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MODEL-PREDICTIVE CASCADE MITIGATION IN ELECTRIC POWER SYSTEMS WITH STORAGE AND RENEWABLES

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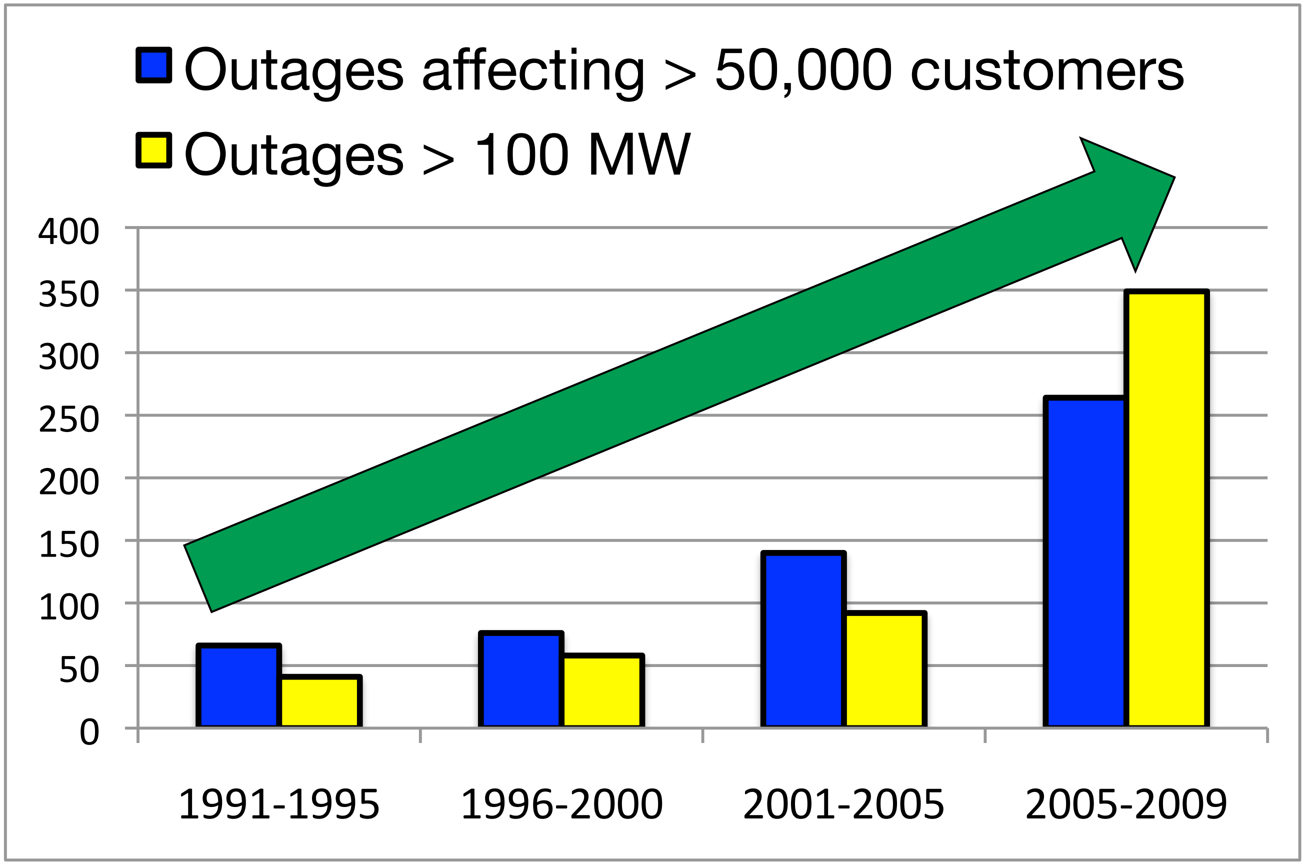
Source: Vincent Laforet / The New York Times Photo Archives.

Was 2003 Blackout atypical?

US electric infrastructure is operating closer to its limits



***Example**: PJM system at all-time winter high in Jan 2014, warned of rolling blackouts*

Source: NERC+EIA, 2011

Can’t we just build our way out?

- **New high-voltage lines are expensive**
  - Up to $2,000,000 per mile
- **Construction is protracted process**
  - Takes up to 10 years (planning + construction)

→ Need to do better with what we already have

Source: T&D World, DOE, EIA

What kind of grid do we have?

In the 20th century

- Supply follows demand
- Large thermal generation
- Limited renewable generation

For the 21st century

- Some demand can follow supply
- Increased renewable generation
- New technologies
  - Improved controllability
  - Improved observability
- Energy storage
  - tighter temporal coupling

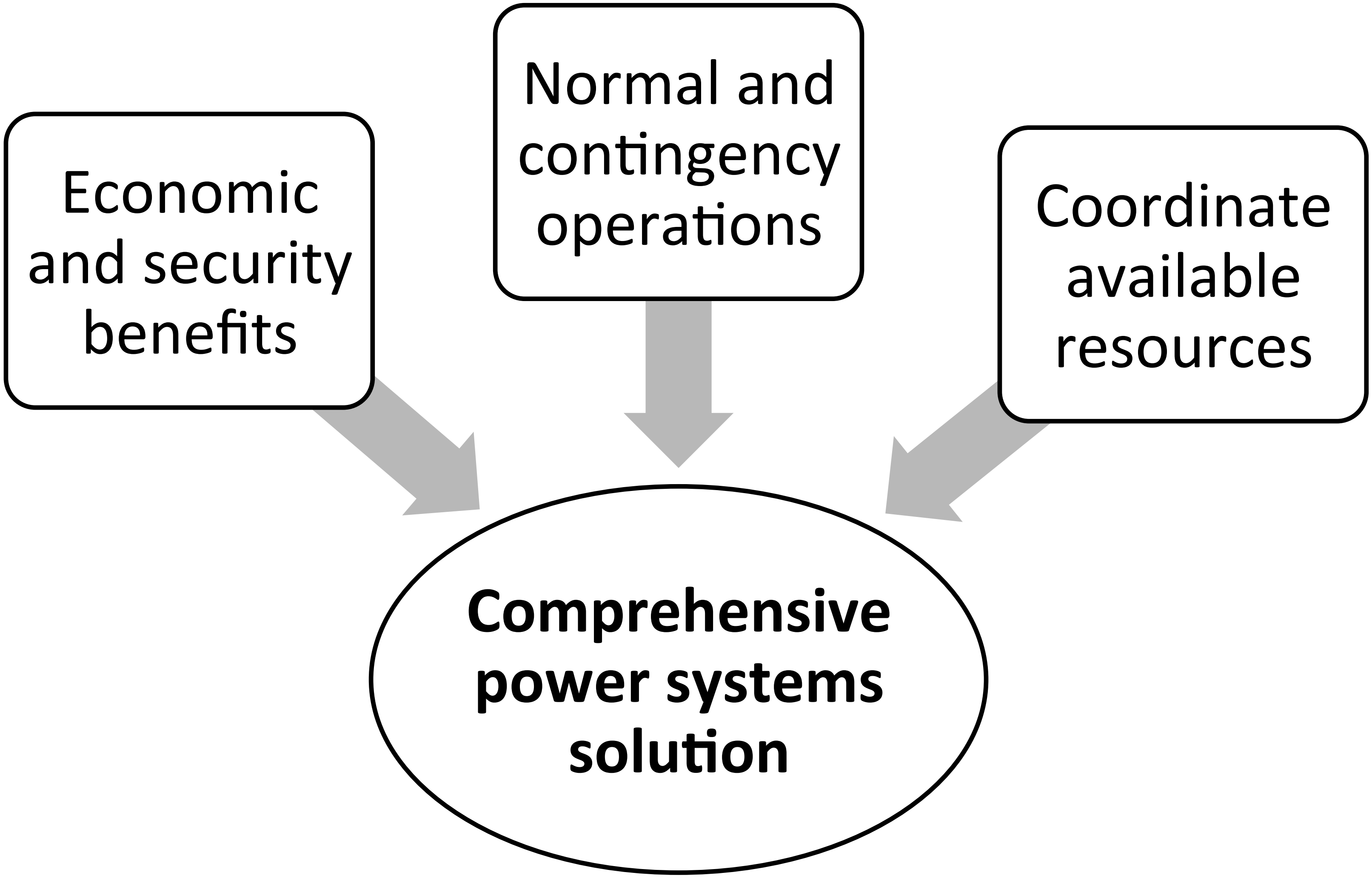
Human grid operators @ PJM

Increased system complexity

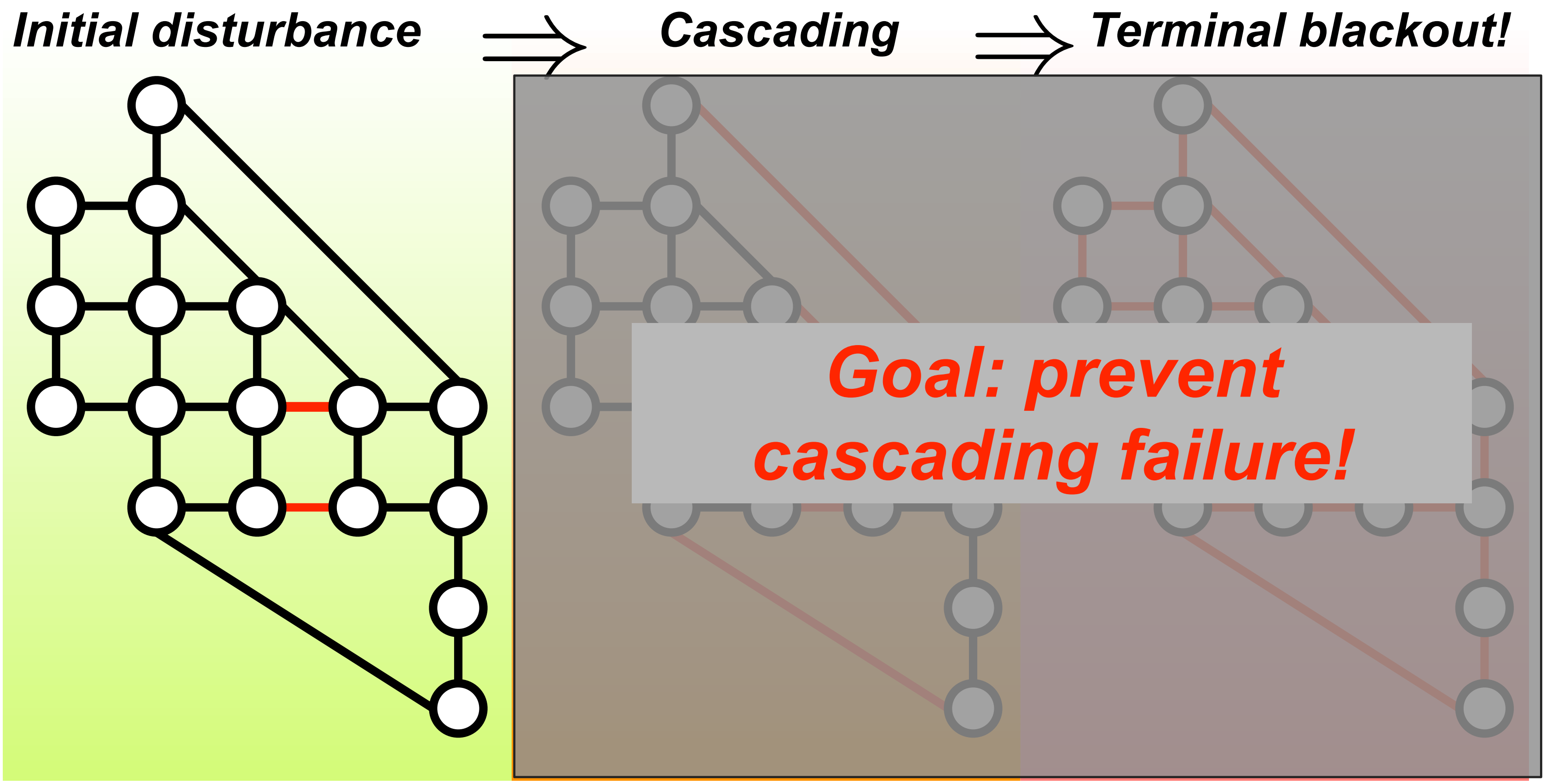
During unanticipated events, human operators need new tools to aid in decision-making

Source: PJM Interconnection

Research Objective



Cascading failure



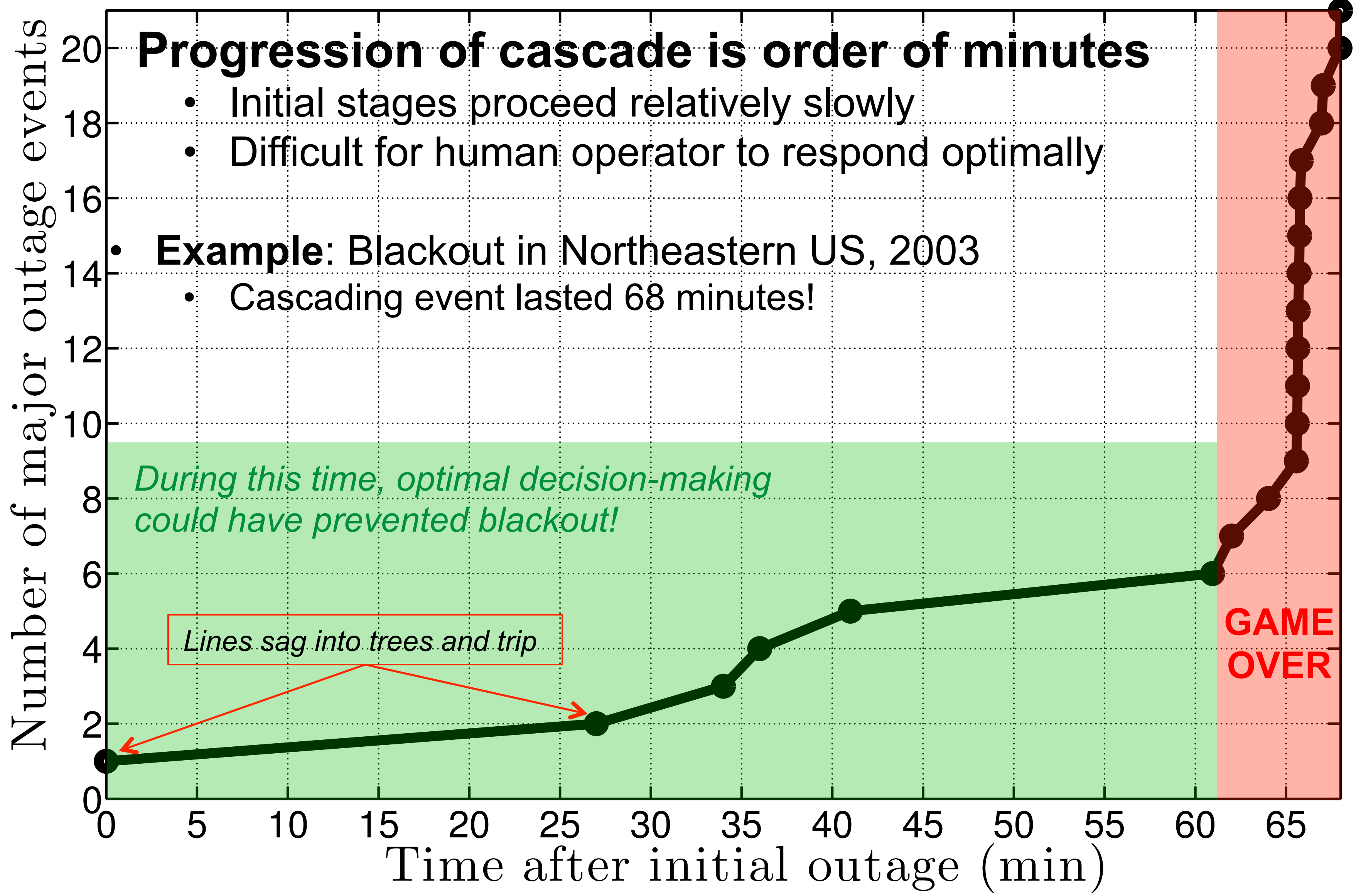
- Cascade is a uncontrolled cycle of flow redistribution, line outages
- Non-trivial to predict and protect against all failures (N-k schemes)

Cascading failure

Progression of cascade is order of minutes

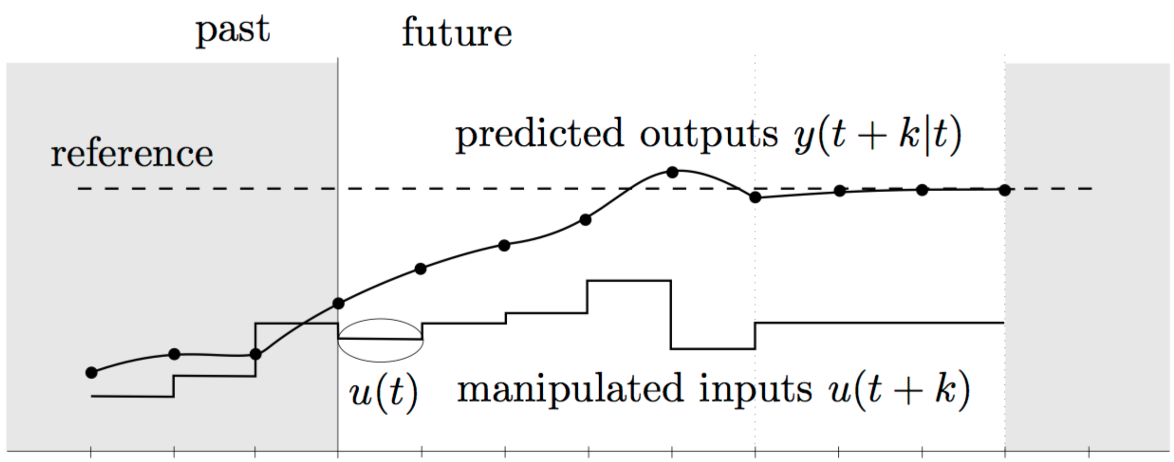
- Initial stages proceed relatively slowly
- Difficult for human operator to respond optimally

- **Example**: Blackout in Northeastern US, 2003
  - Cascading event lasted 68 minutes!



Cascade Mitigation Approach

- **Power systems suffused with constraints on states/inputs**
    - Gen ramp-rate limits, storage power limits, temperature limits, …
- Use ***model-predictive control (MPC)*** *scheme* to halt cascade
    - Compute optimal control law by solving an optimization problem on-line
    - Computationally expensive: need **simple but sufficient model** ← **hard!**



[Borelli, et al, *Predictive Control, 2013*]

- **Ensuring reliability in power systems with MPC:**
    - Voltage stability [*Larsson 2002, Zima 2003, Hiskens 2004*]
    - Static/thermal line overloads [*Galiana 2005, Hines 2009, Carneiro 2010*]

→ **Underestimate line losses**

→ **No comprehensive solution. No active role for energy storage.**

Relevant power system concepts and models

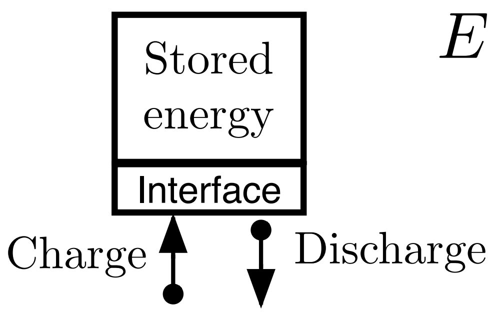
- **Power balance:** for each node, *i*

Flow out – flow in = produced – consumed

- **Power flow:** for each line, (*i, j*)
  - Models the underlying physics of an AC power network
  - Common models: *nonlinear* AC vs. simplified *linear* "DC" models
  - *"DC"* assumes fixed voltage magnitudes, no reactive power, no losses

"DC" Power Flow: $$f_{ij}^{DC}[k] = \frac{\theta_{ij}[k]}{x_{ij}}$$

- **Energy storage model:** an simple first-order model

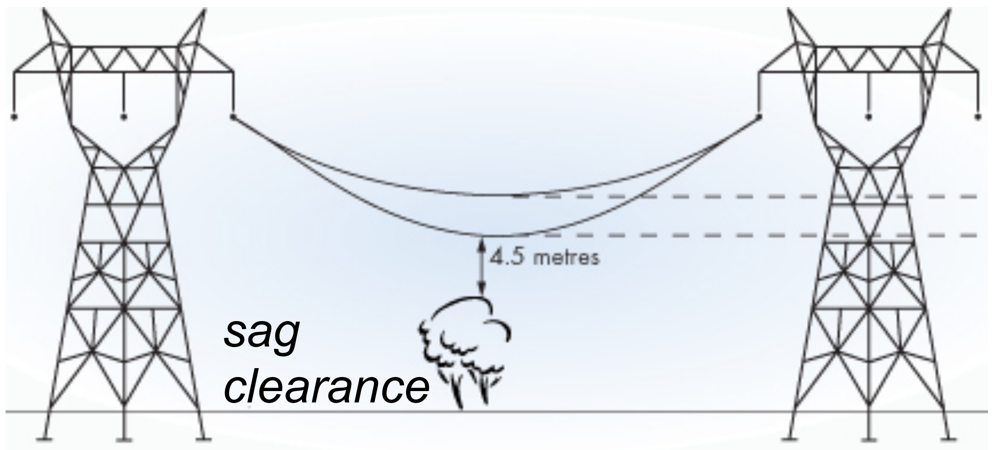


$$E[k+1] = E[k] + \eta_{ch} f_{ch}[k] + \frac{1}{\eta_{dis}} f_{dis}[k]$$

$$0 = f_{ch}[k] f_{dis}[k]$$

Relevant power system concepts and models

Transmission lines are characterized by **static power ratings**
Power rating → Current rating → Temp limit → sag clearance



IEEE Standard 738: conductor temperature model

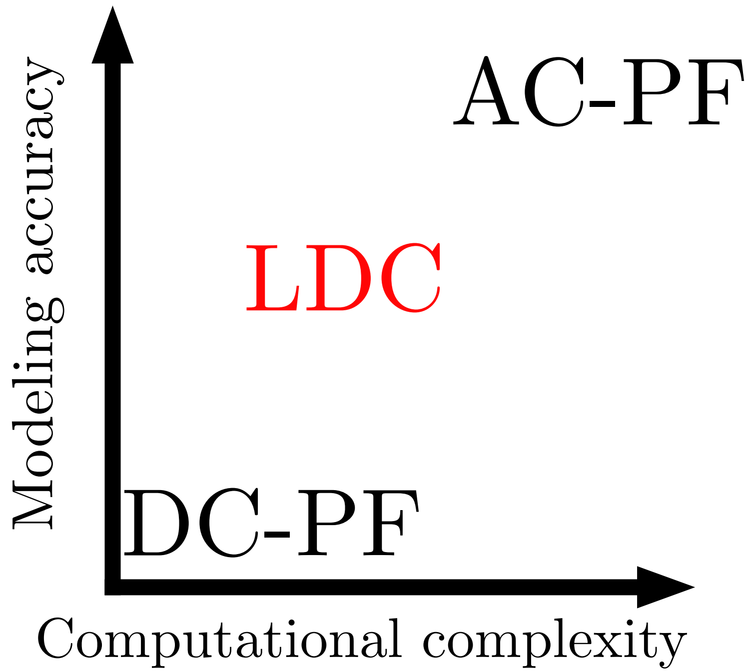
$$\dot{T}(t) = \frac{1}{mC_p}\left(q_s(t) + f^{loss}(t) - q_c(t, T(t)) - q_r(t, T(t)^4)\right)$$

solar heat gain *convection heat loss* *radiated heat loss*

To reduce temperature, must alleviate *I^2R (ohmic)* losses subject to power flows and nominal demand and other constraints

Relevant power system concepts and models

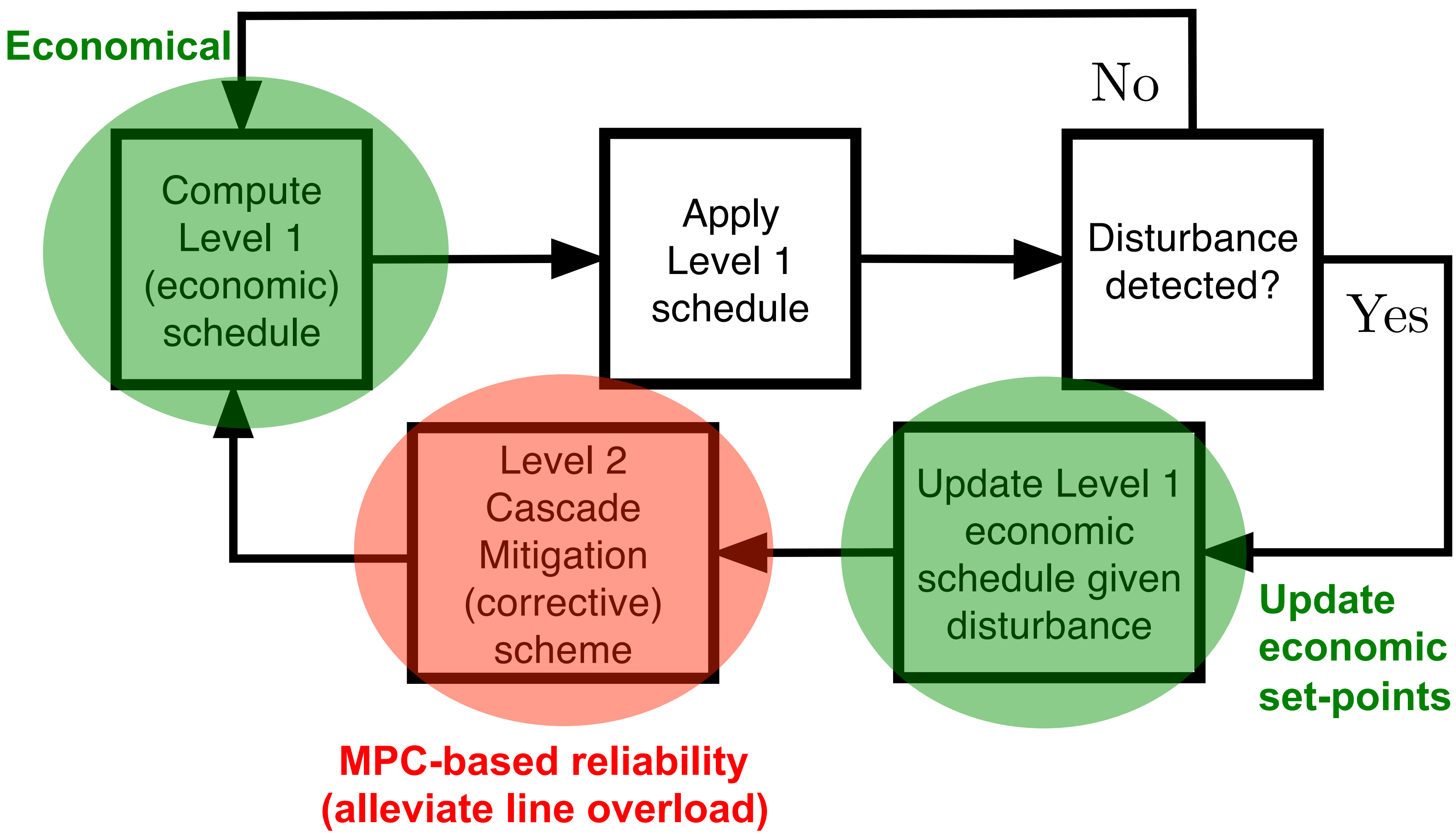
- **Main Technical Challenge**
  - ☑ Optimally alleviate line temperature overloads
  - ☑ AC-PF is accurate but non-convex!
  - ☑ DC-PF is linear but not as accurate!
  - ☑ Temperature *depends* on I^2R-loss
  - ❑ Need a *simple but sufficient model*



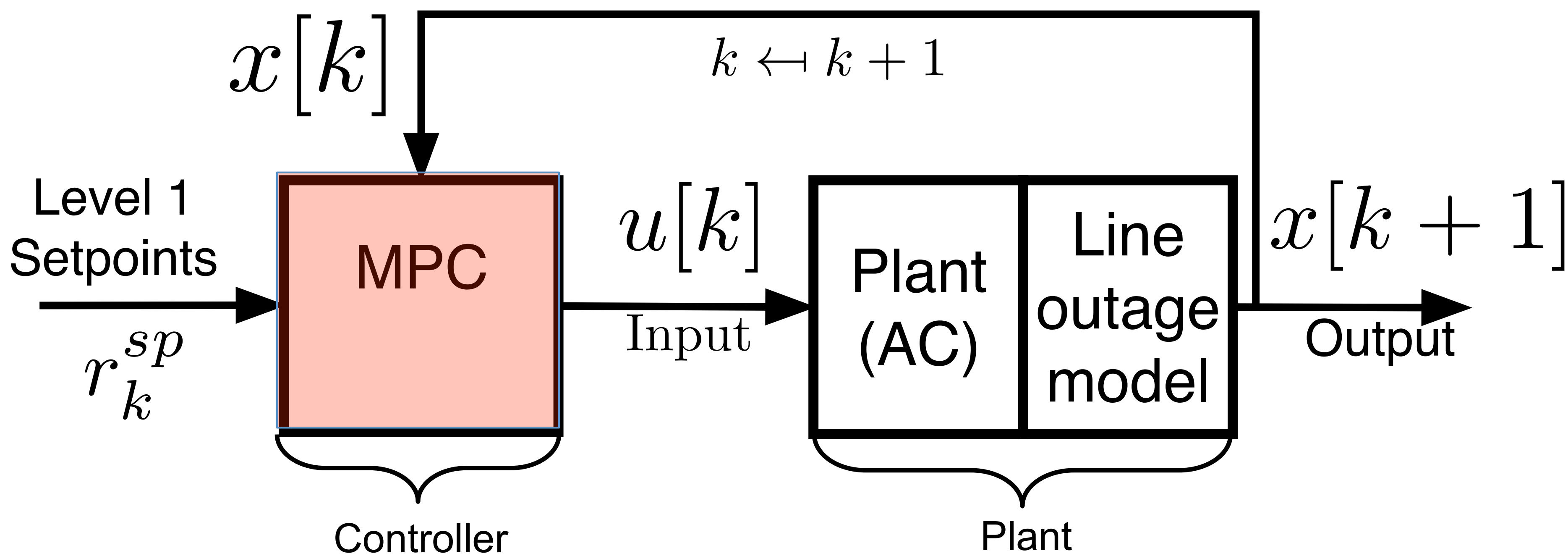
- **Need for compromise**: "*lossy DC power flow*" (*LDC*)
  - *Intuitive*: line losses are given by

$$f_{ij}^{loss}[k] \approx (f_{ij}^{DC}[k])^2 R_{ij}$$

Cascade Mitigation Overview



Level 2: Cascade Mitigation Scheme



x : generator power output, storage energy level, line temperature

u : change to generator output, storage dis/charge rate, load control, wind spill

r : economically optimal set points for x, u

Finite Horizon Open-loop Optimization for MPC

Minimize	• *Line temperature overloads* • *Deviations from Level 1 set points*	$(\max\{0, T_{ij}[k] - T_{ij}^{lim}\})^2$ $(x_m[k] - x_{m,k}^{sp})^2 + (u_n[k] - u_{n,k}^{sp})^2$

subject to

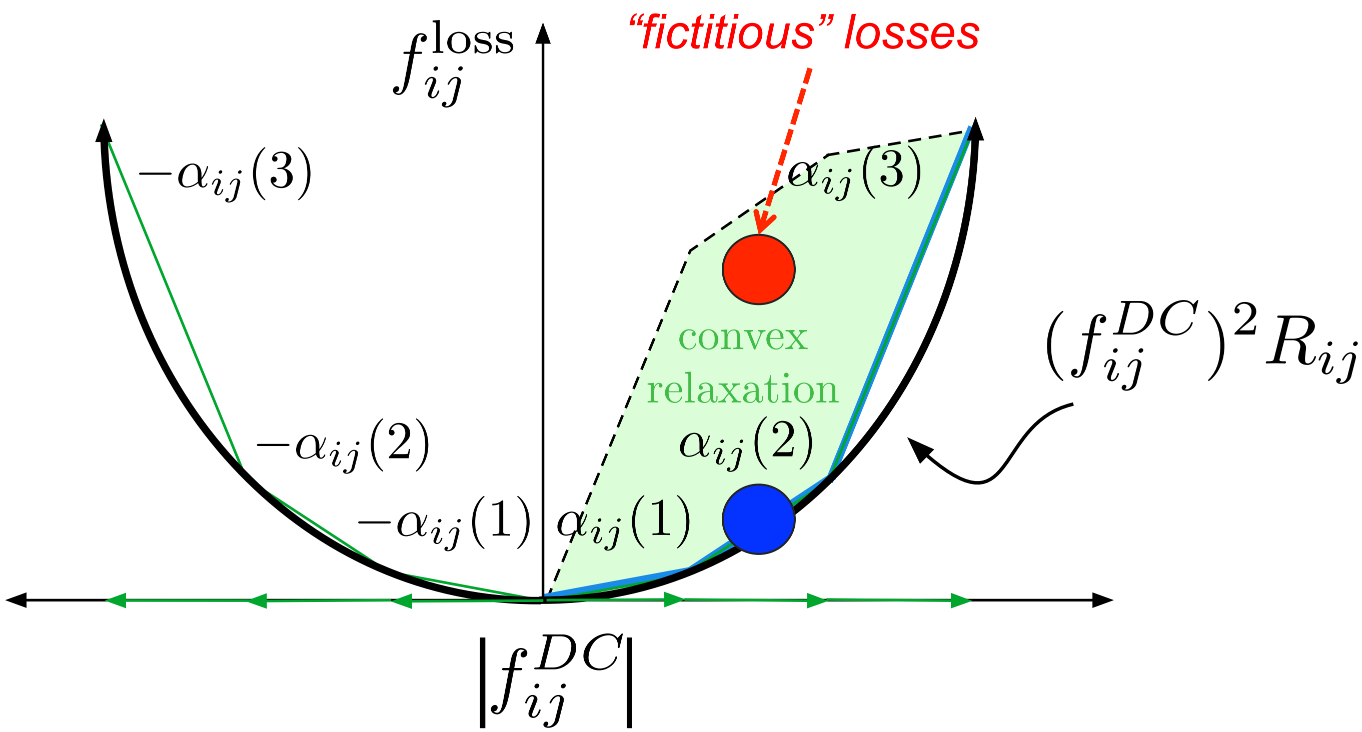
Discrete dynamical constraints
- Linearized temperature dynamics
- Energy storage dynamics
- Generator integrator dynamics

Algebraic constraints
- *Power balance equation*
- *DC power flow*
- *DC line losses* — A) Nonlinear non-convex losses
- *Storage complementarity condition* — B) Nonlinear complementarity constraint

- *Limits on states and inputs*
- *Terminal temperature constraint* ← *Limits overload magnitude*
- *Measured/estimated initial state*

A) Relaxation of Nonlinear Line Loss Constraint

- Overcome non-linearity by relaxing constraint:



Definition: The convex relaxation is ***locally tight*** if losses are exact for a line

A) Relaxation of Nonlinear Line Loss Constraint

- ***Questions***
  - when is relaxation (locally) tight at optimality?
    - Easy: line temperature is overloaded → minimal losses
  - when is relaxation ***not*** (locally) tight?
    - Negative nodal prices? Forced generator ramp-down?
    - Need to consider such conditions…

Idea: modify algebraic power balance constraint:

$$\sum_{(i,j)\in\mathcal{N}_i} f_{ij}^{DC}[k] + \frac{1}{2} f_{ij,k}^{loss,est} = f_{gen,i}[k] - f_{load,i}[k]$$

In controller, use fixed estimate of losses based on last AC measurement

Effectively decouples temperature from network topology and states

A) Relaxation of Nonlinear Line Loss Constraint

Theorem for predicted line losses:

$$\text{If } T_{ij}[k+1] > T_{ij}^{lim} \Rightarrow f_{ij}^{\text{loss}}[l] \text{ is locally tight for all } l \leq k$$

Proof follows from KKT conditions

Reflecting on the convex relaxation:

- Theorem enables MPC to alleviate temperature overloads
- ***Independent of topology, negative LMPs, etc.***

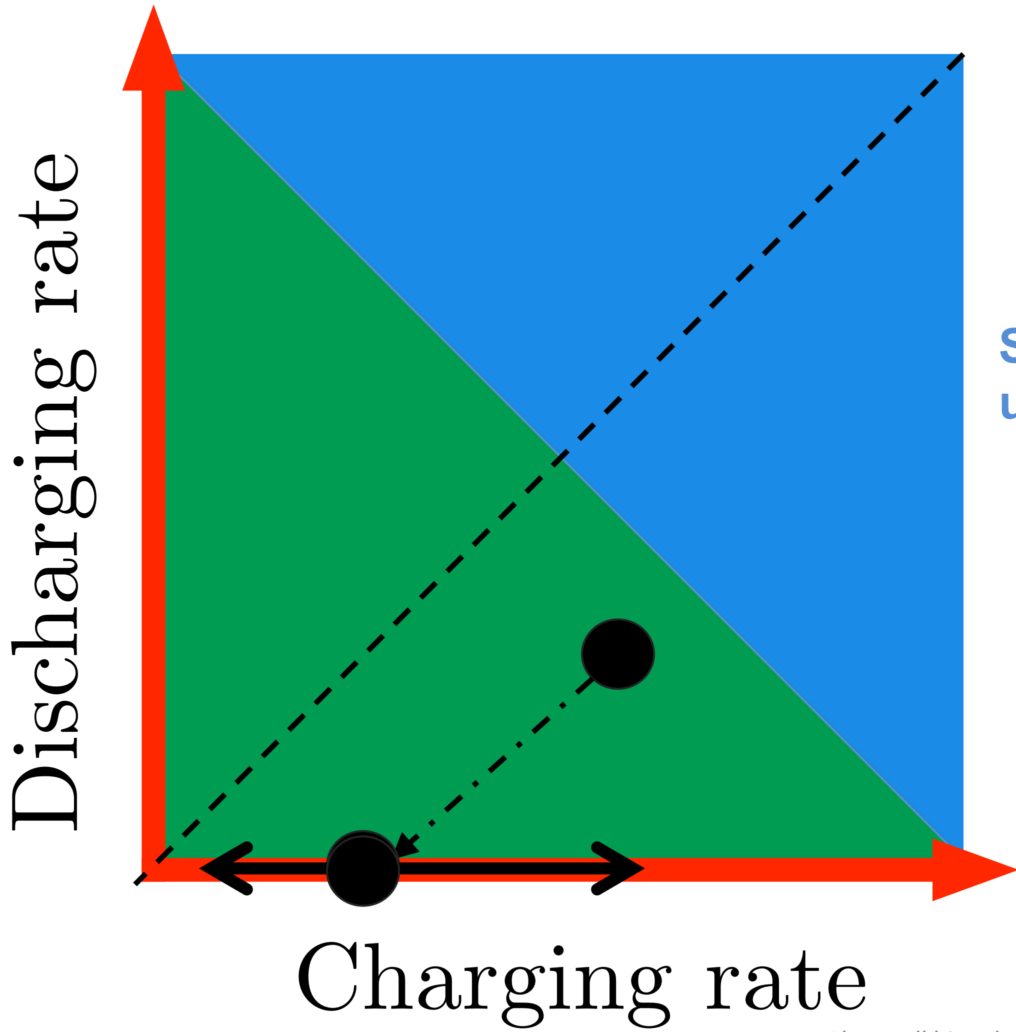
"*Price*" of fixed estimate of losses

- Creates power mismatch between model and actual system
  - Generators and storage are scheduled against mismatch
  - Mismatch is negligible and rejected through feedback

B) Relaxation of complimentarity constraint

Complementarity condition is not convex ➔ want something simple

But, simultaneous charging/discharging allows storage to waste energy



$$0 = f_{ch}[k] f_{dis}[k]$$

$$0 \lessgtr f_{ch}[k] f_{dis}[k]$$

Simulcharge models can significantly underestimate the state-of-charge

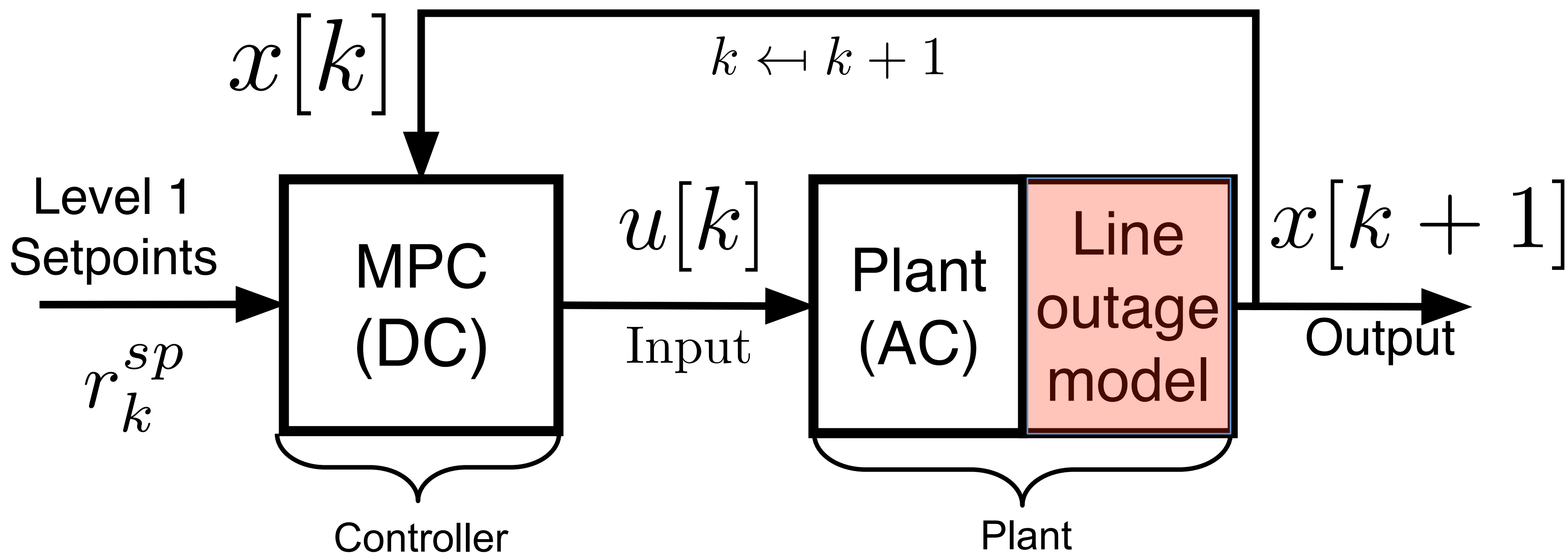
<u>Proposed Heuristic</u>

1. Directly limit simulcharge effect
   a. Add constraint to MPC:

$$f_{ch}[k] + f_{dis}[k] \leq \overline{f_E}$$

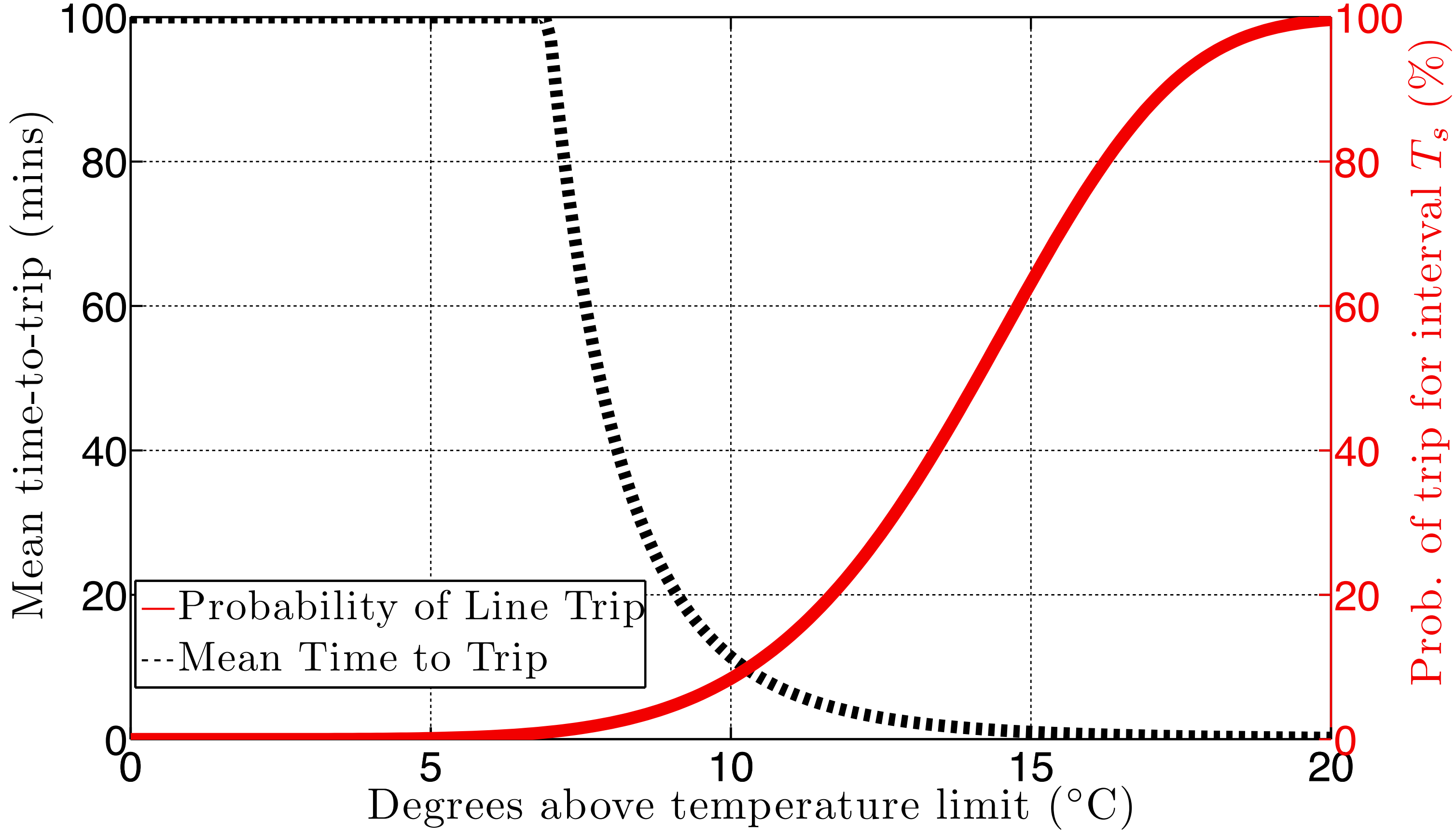
2. Only selectively allow simulcharge
   a. When MPC is initializing (1^{st} run)
   b. When switching storage state
3. Enforce complementarity based on ***<u>previous</u>*** MPC trajectory

MPC Cascade Mitigation



Line outage model

- Line-tripping based on temperature conditions
  - Large temperature overload → decreased mean time-to-trip



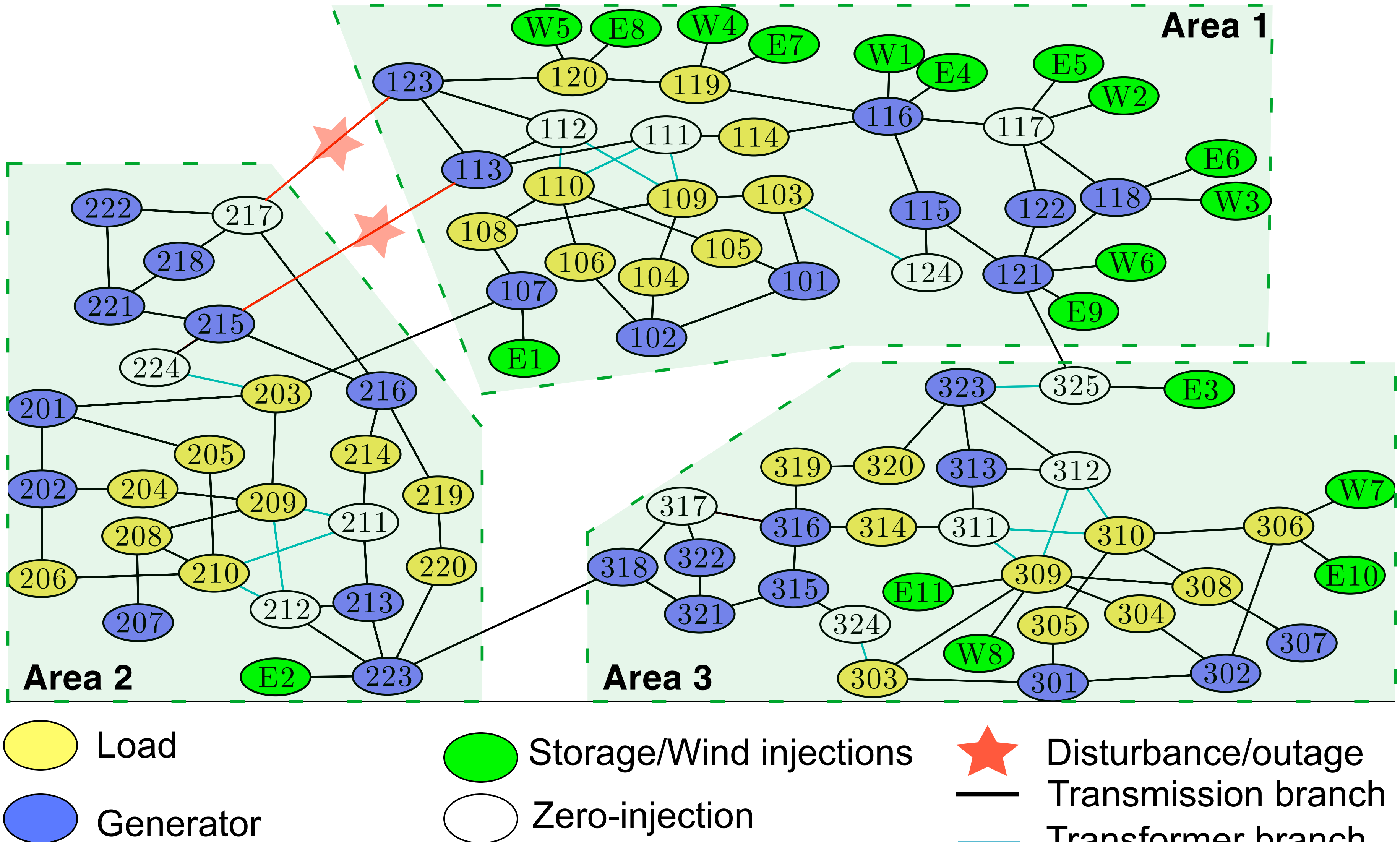
Based on short-term emergency line rating = sustain 25% overload for 15 minutes

Defining a base-case for comparison

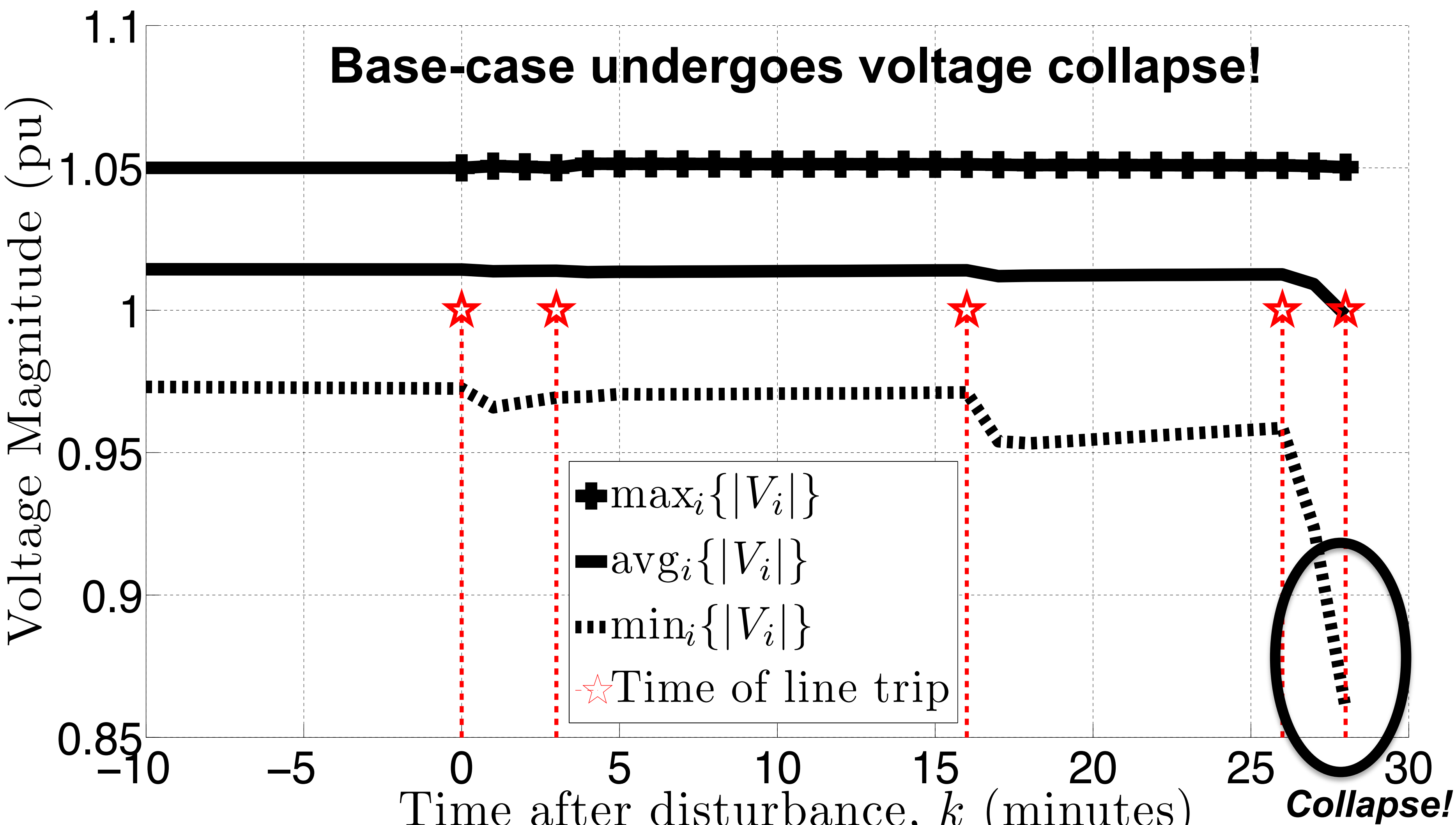
- Based on PJM transmission operator manual
- Focus on power overloads
- Akin to 1-step MPC
- Penalize load control severely
- No control of energy storage

Warning! It's a simple but crude model of human operator!

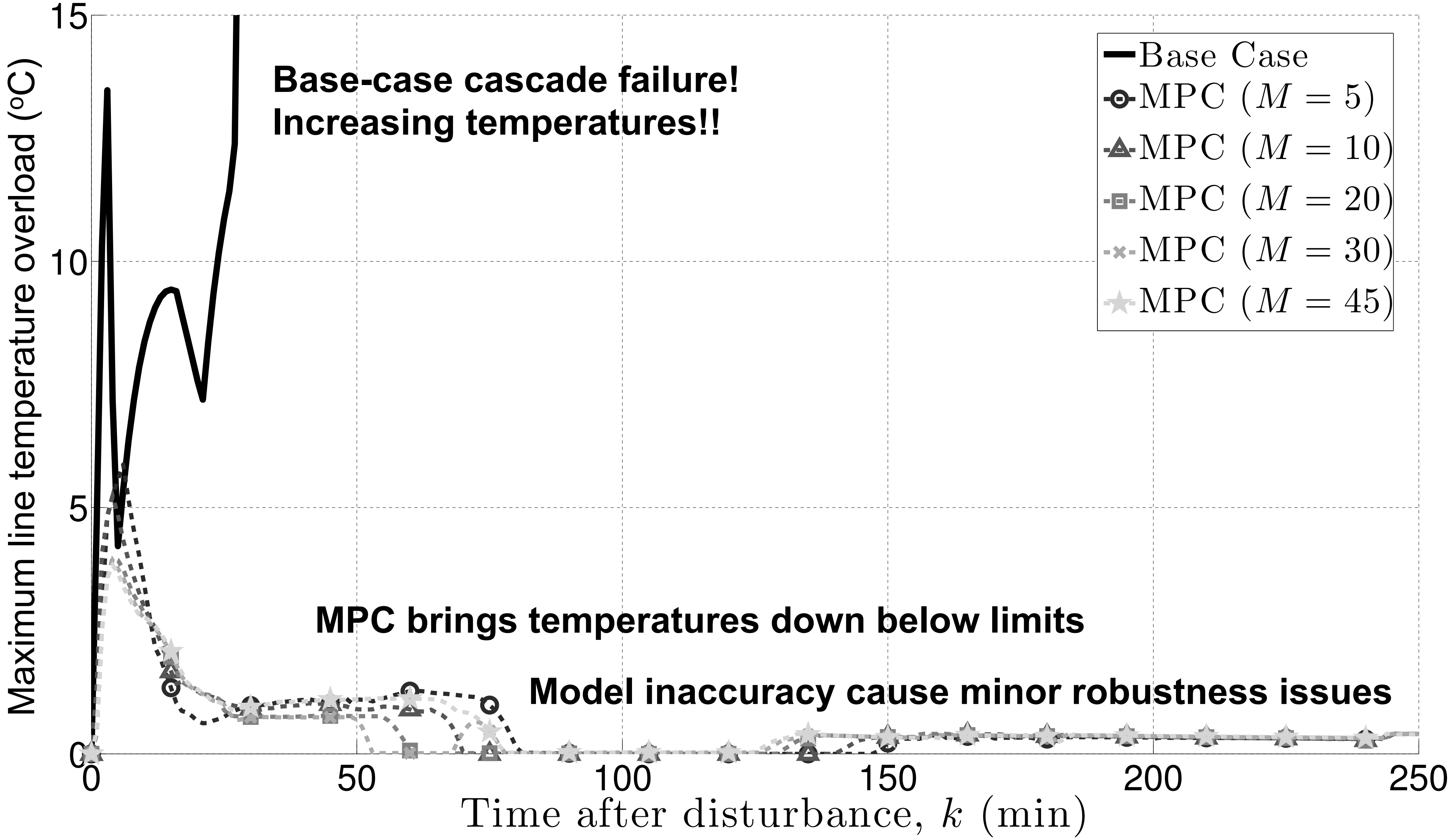
The IEEE Reliability Test System



Base-case performance



Case-study on IEEE Reliability Test System



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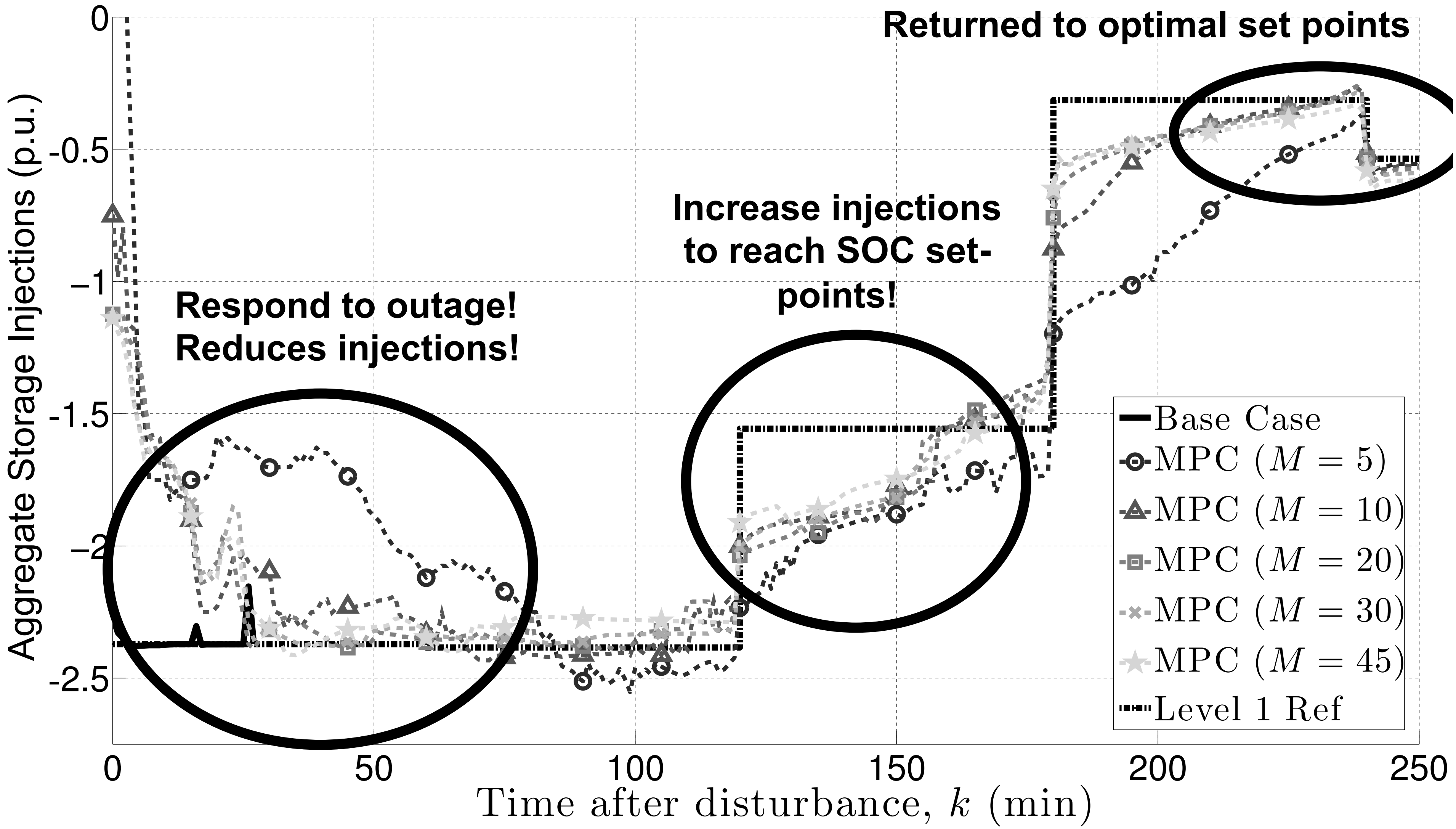
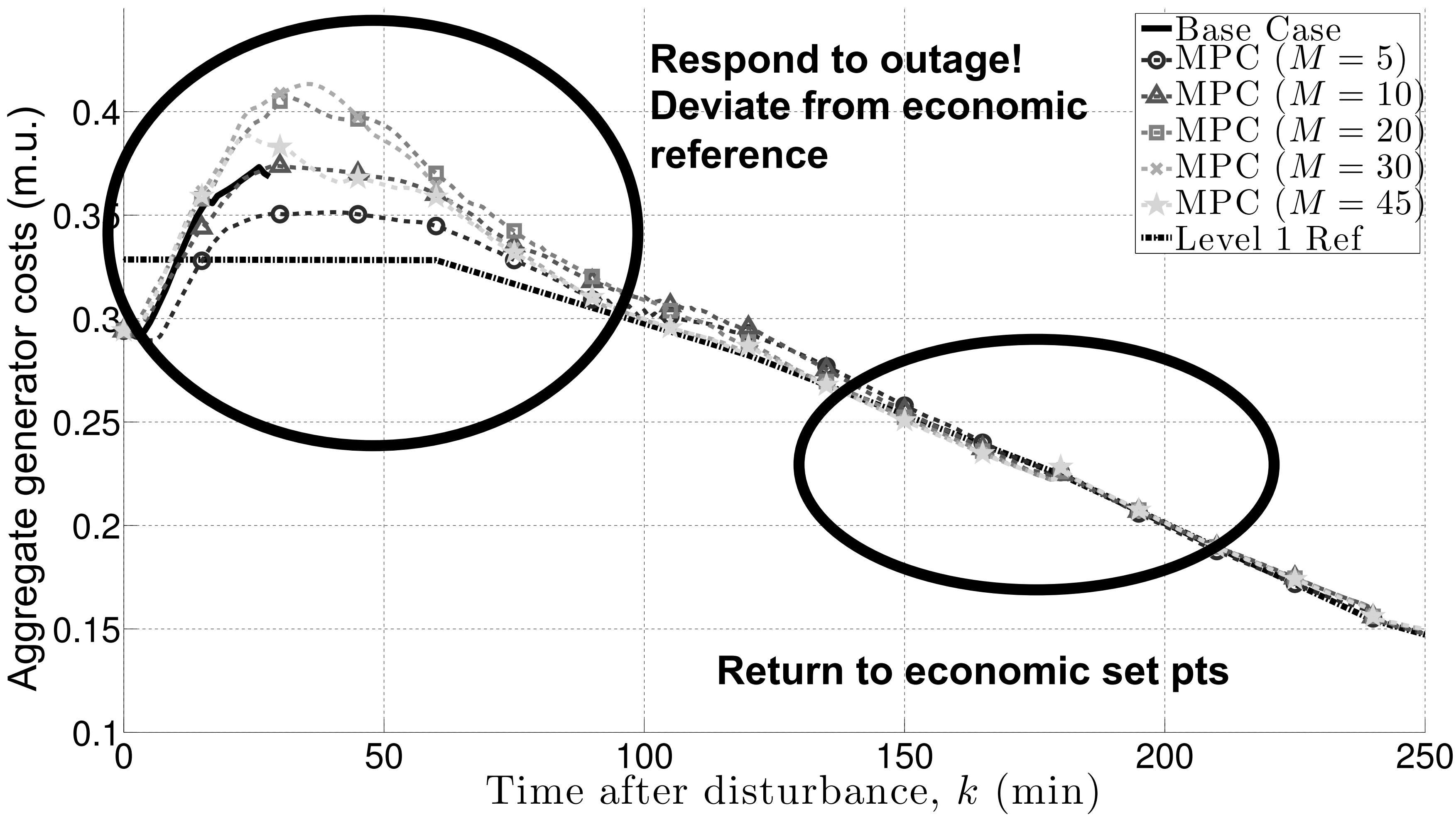
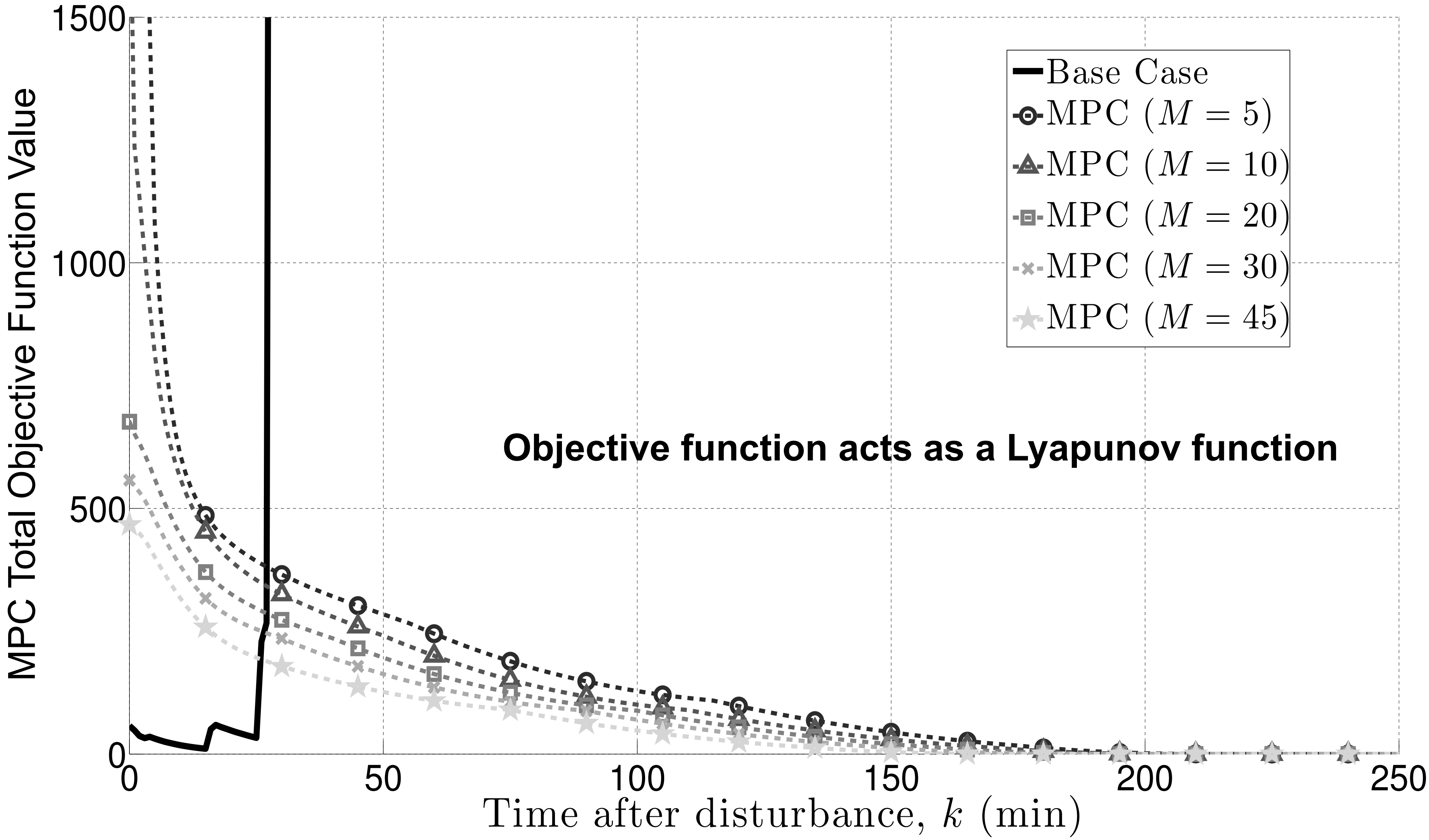


Case-study on IEEE Reliability Test System



Case-study on IEEE Reliability Test System



Immediate next steps…

- **Proof of stability for MPC-scheme is not straightforward**
  - Convex relaxations create non-uniqueness in DAE formulation
  - Hierarchical control scheme (Level 1+2) requires consideration
    - R. Scattolini, "Architectures for distributed and hierarchical Model Predictive Control – A review," *Journal of Process Control,* vol. 19, pp. 723–731, 2009.
- **Valuable to capture voltage info in linear MPC formulation**
  - Enhances role and value of storage
    - C. Coffrin and P. Van Hentenryck,"A linear programming approximation of AC power flows," *INFORMS Journal of Computing.* To appear.
- **Investigate robustness of control scheme**
  - MPC performance under different classes of uncertainty
  - Capture risk of failure from overloading lines → Stochastic optimization
- **Improve Base-case model** (need operator data)
- **Consider distributed MPC**

Thank you!

- FERC organizing committee
- **Collaborators:**

Team UW

- Prof. Daniel Kirschen (UW)
- Dr. Hrvoje Pandzic (UW)
- Ting Qui (UW)
- Yishen Wang (UW)

Team UM

- Jennifer Felder (UM)
- Dr. Mengran Xu (UM)

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References

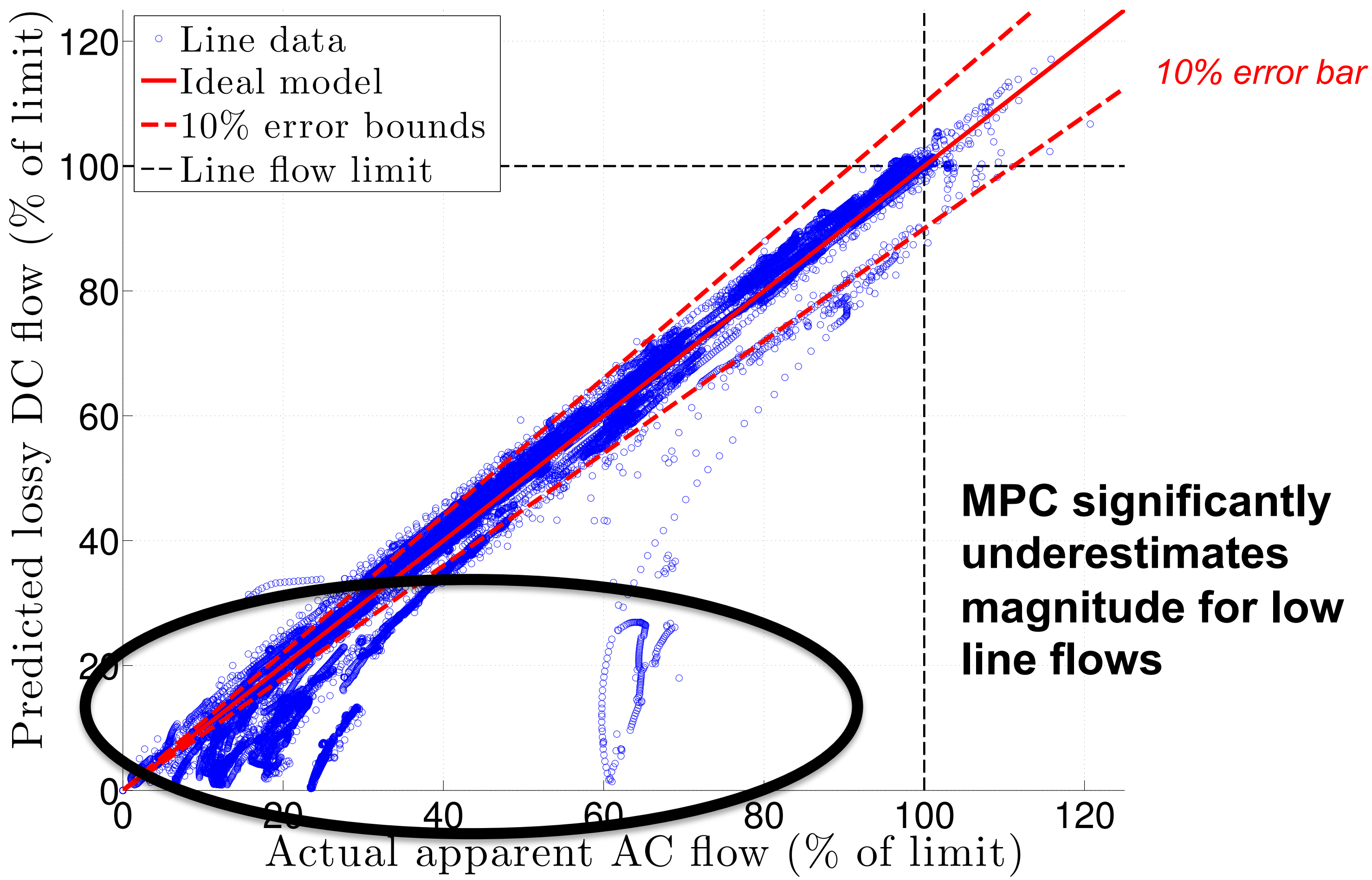
- **Relevant publications for details:**

1. **Almassalkhi** and Hiskens, *Optimization Framework for the Analysis of Large-scale Networks of Energy Hubs*, IEEE PSCC '11
2. **Almassalkhi** and Hiskens, *Cascade Mitigation in Energy Hub Network*, IEEE CDC '11 (invited)
3. **Almassalkhi** and Hiskens, *Impact of Storage on Cascade Mitigation in Multi-energy Systems,* IEEE PES '12 (invited)
4. **Almassalkhi** and Hiskens, *Temperature-based Model-Predictive Cascade Mitigation in Electric Power Systems*, IEEE CDC '13 (invited)
5. I. A. Hiskens, D. Kirschen, M. Xue, **M. Almassalkhi**, and J. Felder, "Energy Positioning: Control and Economics - Part 2," *Allerton Conference on Communication, Control, and Computing* (invited), 2013
6. **Almassalkhi** and Hiskens, *Model-Predictive Cascade Mitigation in Electric Power Systems With Storage and Renewables Part I: Theory & Implementation*, IEEE TPWRS (2014)
7. **Almassalkhi** and Hiskens, *Model-Predictive Cascade Mitigation in Electric Power Systems With Storage and Renewables Part II: Case-study*, IEEE TPWRS (2014)

Extra Content

Simple models and complex systems

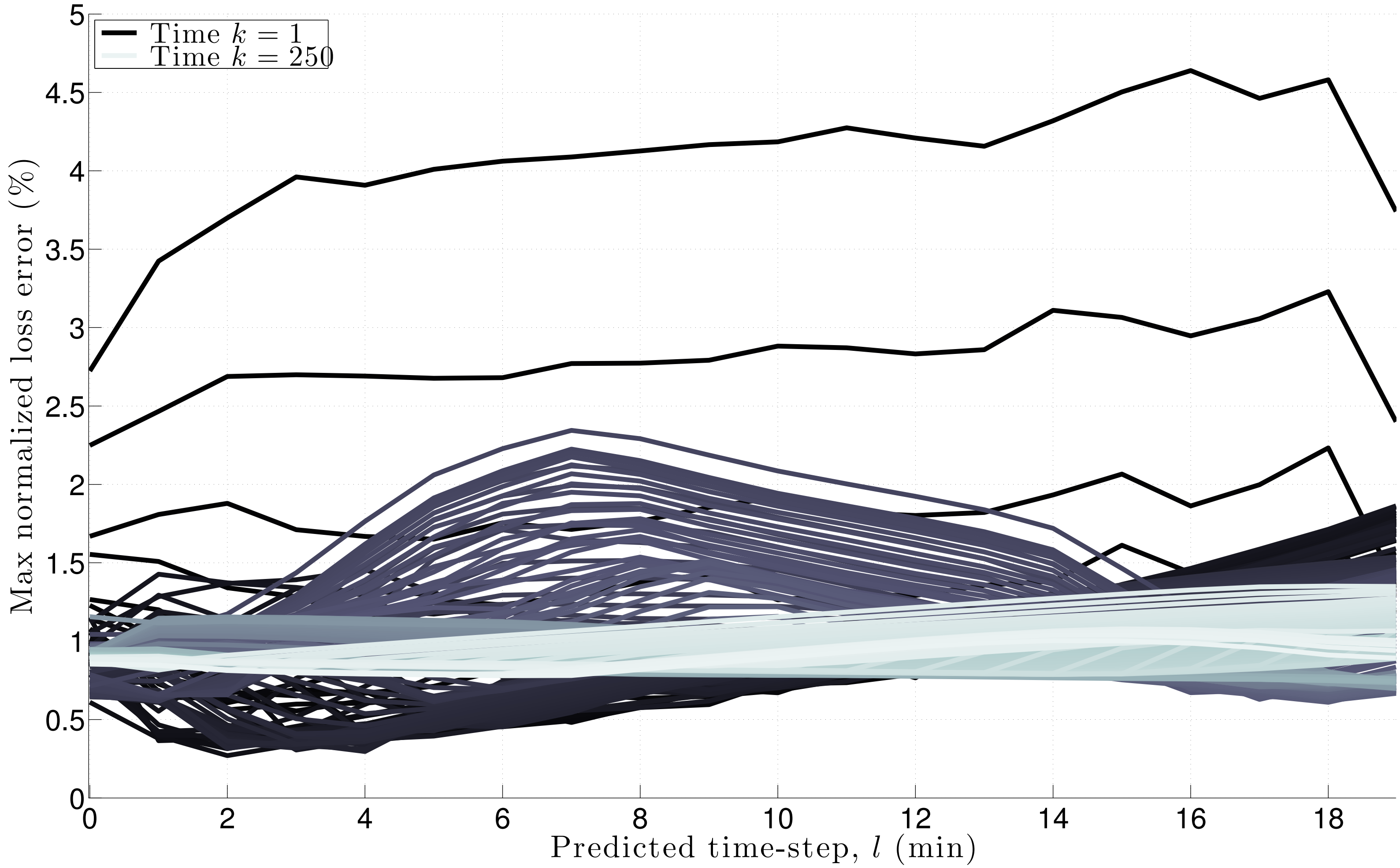
Predicted DC vs. actual AC flow magnitude



MPC significantly underestimates magnitude for low line flows

Simple models and complex systems

Predicted line loss errors from fixed power flow loss term



Data management & communication

- **Initialization of MPC trajectory requires**
  1. *Conductor temperatures*
     - Thermocouple relays, hard limits, or estimation
     - *"Not overly complex for EMS*" [Banakar et al. 2005]
  2. *Energy storage state of charge**
     - Systems today have telemetry for market participation
  3. *Updated network topology**
  4. *Generation output power and load levels**
  5. *Operating points of all FACTS devices**
  6. *Forecasts* (demand, renewables, weather) *
  7. *Minute-by-minute communications**
     - Slower than current control, market signals

***-requirements are consistent with today's operations!**