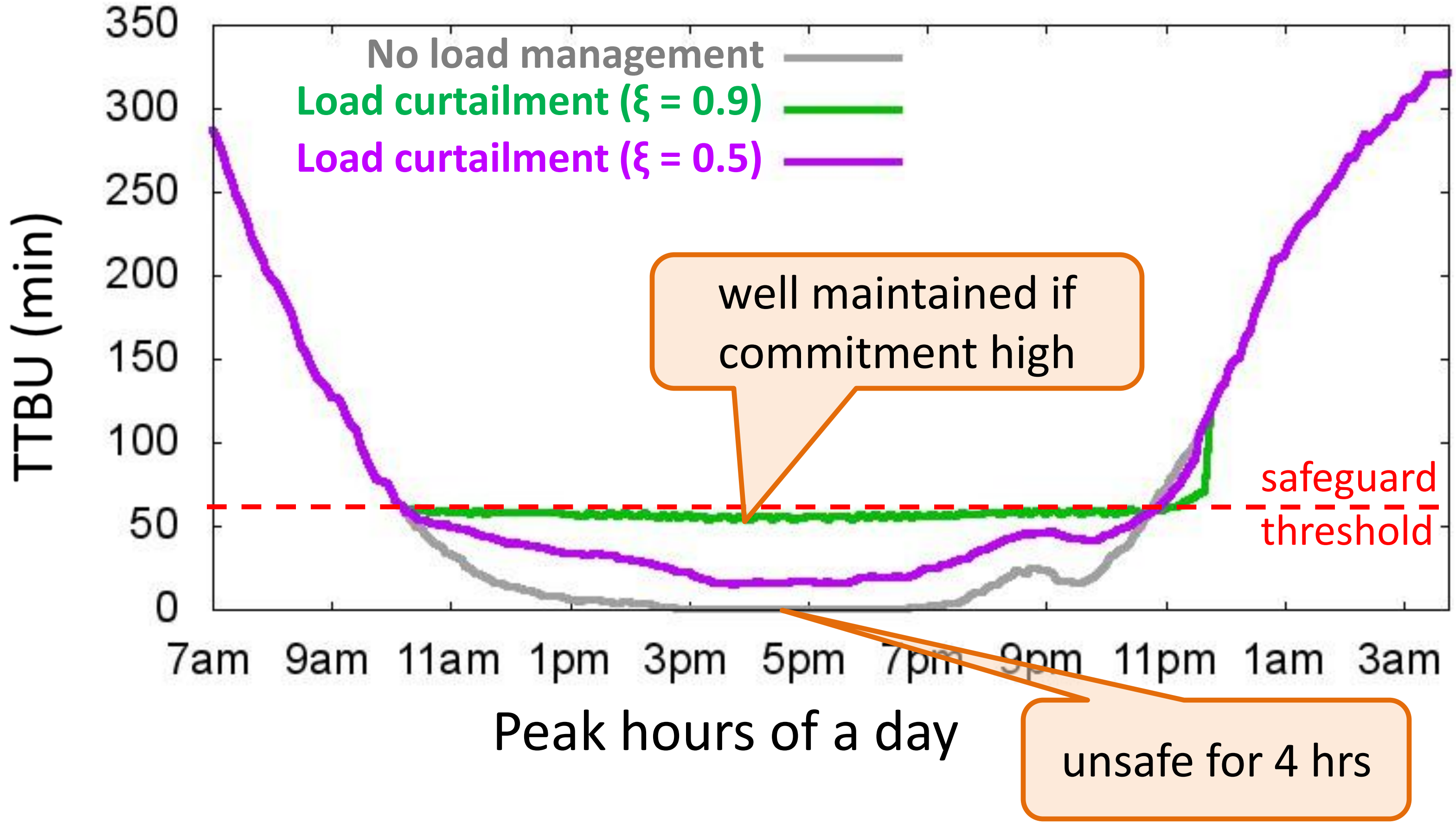
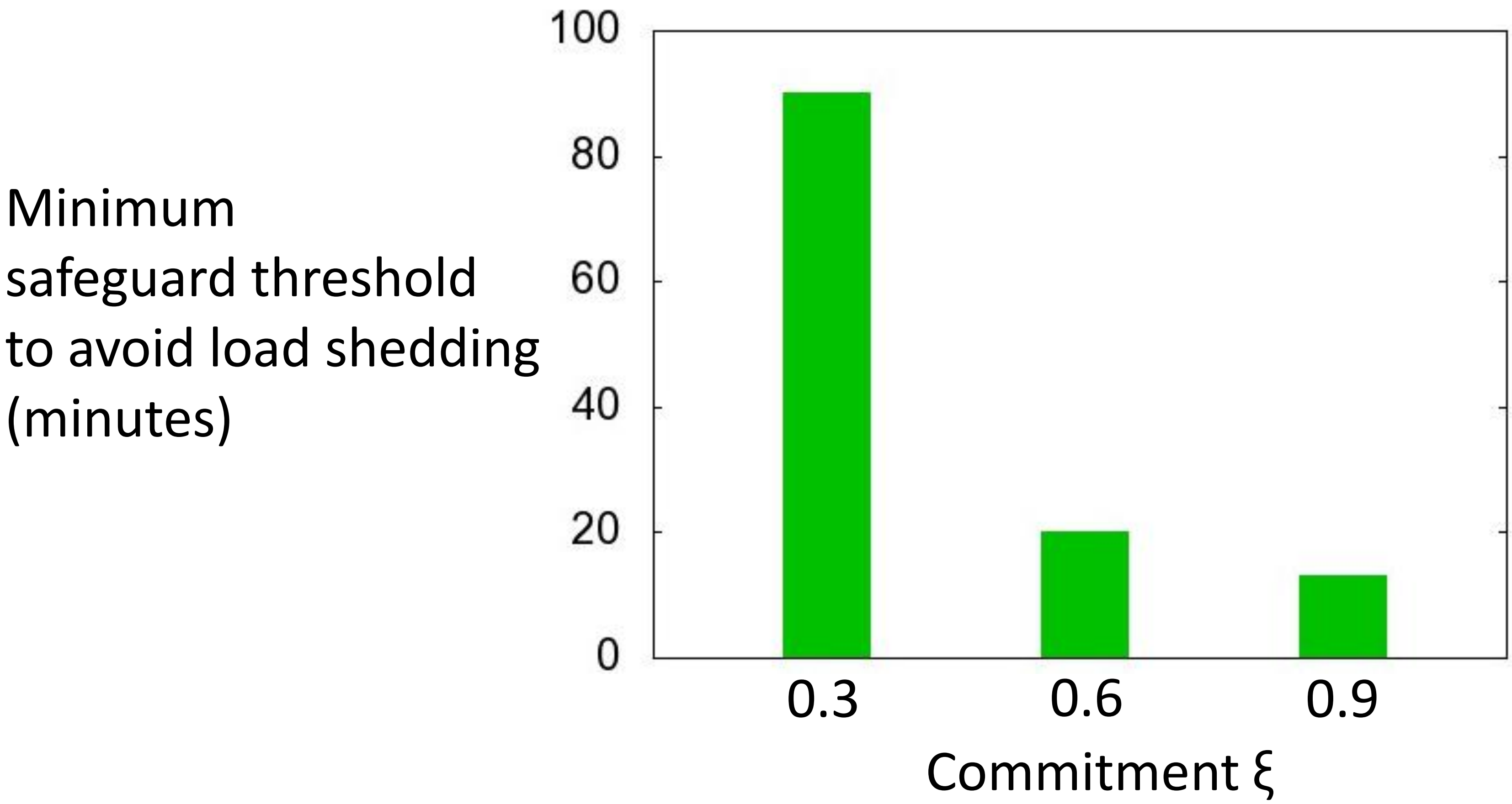


- ξ > 0.4, load shedding avoided

Setting of Safeguard Threshold



- Low commitment
  - High safeguard

Impact of Optimization Horizon

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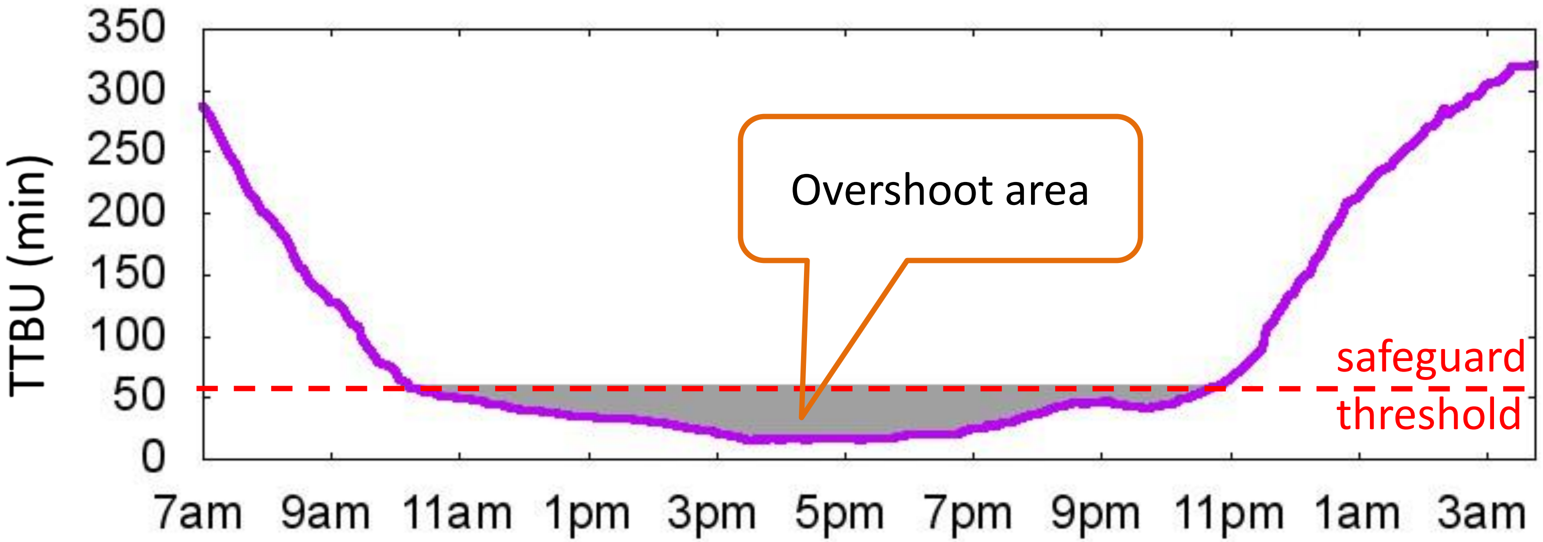

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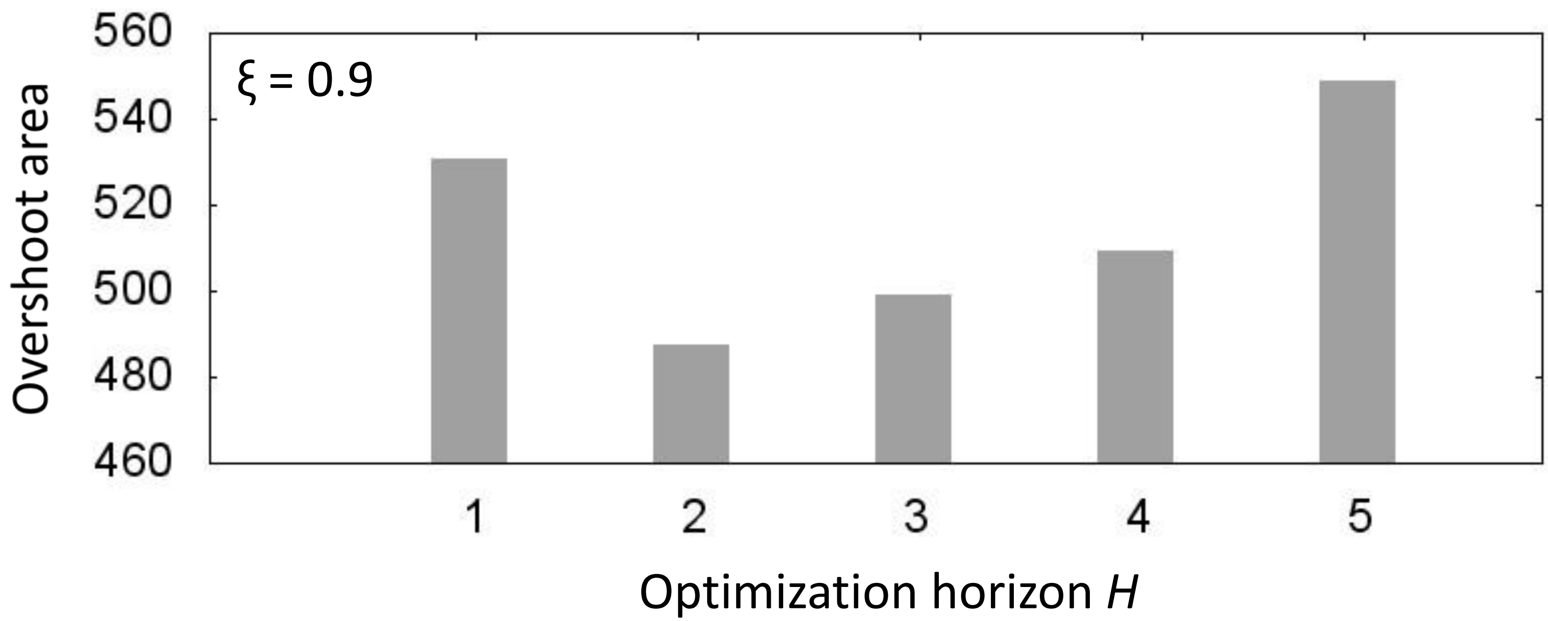
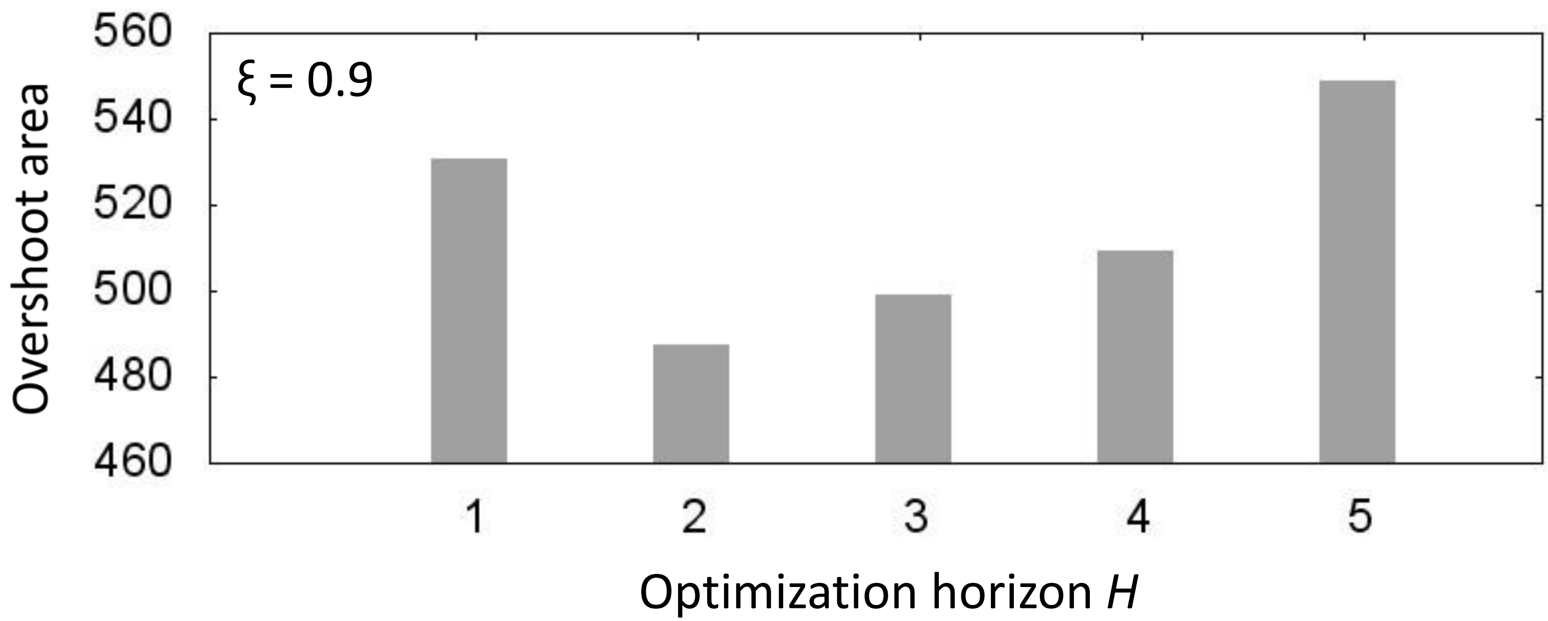
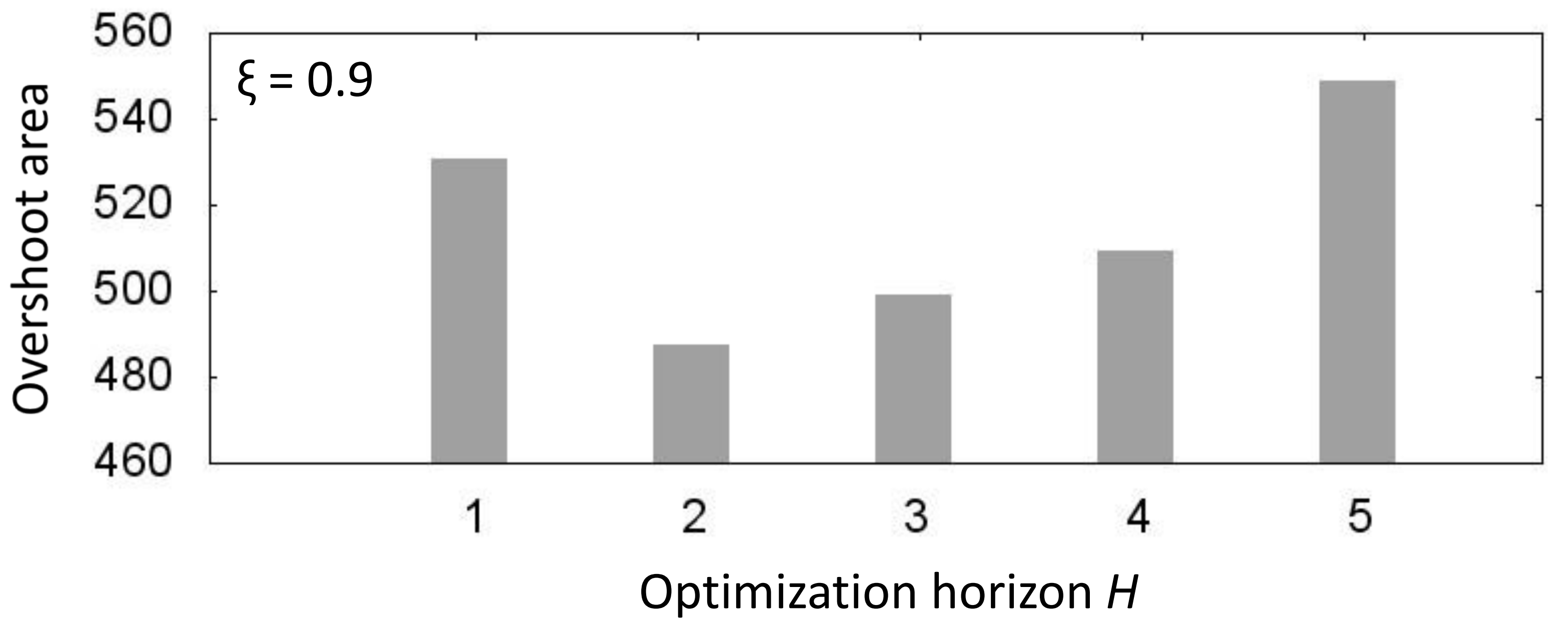


Impact of Optimization Horizon



- Too small *H*
  - Ignore impact (due to demand inertia) on later steps

Impact of Optimization Horizon



- Too small *H*
  - Ignore impact (due to demand inertia) on later steps
- Too large *H*
  - Low prediction accuracy

Conclusion and Future Work

- Safety-assured collaborative load management
  - Time to being unsafe
  - Rapid and predictive safety assessment
  - Predictive curtailment scheduling
- Evaluation on 37-bus system

- Future work
  - Study and integrate empirical commitment models
    - Affected by $\{x_1, \ldots, x_H\}$ and $\sigma(x_1, \ldots, x_H)$