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**:

\[
\begin{align*}
\text{Post-contingency flow on} & \quad = \quad \text{Pre-contingency flow on} & \quad \text{Redistributed flow} \\
\text{transmission line } \ell & \quad \text{transmission line } \ell & \quad \text{from contingency line } c \\
\text{Pre-contingency flow on} & \quad \text{to transmission line } \ell & \quad \text{via LODFs}
\end{align*}
\]

- **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 downflags; 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]

- 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

MISO: Zonal Deliverability Constraints

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

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 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

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:

Minimize: $\sum_n c_n P_n$ \hspace{1cm} (1)

Subject to: Generation cost

$-P_n \geq -P_n^{\text{max}}, \forall n \in N$ \hspace{1cm} (2)

$\sum_n P T D F_{k,n}^R (P_n - D_n) \geq -P_k^{\text{max},a}, \forall k \in K$ \hspace{1cm} (3)

$-\sum_n P T D F_{k,n}^R (P_n - D_n) \geq -P_k^{\text{max},a}, \forall k \in K$ \hspace{1cm} (4)

$\sum_n P_n - D_n = 0,$ \hspace{1cm} (5)

$D_n = \overline{D}_n, \forall n \in N$ \hspace{1cm} (6)

$P_n \geq 0.$
DCOPF Problem: Dual Problem Formulation

- **Objective** of the dual problem:

\[
\text{Maximize } - \sum_n p_n^{\text{max}} \alpha_n - \sum_k f_k^{\text{max},a} (F_k^- + F_k^+) + \sum_n D^-_n \lambda_n
\]

\[
\text{Generation rent} \quad \text{Congestion rent} \quad \text{Load payment}
\]

- **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**

\[
-\alpha_n + \sum_k \text{PTDF}^R_{k,n}(F_k^- - F_k^+) + \delta \leq c_n, \forall n \in N \quad (P_n)
\]

\[
\sum_k \text{PTDF}^R_{k,n}(F_k^+ - F_k^-) - \delta + \lambda_n = 0, \forall n \in N \quad (D_n)
\]
DCOPF Problem: Dual Problem Formulation

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

  \[ \lambda_n = \delta + \sum_k PTDF_{k,n}^R (F_k^- - F_k^+) \], \forall n \in N \quad (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**

  \[ -\alpha_n + \lambda_n \leq c_n, \forall n \in N \quad (P_n) \quad (8a) \]

  - Dual variable, \( \alpha \), signifies the short-term marginal benefit of increasing a generator’s maximum capacity
DCOPF Problem: Dual Problem Formulation

\[-\alpha_n + \lambda_n \leq c_n, \forall n \in N\]  \hspace{1cm} (P_n) \hspace{1cm} (8a)

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

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

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

\[P_n^{max} \alpha_n = \lambda_n P_n - c_n P_n\]
Complete Dual Formulation

- Dual problem:

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

Subject to:

$-\alpha_n + \sum_k \text{PTDF}_{k,n} (F_k^- - F_k^+) + \delta \leq c_n, \forall n \in N \quad (P_n) \quad (8)$

$\sum_k \text{PTDF}_{k,n} (F_k^+ - F_k^-) - \delta + \lambda_n = 0, \forall n \in N \quad (D_n) \quad (9)$

$\alpha_n \geq 0, F_k^- \geq 0, F_k^+ \geq 0, \delta \text{ free}, \lambda_n \text{ free}.$
Generator Contingency Modeling: Derivation of Prices via Duality Theory
Enhanced DCOPF Problem: Primal Problem

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

\[
\begin{align*}
\text{Minimize: } & \sum_n c_n P_n \\
\text{Subject to: } & -P_n \geq -P_{n \text{max}}, \forall n \in N \\
& \sum_n P T D F_{k,n}^R (P_n - D_n) \geq -P_{k \text{max},a}, \forall k \in K \\
& - \sum_n P T D F_{k,n}^R (P_n - D_n) \geq -P_{k \text{max},a}, \forall k \in K \\
& \sum_n P T D F_{k,n}^R (P_n + GDF_{n'(c),n} P_{n'(c)} - D_n) \geq -P_{k \text{max},c}, \forall k \in K^{crt}, c \in C^{g^{crt}} \\
& - \sum_n P T D F_{k,n}^R (P_n + GDF_{n'(c),n} P_{n'(c)} - D_n) \geq -P_{k \text{max},c}, \forall k \in K^{crt}, c \in C^{g^{crt}} \\
& \sum_n P_n - D_n = 0, \\
& D_n = D_{n'}, \forall n \in N \\
& P_n \geq 0.
\end{align*}
\]  

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

Generation Loss Distribution Factors (GDFs)

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

\[
GDF_{n}(c), n = \begin{cases} 
-1, & n = n'(c) \\
0, & n \neq n'(c) \land n \notin S^{FR} \\
\frac{u_n p_{n}^{\text{max}}}{\sum_{n \in S^{FR} \land n \neq n'(c)} u_n p_{n}^{\text{max}}}, & n \neq n'(c) \land n \in S^{FR}, \forall n \in N, c \in C^{g_{\text{crit}}}.
\end{cases}
\]

- **Prorated** based on maximum online (*frequency responsive*) capacity
- **Aim**: Estimate the effect of generator loss and system response

Generation Loss Distribution Factors (GDFs)

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

\[ \Sigma P_{\text{TD}DF}^R_{k,n}(P_n + GDF_{n',c,n}P_{n',c} - D_n) \geq -P_{k,\max,c}, \forall k \in K^{\text{cr}t}, c \in C^{g^{\text{cr}t}} \]

- **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

Enhanced Primal: Dual Formulation

- Dual problem:

\[
\begin{align*}
\text{Maximize} & \quad \alpha_n, F^+_k, F^-_k, F^c_+, F^c-, \delta, \lambda_n \\
& \quad : -\sum_n (P_n^{\text{max}} \alpha_n) - \sum_k \left( p^{\text{max},a} (F^-_k + F^+_k) \right) - \sum_{k \in K^{\text{cert}}} \left( p^{\text{max},c} (F_c^- + F_c^+) \right) + \sum_n (D_n \lambda_n) \\
\text{Subject to:} & \quad -\alpha_n + \sum_k \text{PTDF}_{k,n} (F^-_k - F^+_k) + \left( \sum_{k \in K^{\text{cert}}} (F_c^- - F_c^+) \left( \text{PTDF}_{k,n} + \bar{\gamma}_{n'(c),n} \sum_{n \in N} \text{PTDF}_{k,s} \text{GDF}_{n'(c),s} \right) \right) + \delta \leq c_n, \forall n \in N \\
& \quad \sum_k \text{PTDF}_{k,n} (F^+_k - F^-_k) + \sum_{k \in K^{\text{cert}}} \text{PTDF}_{k,n} (F_c^+ - F_c^-) - \delta + \lambda_n = 0, \forall n \in N \\
& \quad \alpha_n \geq 0, F^-_k \geq 0, F^+_k \geq 0, F_c^- \geq 0, F_c^+ \geq 0, \delta \text{ free}, \lambda_n \text{ free.}
\end{align*}
\]

where, \( \bar{\gamma}_{n'(c),n} = \begin{cases} 
0, & n \neq n'(c) \\
1, & n = n'(c)
\end{cases}, \forall n \in N, c \in C^{g^{\text{cert}}}. \)
Objective of the Dual Problem

### Objective of the dual problem:

$$\text{Maximize } \alpha_n, F_k^-, F_k^+, F_k^c-, F_k^c+, \delta, \lambda_n : - \sum_n (P_n^{max} \alpha_n) + \sum_n (D_n \lambda_n)$$

- **Generation rent**
- **Load payment**

$$- \sum_k \left( P_k^{max,a} (F_k^- + F_k^+) \right) - \sum_{k \in K^{crt}} \left( P_k^{max,c} (F_k^c^- + F_k^c+) \right)$$

*Congestion rent*

### 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

\[
\sum_k PTDF_k,n (F_k^+ - F_k^-) + \sum_{k \in K_{crt}} PTDF_k,n (F_k^{c+} - F_k^{c-})
\]

\[-\delta + \lambda_n = 0, \forall n \in N \quad (D_n) \quad (20)\]

- Primary impact on pricing: Affects the LMP

\[
\lambda_n = \delta + \sum_k PTDF_k,n (F_k^- - F_k^+) + \sum_{k \in K_{crt}} PTDF_k,n (F_k^{c-} - F_k^{c+})
\]

\[\forall n \in N \quad (D_n) \quad (20a)\]

- 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]

\[ \lambda_n = \delta + \sum_k PTD F_{k,n}^R (F_k^- - F_k^+) \]
\[ + \sum_{k \in K_{crt}} \left[ (F_k^{c-} - F_k^{c+}) (PTDF_{k,n}^R + \mathcal{V}_{n' (c), n} \sum_{s \in N} PTD F_{k,s}^R GDF_{n' (c), s}) \right], \]
\[ \forall n \in N \]

Compared to

\[ \lambda_n = \delta + \sum_k PTD F_{k,n}^R (F_k^- - F_k^+) \]
\[ + \sum_{k \in K_{crt}} PTD F_{k,n}^R (F_k^{c-} - F_k^{c+}), \]
\[ \forall n \in N \]

Marginal pre-contingency congestion component
Marginal energy component
Marginal post-contingency congestion component

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
Generator Rent: Non-Critical Generators

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

\[ P_n^{\text{max}} \alpha_n = \lambda_n P_n - c_n P_n \]  

(21)

- Identical to standard DCOPF problem (but LMP has an added term)
Generator Rent: Critical Generators

- Generator rent earned by critical generators:

\[
P_{n}^{\text{max}} \alpha_n = \lambda_n P_n + \sum_{k \in K^{\text{crt}}} \left[ (F_{k}^{C^{-}} - F_{k}^{C^{+}}) \left( \sum_{s \in \mathcal{N}} \text{PTDF}_{k,s}^{R} GDF_{n'}(c,s) P_s \right) \right]
\]

- CAISO’s proposed LMP definition [3]

\[
\lambda_n = \delta + \sum_{k} \text{PTDF}_{k,n}^{R} (F_{k}^{-} - F_{k}^{+}) + \sum_{k \in K^{\text{crt}}} \text{PTDF}_{k,n}^{R} (F_{k}^{C^{-}} - F_{k}^{C^{+}}) + \sum_{k \in K^{\text{crt}}} \left[ (F_{k}^{C^{-}} - F_{k}^{C^{+}}) \left( \sum_{s \in \mathcal{N}} \text{PTDF}_{k,s}^{R} GDF_{n'}(c,s) \right) \right],
\]

\[
\forall n \in \mathcal{N} \quad (D_n) \quad (20b)
\]
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

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