Generator Contingency Modeling in Electric Energy Markets

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Outline

- Key Takeaway Points
- Existing Industry Practices
- Review: Standard DCOPF Problem
- Generator Contingency Modeling Enhancements: Derivation of Prices via Duality Theory
- Conclusions and Future Research Topics

Key Takeaway Points

- Challenges faced by traditional market auction models:
  - Dramatic changes in the resource mix due to the **increased reliance on renewable energy resources**
  - **Inadequately handle generator contingencies** and other typical forms of uncertainties (load, renewable)
- Ideal solution: Model the uncertainty explicitly
  - Stochastic programming approaches (scalability, market barriers)
- Practical outlook: Modern-day market modifications
  - Market advancements: New products (flexible ramping product), market reformulations (contingency modeling enhancements)
  - Such adjustments have associated market implications
- **This research proposes new approaches for these market advancements to improve efficiency, enhance price signals, maintain scalability, and transparency**

Research Projects and Funding

- Project: **Dynamic Reserve Policies for Market Management Systems**
  - Funding: The Consortium for Electric Reliability Technology Solutions (**CERTS**) with the U.S. Department of Energy (DOE)
- Project: **Network Optimized Distributed Energy Systems** (**NODES**)
  - Funding: The Advanced Research Projects Agency – Energy (**ARPA-E**) with the U.S. DOE

Existing Industry Practices

Transmission Contingency Modeling

- Long standing (traditional) practice:
  - **Models uncertainty**: Explicit representation of transmission contingencies (stochastic program)
  - **Security constraints to ensure second-stage feasibility**:

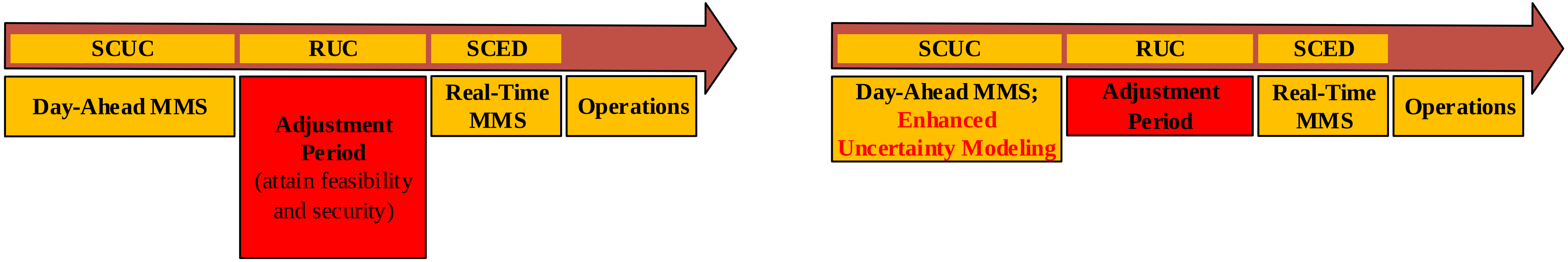
Post-contingency flow on transmission line ℓ **=** Pre-contingency flow on transmission line ℓ **+** **Redistributed flow** from contingency line c to transmission line ℓ via **LODFs**

- Generator post-contingency set point **equals** its pre-contingency set point (**no second-stage recourse decision variables**)
- Pricing implications:
  - **LMP congestion component** is based on pre-contingency congestion and post-transmission contingency congestion
  - Pricing is straightforward: no re-dispatch; transmission not a market participant

Generator Contingency Modeling

- Contemporary market structures:
  - **Myopic reserve policies**: System-wide requirements; procure reserve that may not be deliverable post-contingency
  - **Reserve zones**: Regional requirements; static despite changing system conditions; ignore local congestion within zones
  - **Dynamic zones**: Opposition from stakeholders; affects their profit and bidding strategy (due to zone reconfiguration)
  - **Reserve sharing**: Available transfer capability on interfaces; artificially de-rating; nomograms; unanticipated congestion
- Day-ahead market model is imprecise
- Part of the decision making gets pushed to the adjustment period to attain feasibility and security
  - Operator-initiated discretionary out-of-market corrections (OMCs)
  - **Terms**: exceptional dispatch; out-of-sequence dispatch; reserve disqualification; reserve down-flags; uneconomic adjustment

Generator Contingency Modeling



- **Industry push**: Zonal to nodal *analogous* to energy product
- **Goal**:
  - Procure **deliverable reserve**
  - Account for the **value of reserve** provided by each generator
  - Enable scheduling models to **optimally handle more products** (reserve) instead of relying on manual OMCs
- **Approach**: Explicit representation of generator contingencies
- **Anticipated impacts**: Price signals to better reflect actual operational requirements; quality of service provided by generators

MISO: Zonal Deliverability Constraints

- MISO utilizes post-generator contingency security constraints to determine their zonal reserve requirements [1]

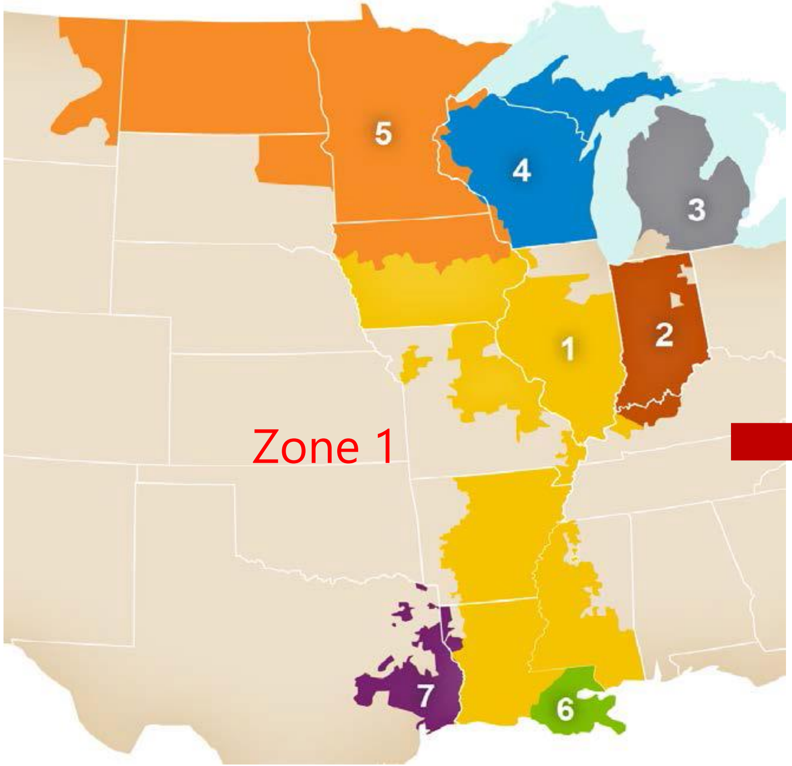
Post-contingency flow **=** Pre-contingency flow **−** Effect of **supply loss** on flow **+** Effect of **zonal reserve deployment** on flow

- Zonal model: Employs **zonal PTDFs**; ignores network within the zone
- Employs a simplistic approach to pre-determine **zonal reserve deployment factors**
- Models **only** largest generator outage per zone
- Examines impacts on **few** critical interfaces; improves transfer of reserve between (and not within) zones

[1] Y. Chen, P. Gribik, and J. Gardner, "Incorporating post zonal reserve deployment transmission constraints into energy and ancillary service co-optimization," *IEEE Trans. Power Syst.*, vol. 29, no. 2, pp. 537-549, Mar. 2014.

MISO: Zonal Deliverability Constraints

- MISO's recent proposal: Split zone 1 between north and south (September, 2017) [2]



[2] MISO Market Subcommittee, "Proposed changes to reserve zone calculations - Responding to 4/1 spin shortage event," Aug. 2017.

CAISO: Generator Contingency and Remedial Action Scheme (RAS) Modeling

- CAISO intends to enhance its market models to include [3]:
  - Generator contingencies and pre-defined RAS explicitly
  - Combined transmission and generator contingencies explicitly

Post-contingency flow = Pre-contingency flow − Effect of **supply loss** on flow + Effect of **reserve response** on flow via GDFs

- Post-contingency security constraints for each modeled generator contingency case [3]
  - Explicit representation of generator contingencies
  - No second-stage recourse decisions (well... sort of)
  - Need: Contribute to the theoretical domain to pave the way for market reform associated to uncertainty modeling and modeling of corrective actions

[3] CAISO, "Draft final proposal: Generator contingency and remedial action scheme modeling," [Online]. Available: https://www.caiso.com/Documents/DraftFinalProposal-GeneratorContingencyandRemedialActionSchemeModeling_updatedjul252017.pdf, July 25, 2017.

Review of the DCOPF Problem

DCOPF Problem

- There are many different ways to formulate the DCOPF problem
- **Focus**: PTDF-based formulation of the DCOPF problem
- **Note**: Economic interpretations of its dual apply to this DCOPF formulation
- If the DCOPF is formulated differently, the dual will not be the same and may result in different interpretations of that different dual, e.g., the $B{-}\theta$ formulation

DCOPF Problem: Primal Problem

- Primal problem:

$$\underset{P_n, D_n}{\text{Minimize:}} \underbrace{\sum_n c_n P_n}_{\text{Generation cost}} \qquad (1)$$

Subject to:

$$-P_n \geq -P_n^{max}, \forall n \in N \qquad (\boldsymbol{\alpha_n}) \qquad (2)$$

$$\sum_n PTDF_{k,n}^R (P_n - D_n) \geq -P_k^{max,a}, \forall k \in K \qquad (\boldsymbol{F_k^-}) \qquad (3)$$

$$-\sum_n PTDF_{k,n}^R (P_n - D_n) \geq -P_k^{max,a}, \forall k \in K \qquad (\boldsymbol{F_k^+}) \qquad (4)$$

$$\sum_n P_n - D_n = 0, \qquad (\boldsymbol{\delta}) \qquad (5)$$

$$D_n = \overline{D_n}, \forall n \in N \qquad (\boldsymbol{\lambda_n}) \qquad (6)$$

$$P_n \geq 0.$$

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DCOPF Problem: Dual Problem Formulation

- **Objective** of the dual problem:

$$\underset{\alpha_n, F_k^-, F_k^+, \delta, \lambda_n}{\text{Maximize}} : -\underbrace{\sum_n P_n^{max} \alpha_n}_{\text{Generation rent}} - \underbrace{\sum_k P_k^{max,a} (F_k^- + F_k^+)}_{\text{Congestion rent}} + \underbrace{\sum_n \overline{D_n} \lambda_n}_{\text{Load payment}} \qquad (7)$$

- **Strong duality** (SD): conveys exchange of money, payments, and expenses resulting from an auction
  - Dual objective is equal to primal objective, at optimality (by SD)
  - Load payment is equal to generation revenue plus congestion rent
- **Dual constraints corresponding to the generator production and the demand variables in primal**

$$-\alpha_n + \sum_k PTDF_{k,n}^R (F_k^- - F_k^+) + \delta \leq c_n, \forall n \in N \qquad (\boldsymbol{P_n}) \qquad (8)$$

$$\sum_k PTDF_{k,n}^R (F_k^+ - F_k^-) - \delta + \lambda_n = 0, \forall n \in N \qquad (\boldsymbol{D_n}) \qquad (9)$$

DCOPF Problem: Dual Problem Formulation

- **Locational marginal price** (LMP):

$$\lambda_n = \underbrace{\delta}_{\text{Marginal energy component}} + \underbrace{\sum_k PTDF^R_{k,n}(F^-_k - F^+_k)}_{\text{Marginal congestion component}}, \forall n \in N \qquad (\boldsymbol{D_n}) \quad (9a)$$

  – Dual variable that signifies the increase (or decrease) to the primal objective if there is slightly more (or less) consumption by the load

  – **No loss component**: DC, lossless model

  – **No post-transmission contingency congestion component**

- **Dual constraint corresponding to generator production reduces to**

$$-\alpha_n + \lambda_n \le c_n, \forall n \in N \qquad (\boldsymbol{P_n}) \quad (8a)$$

  – Dual variable, α, signifies the short-term marginal benefit of increasing a generator's maximum capacity

DCOPF Problem: Dual Problem Formulation

$$-\alpha_n + \lambda_n \leq c_n, \forall n \in N \qquad (\boldsymbol{P_n}) \quad \text{(8a)}$$

- **Complementary slackness** (CS) tells us, at optimality:

$$(-\alpha_n + \lambda_n)P_n = c_n P_n, \forall n \in N$$

$$-P_n \alpha_n = -P_n^{max} \alpha_n, \forall n \in N$$

$$\underbrace{P_n^{max} \alpha_n}_{\text{Generator rent}} = \underbrace{\lambda_n P_n}_{\text{Generator revenue}} - \underbrace{c_n P_n}_{\text{Generator cost}}$$

Complete Dual Formulation

- Dual problem:

$$\underset{\alpha_n, F_k^-, F_k^+, \delta, \lambda_n}{\text{Maximize}} : -\sum_n P_n^{max} \alpha_n - \sum_k P_k^{max,a} (F_k^- + F_k^+) + \sum_n \overline{D_n}\, \lambda_n \qquad (7)$$

Subject to:

$$-\alpha_n + \sum_k PTDF_{k,n}^R (F_k^- - F_k^+) + \delta \le c_n, \forall n \in N \qquad (\boldsymbol{P_n}) \qquad (8)$$

$$\sum_k PTDF_{k,n}^R (F_k^+ - F_k^-) - \delta + \lambda_n = 0, \forall n \in N \qquad (\boldsymbol{D_n}) \qquad (9)$$

$$\alpha_n \ge 0, F_k^- \ge 0, F_k^+ \ge 0, \delta \text{ free}, \lambda_n \text{ free}.$$

Generator Contingency Modeling: Derivation of Prices via Duality Theory

Enhanced DCOPF Problem: Primal Problem

- Primal reformulation [3]: Focuses on key proposed change

$$\underset{P_n, D_n}{\text{Minimize:}} \sum_n c_n P_n \quad (10)$$

Subject to:

$$-P_n \geq -P_n^{max}, \forall n \in N \quad (\boldsymbol{\alpha_n}) \quad (11)$$

$$\sum_n PTDF_{k,n}^R (P_n - D_n) \geq -P_k^{max,a}, \forall k \in K \quad (\boldsymbol{F_k^-}) \quad (12)$$

$$-\sum_n PTDF_{k,n}^R (P_n - D_n) \geq -P_k^{max,a}, \forall k \in K \quad (\boldsymbol{F_k^+}) \quad (13)$$

$$\sum_n PTDF_{k,n}^R (P_n + GDF_{n'(c),n} P_{n'(c)} - D_n) \geq -P_k^{max,c}, \forall k \in K^{crt}, c \in C^{g^{crt}} \quad (\boldsymbol{F_k^{c-}}) \quad (14)$$

$$-\sum_n PTDF_{k,n}^R \left(P_n + GDF_{n'(c),n} P_{n'(c)} - D_n\right) \geq -P_k^{max,c}, \forall k \in K^{crt}, c \in C^{g^{crt}} \quad (\boldsymbol{F_k^{c+}}) \quad (15)$$

$$\sum_n P_n - D_n = 0, \quad (\boldsymbol{\delta}) \quad (16)$$

$$D_n = \overline{D_n}, \forall n \in N \quad (\boldsymbol{\lambda_n}) \quad (17)$$

$$P_n \geq 0.$$

- The enhanced DCOPF problem **does not** include: Transmission contingency modeling, reserve requirements, inter-temporal restrictions, ramping restrictions...

[3] CAISO, “Draft final proposal: Generator contingency and remedial action scheme modeling,” [Online]. Available: https://www.caiso.com/Documents/DraftFinalProposal-GeneratorContingencyandRemedialActionSchemeModeling_updatedjul252017.pdf, July 25, 2017.

Generation Loss Distribution Factors (GDFs)

- **Generator loss**: Distributed across the system via **GDFs** [3]

$$GDF_{n'(c),n} = \begin{cases} -1, n = n'(c) \\ 0, n \neq n'(c) \wedge n \notin S^{FR} \\ \dfrac{u_n P_n^{max}}{\sum_{\substack{n \in S^{FR} \\ n \neq n'(c)}} u_n P_n^{max}}, n \neq n'(c) \wedge n \in S^{FR} \end{cases}, \forall n \in N, c \in C^{g^{crt}}.$$

  – **Prorated** based on maximum online (*frequency responsive*) capacity

  – **Aim**: Estimate the effect of generator loss and system response

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Generation Loss Distribution Factors (GDFs)

- Ignores: Dispatch set point; capacity, reserve, and ramp restrictions; multiple units at a node

$$\sum_n \boldsymbol{PTDF}^{R}_{k,n}(\boldsymbol{P}_n + \boldsymbol{GDF}_{n'(c),n}\boldsymbol{P}_{n'(c)} - \boldsymbol{D}_n) \geq -\boldsymbol{P}^{max,c}_{k}, \forall \boldsymbol{k} \in \boldsymbol{K}^{crt}, \boldsymbol{c} \in \boldsymbol{C}^{g^{crt}}$$

- Note: GDF shows up only in security constraints and is multiplied by the MW dispatch variable for the simulated contingency generator
  - This variable (and the GDF, fixed input) drives the only functional relationship between the change in a line's flow between the pre- and post-contingency states
  - GDFs mask the response provided by frequency responsive units to a drop in supply; has implications on generator rent

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Enhanced Primal: Dual Formulation

- Dual problem:

$$\underset{\alpha_n, F_k^-, F_k^+, F_k^{c-}, F_k^{c+}, \delta, \lambda_n}{\text{Maximize}} : -\sum_n (P_n^{max} \alpha_n) - \sum_k \left(P_k^{max,a} (F_k^- + F_k^+) \right) - \sum_{\substack{k \in K^{crt}, \\ c \in C^{g^{crt}}}} \left(P_k^{max,c} (F_k^{c-} + F_k^{c+}) \right) + \sum_n (\overline{D_n} \lambda_n) \quad (18)$$

Subject to:

$$-\alpha_n + \sum_k PTDF_{k,n}^R (F_k^- - F_k^+) + \left(\sum_{\substack{k \in K^{crt}, \\ c \in C^{g^{crt}}}} (F_k^{c-} - F_k^{c+}) \left(PTDF_{k,n}^R + \bar{\gamma}_{n'(c),n} \sum_{s \in N} PTDF_{k,s}^R GDF_{n'(c),s} \right) \right) + \delta \leq c_n, \forall n \in N \quad (\boldsymbol{P_n}) \quad (19)$$

$$\sum_k PTDF_{k,n}^R (F_K^+ - F_k^-) + \sum_{\substack{k \in K^{crt}, \\ c \in C^{g^{crt}}}} PTDF_{k,n}^R (F_K^{c+} - F_k^{c-}) - \delta + \lambda_n = 0, \forall n \in N \quad (\boldsymbol{D_n}) \quad (20)$$

$$\alpha_n \geq 0, F_k^- \geq 0, F_k^+ \geq 0, F_k^{c-} \geq 0, F_k^{c+} \geq 0, \delta \text{ free}, \lambda_n \text{ free}.$$

$$\text{where, } \bar{\gamma}_{n'(c),n} = \begin{cases} 0, & n \neq n'(c) \\ 1, & n = n'(c) \end{cases}, \forall n \in N, c \in C^{g^{crt}}.$$

Objective of the Dual Problem

- **Objective** of the dual problem:

$$\underset{\alpha_n, F_k^-, F_k^+, F_k^{c-}, F_k^{c+}, \delta, \lambda_n}{\text{Maximize}} : -\underbrace{\textstyle\sum_n (P_n^{max} \alpha_n)}_{\text{Generation rent}} + \underbrace{\textstyle\sum_n (\overline{D_n} \lambda_n)}_{\text{Load payment}}$$

$$\underbrace{-\textstyle\sum_k \left(P_k^{max,a}(F_k^- + F_k^+)\right) - \sum_{\substack{k \in K^{crt}, \\ c \in C^{g^{crt}}}} \left(P_k^{max,c}(F_k^{c-} + F_k^{c+})\right)}_{\text{Congestion rent}} \qquad (18)$$

- The dual objective must equal the primal objective at optimality (by SD)
  - Load payment is equal to generation revenue plus congestion rent
  - **Strong duality communicates the exchange of money, payments and expenses resulting from the auction**

Enhanced DCOPF: New LMP Definition

- **Dual constraint corresponding to the demand variable in the primal reformulation**

$$\sum_k PTDF^R_{k,n}(F_k^+ - F_k^-) + \sum_{\substack{k\in K^{crt},\\ c\in C g^{crt}}} PTDF^R_{k,n}(F_K^{c+} - F_k^{c-})$$

$$-\delta + \lambda_n = 0, \forall n \in N \qquad (\boldsymbol{D_n}) \quad (20)$$

- **Primary impact on pricing: Affects the LMP**

$$\lambda_n = \underbrace{\delta}_{\text{Marginal energy component}} + \underbrace{\sum_k PTDF^R_{k,n}(F_k^- - F_k^+)}_{\text{Marginal pre-contingency congestion component}} + \underbrace{\sum_{\substack{k\in K^{crt},\\ c\in C g^{crt}}} PTDF^R_{k,n}(F_k^{c-} - F_k^{c+})}_{\text{Marginal post-contingency congestion component}},$$

$$\forall n \in N \qquad (\boldsymbol{D_n}) \quad (20a)$$

  - Additional congestion component comes from the modeling of critical generator contingencies
  - Transmission contingencies? Losses?

CAISO's Proposed LMP Definition

- **CAISO's proposed LMP definition** [3]

$$\lambda_n = \delta + \sum_k PTDF^R_{k,n}(F^-_k - F^+_k) + \sum_{\substack{k\in K^{crt},\\ c\in C^{g^{crt}}}} \left[(F^{c-}_k - F^{c+}_k)\left(PTDF^R_{k,n} + \overline{\gamma}_{n'(c),n} \sum_{s\in N} PTDF^R_{k,s} GDF_{n'(c),s} \right) \right],$$

$\forall n \in N$ $\qquad (\boldsymbol{D_n}) \quad$ (20b)

- **Compared to**

$$\lambda_n = \underbrace{\delta}_{\text{Marginal energy component}} + \underbrace{\sum_k PTDF^R_{k,n}(F^-_k - F^+_k)}_{\text{Marginal pre-contingency congestion component}} + \underbrace{\sum_{\substack{k\in K^{crt},\\ c\in C^{g^{crt}}}} PTDF^R_{k,n}(F^{c-}_k - F^{c+}_k)}_{\text{Marginal post-contingency congestion component}},$$

$\forall n \in N$ $\qquad (\boldsymbol{D_n}) \quad$ (20a)

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Short-Term Generator Profit (Rent)

- **System-wide generation rent**:
  - Broken down for generators that are (*and are not*) contained in the critical generator contingency list
- **Aim**: To analyze impact of the proposed changes on prices and revenues for generators that are (and are not) contained in the critical generator contingency list

Short-Term Generator Profit (Rent)

$$\sum_n PTDF^R_{k,n}(P_n + GDF_{n'(c),n}P_{n'(c)} - D_n) \geq -P^{max,c}_k, \forall k \in K^{crt}, c \in C^{g^{crt}}$$

- Note: GDF shows up only in security constraints and is multiplied by the MW dispatch variable for the simulated contingency generator
  - Post-contingency congestion (and the new LMP component): *driven by cost of the contingency generator* and not the cost associated to responding units
  - Power systems outlook: What is critical to ensure security? Model the change in injection at the nodes of responding units? Or their cost?
  - Economic outlook:
    - Cost **not** related to units that respond (e.g., fast-starts)
    - Result: Pricing that pairs with ***incorrect economic incentives***
  - Model does not acknowledge any costs due to re-dispatch of units post-contingency (or costs due to reserve activation)
  - Cost changes *only* by forcing a different pre-contingency dispatch set point that is secure

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Generator Rent: Non-Critical Generators

- Generator rent earned by **non-critical** generators: Generator revenue less generator cost

$$\underbrace{P_n^{max}\alpha_n}_{\text{Generator rent}} = \underbrace{\lambda_n P_n}_{\text{Generator revenue}} - \underbrace{c_n P_n}_{\text{Generator cost}} \tag{21}$$

- Identical to standard DCOPF problem (but LMP has an added term)

Generator Rent: Critical Generators

- Generator rent earned by **critical** generators:

$$\underbrace{P_n^{max}\alpha_n}_{\text{Generator rent}} = \lambda_n P_n + \underbrace{\sum_{\substack{k\in K^{crt},\\ c\in C^{g^{crt}}}} \left[(F_k^{c-} - F_k^{c+})\left(\sum_{s\in N} PTDF_{k,s}^{R} GDF_{n'(c),s} P_s\right)\right]}_{\text{Generator revenue}}$$

$$\underbrace{-c_n P_n}_{\text{Generator cost}} \qquad (22)$$

- **CAISO's proposed LMP definition** [3]

$$\lambda_n = \delta + \sum_k PTDF_{k,n}^{R}(F_k^{-} - F_k^{+}) + \sum_{\substack{k\in K^{crt},\\ c\in C^{g^{crt}}}} PTDF_{k,n}^{R}(F_k^{c-} - F_k^{c+})$$

$$+ \sum_{\substack{k\in K^{crt},\\ c\in C^{g^{crt}}}} \left[(F_k^{c-} - F_k^{c+})\left(\sum_{s\in N} \boldsymbol{PTDF_{k,s}^{R} GDF_{n'(c),s}}\right)\right],$$

$$\forall n \in N \qquad (\boldsymbol{D_n}) \quad (20b)$$

Generator Rent: Critical Generators

- Generator profit **not** as defined:
  - ISO will have revenue shortfall overall or surplus: Not **revenue neutral**
- Confirms the payment for generators in the critical list
- Interpretation:
  - Combination of the extra term and the post-contingency congestion component of the LMP: Congestion transfer cost
  - Critical generator pays a congestion charge for the difference between injecting at its location and instead injecting at the locations identified by the GDFs
  - Model still acknowledges that the generator is producing; it is just producing now *magically* at different locations
  - Right way: Critical generator should buy from the locations identified by the GDF or have some sort of a side contract with the generators at those locations

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Conclusions and Future Research Topics

Conclusions: GDF Pricing Impacts

- **Industry push**: Explicit inclusion of generator contingencies
  - Improves representation of resources; enhances uncertainty modeling
- **This research:** Demonstrated the importance of performing a rigorous evaluation via duality theory
  - Provided insightful guidance in understanding market implications
  - Provided recommendations on necessary changes to ensure a fair and transparent market structure
  - Pave way for *different reformulations* to introduce corrective actions
- **Enabled a theoretical analysis of the anticipated changes**
  - Effect on market prices, settlements, and revenues
- **Primary impact of impending changes**
  - New congestion component within the traditional LMP; reflects impact of congestion in the post-generator contingency states

Future Research and Next Steps

- Evaluate the **impact of market reformulations on FTR markets**
  - Implications of corrective actions on **revenue adequacy** of FTR auctions
  - Investigate associated modifications to the **simultaneous feasibility test (SFT)** for FTR auctions
- **Relation to stochastic programs** and **market clearing in a stochastic environment**
- Investigate **more systematic and suitable ways** to determine **generator participation factors**
  - Based on inertia, synchronizing power coefficients, electrical distance (proximity) to the source of uncertainty
  - Advanced stochastic look-ahead scheduling models

Questions and Comments?

Together…Shaping the Future of Electricity