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Robust Corrective Transmission Switching Schemes

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Outline

- Overview
- Prior Research
- Robust Corrective Switching
- Robust Corrective Switching Framework
- Results
- Future Work and Conclusions

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Overview

Motivation for Topology Control

- Control over transmission not fully utilized today
  - Transmission assets are treated as static in the short term
  - Transmission assets are traditionally modeled as an asset that is not controllable

- However, currently operators change transmission assets' states on ad-hoc basis
  - Special Protection Schemes (SPSs) in the PJM ISO
  - California ISO, congestion management procedures

- **Corrective switching: enables the shift from preventive to corrective**

Motivation for Topology Control

- Model transmission assets as controllable (switchable) assets
  - Improvements in reliability
  - Congestion management
  - Improving deliverability of reserves (through congestion management)
  - Useful for integration of variable renewable resources (through congestion management)
- Short-term reconfiguration of the transmission network

Motivation for Robust Corrective Switching

The presented research:

- Identifies and addresses technology gap between real-time corrective switching and planning based corrective switching

- Develops a robust corrective switching methodology for contingencies

- Develops a robust corrective switching methodology for contingencies

Industrial Practices

Special Protection Schemes

- **PJM (2010) Manual 3**: Transmission Operations. http://pjm.com/~/media/documents/manuals/m03.ashx

- Sunnyside-Torrey 138 kV Operating Guide (AEP Operating Memo T029)
  - Historically, the Sunnyside-Torrey 138 kV overloads on the outage of the South Canton – Torrey 138 kV line. **Opening the S.E. Canton 138 kV CB at Sunnyside** will help to reduce the post-contingency flow on the Sunnyside-Torrey 138 kV line.
  - Page 133

- The 138 kV tieline L28201 from Zion to Lakeview (WEC) can be **opened to relieve contingency overloads** for the loss of either of the following two lines:
  - Zion Station 22 to Pleasant Prairie (WEC) 345 kV Red (L2221)
  - Zion Station 22 to Arcadian (WEC) 345 kV Blue (L2222)
  - Page 209

Industrial Practices

Topology Control for Congestion Management

- California ISO, *Minimum Effective Threshold Report*. [Online]. Available: http://www.caiso.com/274c/274ce77df630.pdf.

- Event caused substantial congestion in 115kV network in Sacramento Valley
  - "These constraints resulted from outages in the higher voltage transmission system running north-to-south through the Sacramento Valley; the ISO had multiple days around this time when this 115 kV transmission system had significant congestion costs due to the north-to-south flows, until the ISO was able to later identify a remedy of **transmission circuit switching to relieve this congestion**."
  - Page 4.

Manage Congestion in Germany to Mitigate Wind Intermittency

- F. Kuntz, "Congestion management in Germany – the impact of renewable generation on congestion management costs," Available: http://idei.fr/doc/conf/eem/papers_2011/kunz.pdf.
  - Use of transmission switching to mitigate line overloads caused by intermittent resources

Prior Research

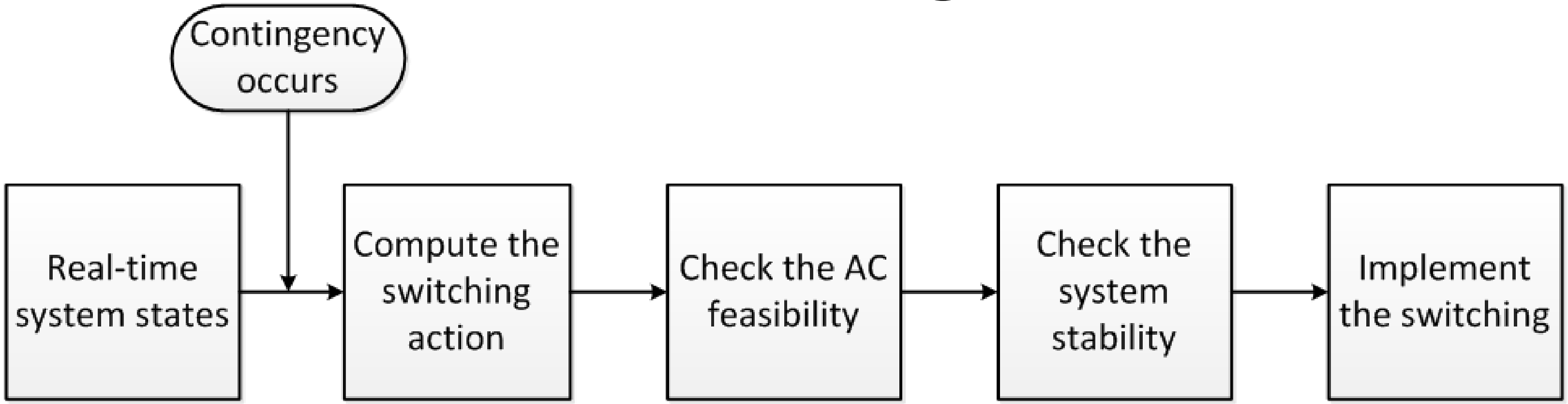
Literature review

- Research since the 1980s demonstrating that topology control can be used to mitigate: line overloads, voltage violations

- **Corrective switching**

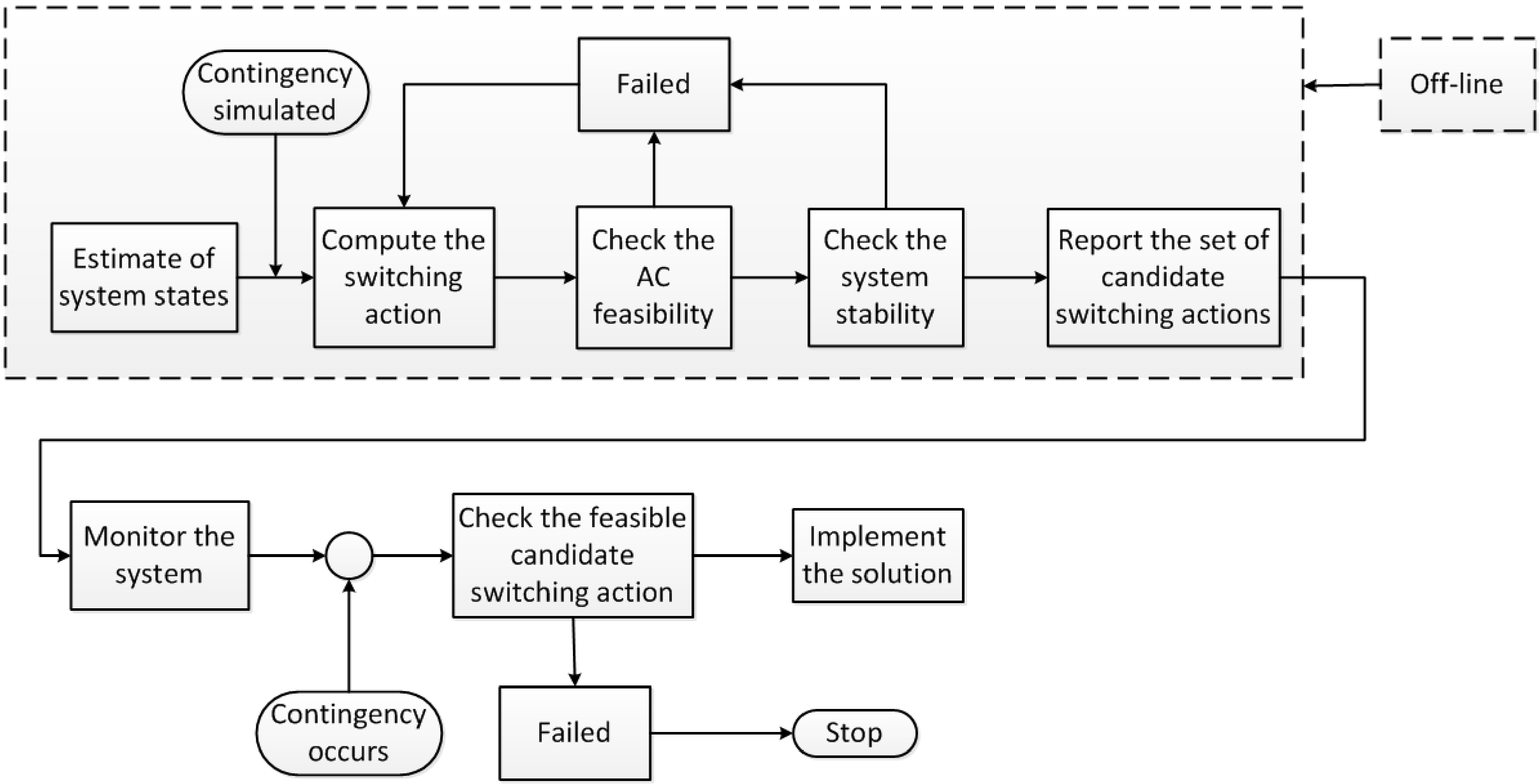
- A. A. Mazi, B. F. Wollenberg, and M. H. Hesse, “Corrective control of power system flows by line and bus-bar switching,” IEEE Transactions on Power Systems, vol. 1, no.3, pp.258-264, Aug.1986.
- G. Schnyder and H. Glavitsch, "Security enhancement using an optimal switching power flow," IEEE Transactions on Power Systems, vol. 5, pp. 674-681, May 1990.
- W. Shao and V. Vittal, "Corrective switching algorithm for relieving overloads and voltage violations," IEEE Transactions on Power Systems, vol. 20, no. 4, pp. 1877-1885, Nov. 2005.
- W. Shao and V. Vittal, “BIP-based OPF for line and bus-bar switching to relieve overloads and voltage violations,” in the Proceedings of the 2006 IEEE Power System Conference and Exposition, Nov. 2006.

Real-time Corrective Transmission Switching



- **Benefits:** Operating state known
- **Drawbacks:**
  - Demands extremely fast solution time
  - Computationally challenging
- Limited implementation of real-time corrective switching today since it is not fast enough for real-time operations

Planning Based Corrective Transmission Switching



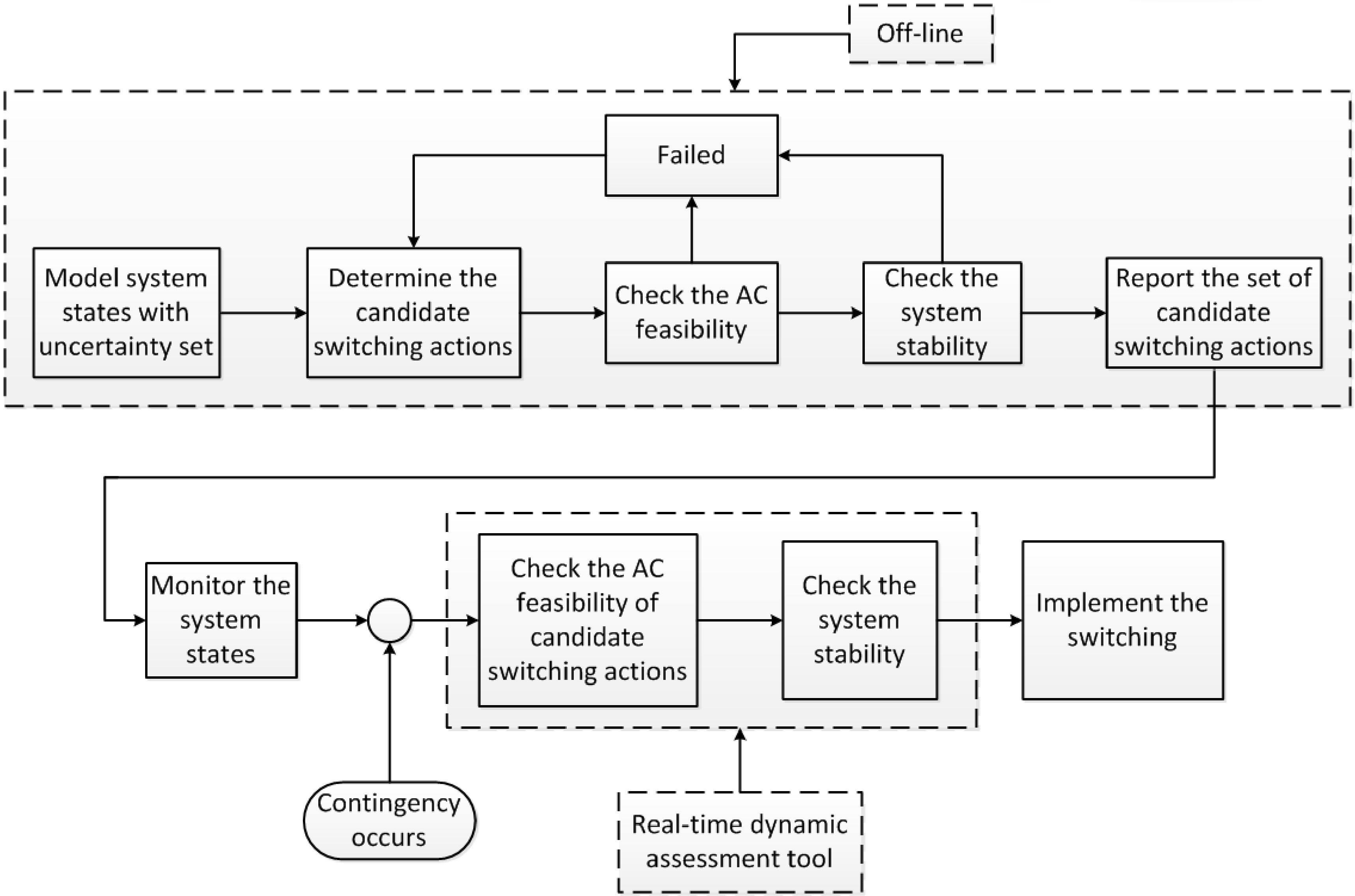
Planning Based Corrective Transmission Switching

- **Benefits:** Offline study
  - Fast implementation in real-time

- **Drawbacks:**
- Must make a-priori assumptions regarding future system operating state
- If this assumption is incorrect, the corrective switching action may not work – and **may make the system worse**

Robust Corrective Switching

Robust Corrective Transmission Switching



Robust Corrective Switching

Benefits:

- Guarantees solution feasibility within the uncertainty set
- Can be implemented in real-time with online dynamic assessment tool
- Addresses computational limitation of real-time methods through an off-line model
- Addresses problematic, required assumptions necessary for deterministic off-line models
    - No need of extremely fast solution time (real time model)
    - No need to assume exact future system operating state (off-line model)

- Fills the **technology gap** between real-time corrective switching and planning based corrective switching

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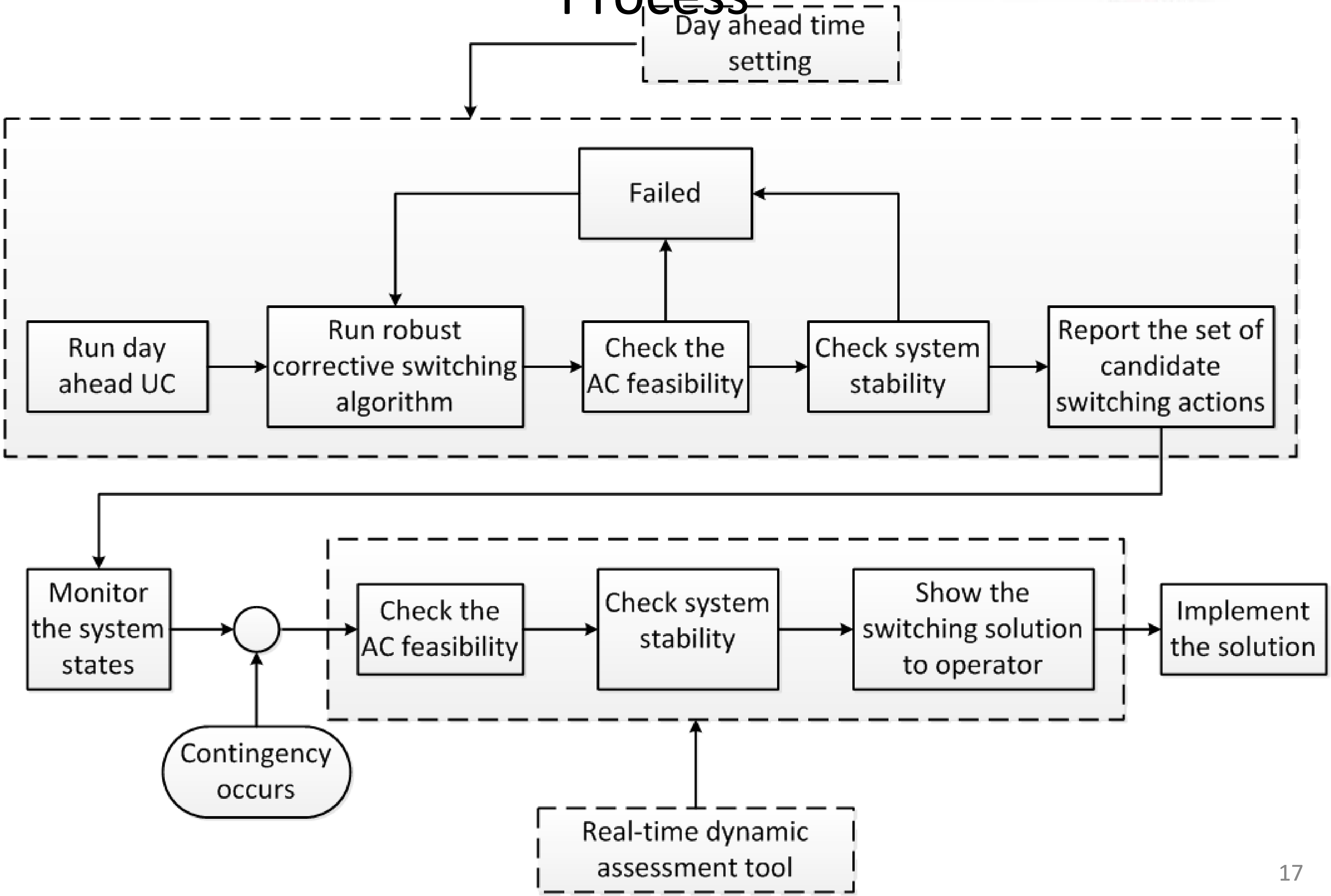
Robust Transmission Switching – End to End Process



Robust Optimization and Corrective Switching

Robust Optimization

Benefits of robust optimization:

- Enables the modeling of an uncertainty set
  - Demand: $d^{min} \leq d \leq d^{max}$
  - Wind: $w^{min} \leq w \leq w^{max}$
- Solution is feasible for any realization within the uncertainty set
  - Robust optimization is more conservative – in line with power industry due to the importance of ensuring a continual supply of electricity
- Accuracy of uncertainty modeling is less critical with robust optimization than compared to other approaches (stochastic)
- Generally less computationally intensive as compared to stochastic programming

Robust Optimization

- Robust optimization: minimizes the potential worst case outcome
- Generic formulation:

$$\min_{x \in X} C^T x + \max_{d \in D} \min_{y \in \Omega} b^T y$$

s.t.

$$X = \{x \in \{0,1\}: Fx \le f\}$$

$$D = \{d: d^{min} \le d \le d^{max}\}$$

$$\Omega = \{y: Hy \le h, A\bar{x} + By \le g, Iy = \bar{d}\}$$

Robust Optimization

$$\min_{x \in X} C^T x + \max_{d \in D} \min_{y \in \Omega} b^T y$$

s.t.

$$X = \{x \in \{0,1\}: Fx \leq f\}$$

$$D = \{d: d^{min} \leq d \leq d^{max}\}$$

$$\Omega = \{y: Hy \leq h, A\bar{x} + By \leq g, Iy = \bar{d}\}$$

Standard OPF

Find the least worst case solution

Choose the demand to produce the most expensive OPF solution (OPF minimizes cost subject to the chosen demand)

Reformulation of Robust Optimization

$$\min_x C^T x + \max_{d \in D} \min_{y \in \Omega} b^T y$$

s.t.

$$Fx \le f, x \in \{0,1\}, d^{min} \le d \le d^{max}, \Omega = \{y: Hy \le h, A\bar{x} + By \le g, Iy = \bar{d}\}$$

Linear Program

Its dual

$$\min_x C^T x + \max_{d \in D} \max_{\beta,\gamma,\delta \in \Psi} \delta^T h + \gamma^T (g - A\bar{x}) + \beta^T d$$

s.t.

$$Fx \le f, x \in \{0,1\}, d^{min} \le d \le d^{max}, \Psi = \{\beta,\gamma,\delta: \delta^T H + \gamma^T B + \beta^T d = b^T, \delta,\gamma \le 0\}$$

Combine

$$\min_x C^T x + \max_{\beta,\gamma,\delta \in \Psi, d \in D} \delta^T h + \gamma^T (g - A\bar{x}) + \beta^T d$$

s.t.

$$Fx \le f, x \in \{0,1\}, d^{min} \le d \le d^{max}, \Psi = \{\beta,\gamma,\delta: \delta^T H + \gamma^T B + \beta^T d = b^T, \delta,\gamma \le 0\}$$

$\beta^T d$ – Bilinear term, can be solved by

- outer approximation (Bertsimas, Litvinov, et al., 2011)
- MIP formulation describing extreme points

Robust Corrective Switching Framework

- Chosen topology:
  - Feasible for any realizable demand (or renewable production) in the defined uncertainty set

- Robust Corrective Switching
  - Enables the modeling of many operating states offline while guaranteeing feasibility

Previous Robust Optimization Research

D. Bertsimas, E. Litvinov, et al., “Adaptive robust optimization for the security constrained unit commitment problem,” IEEE Trans. Power Syst., submitted for publication. [Online]. Available: http://web.mit.edu/sunx/www/Adaptive_Robust_UC_IEEE.pdf

- Robust Optimization creates a non-linear program (bilinear term in objective)

- Previous work uses an outer-approximation technique to solve this problem along with a decomposition technique
    - Does not guarantee solution feasibility due to approximation technique

- Feasibility is critical for Robust Corrective Switching

- Our approach:
    - Reformulate the problem into a MIP describing extreme points
    - Guarantees feasibility over entire uncertainty set

Results

Results

IEEE 118-bus test case, 24-hour unit commitment solved
Peak load hour: **demand uncertainty = 6%** (+/- 152MW over 4519MW base load)

- 4 transmission contingencies require corrective transmission switching action in order to avoid load shedding
  - All 4 have multiple robust corrective switching actions
  - Create a set of candidate actions
  - Feed into a real-time dynamic security assessment tool
- One switching action alleviates multiple contingencies
  - Robust switching solution “open line from Riverside to Pokagon” mitigated **18** transmission contingencies
- Computational time increases with the increase in uncertainty set
  - With 1% increase in uncertainty set (over 6%) computational time increases by 13%

Results

IEEE 118-bus test case, 24-hour unit commitment solved, 20% wind integration
Peak load hour: **wind uncertainty = 16%** (+/-144MW on 4519MW base generation)
Reserve requirement: 5% non-wind + 10% wind

- 12 transmission contingencies require robust corrective transmission switching action in order to avoid load shedding
  - All 12 have multiple robust corrective switching actions
  - Create a set of candidate actions
  - Feed into a real-time dynamic security assessment tool

- One switching action alleviates multiple contingencies
  - Robust switching solution “open line from Logan Sprigg” mitigated **14** transmission contingencies

Results

IEEE 118-bus test case, 24-hour unit commitment solved, 20% wind integration
Peak load hour: **wind uncertainty = 16%** (+/-144MW on 4519MW base generation)
Reserve requirement: 5% non-wind + 10% wind

- Deterministic N-1 Analysis:
  - Loss of line Randolph to CollCrnr causes load shedding – no feasible re-dispatch solution

- Implement Robust Corrective Switching:
  - Robust N-1 Analysis (uncertainty set for wind)
  - Open line from Muskngum to Summerfl
  - The **system survives** without load shedding

Deterministic N-1 Analysis: Failed

Robust N-1 Analysis: Adding corrective switching: PASS

Future Work and Conclusions

Future Work

- Validate AC feasibility, system stability
- Large-scale testing: PJM test case (via FERC), TVA test case (via on-going ARPA-E GENI project)
- Address computational time
- Develop robust AC model
- Develop robust/probabilistic stability model

Conclusions

- Real-time corrective switching is difficult to implement in practice due to ***lack of computational power.***
- Planning based corrective switching ***lacks robustness properties***, hence limited use.
- **Robust corrective switching scheme produces a robust solution for a wide range of system states**
  - **Offline mechanism that can generate multiple robust corrective solutions for real-time implementation**

Conclusions

- Robust corrective switching
  - Enables the transition from preventive to corrective
  - Can be used to alleviate constraint violations caused by load, wind, area interchange, etc.
  - Improves reliability and operational efficiency

- **Robust corrective switching methodology has a potential to bring corrective switching into every day operations**

Thank You!

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