N-1-1 Contingency-Constrained Grid Operations

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Increasing Real-Time and Day-Ahead Market Efficiency through Improved Software

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Reliability of Power Systems

- In recent years, the number of large blackouts have been on the rise. For examples:
  - June 2012 India (over 620 million people affected)
  - Sept. 2011 Southwest, USA (initiating event by loss of a 500kV line)
- Growing complexity of power systems: distributed generations and significant generation uncertainty
- Systems operating closer to feasibility limits are more vulnerable to failures, due to natural causes and/or intelligent adversaries.
- Survivability: system's ability to survive imminent disturbances (contingencies) without interruption of customer service

NERC Standard

North American Electric Reliability Corporation (NERC):

- develop and enforce standards to ensure the reliability of the power systems in North America

Transmission planners and planning coordinators:

- prepare necessary performance assessments for their portion of the system under different contingency conditions
- ensure that system complies with approved NERC TPL standards

NERC Standard

Transmission Planning Standard (TPL-001-1): system performance requirements under both normal and various contingency conditions

- No contingencies (Category A)
- Events resulting in the loss of a single system element (Category B)
- Event(s) resulting in the loss of two or more elements (Category C)
- Extreme event resulting in two or more elements removed or cascading out of service (Category D)

NERC Standard

TPL-001-1 standards

Category	System Stable	Loss of Demand	Cascading Outages
N-0	Yes	No	No
N-1	Yes	No	No
N-k	Yes	Planned/Controlled	No
N-1-1	Yes	Planned/Controlled	No

- Category B events: loss of a single system component
  - N-1 contingency
- Category C events: loss of two or more components
  - (near-)simultaneous losses: N-k ($k \geq 2$) contingency
  - Consecutive losses: N-1-1 contingency

Contingency Analysis

- Contingency analysis: a key function in the Energy Management System
- N-1 contingency analysis:
  - system to operate under normal conditions (per TPL-001-1)
  - not sufficient to model/evaluate vulnerabilities of power grids
  - N-1 reliability analysis: UC with transmission switching (Hedman et al. 2010)

Contingency Analysis

- Contingency analysis: a key function in the Energy Management System
- *N*-*k* contingency analysis:
  - a substantial computational burden for analysis, $\sum_{i=1}^{k} \binom{N}{i}$
  - vulnerability analysis (Pinar et al. 2010, Bienstock et al. 2010)
  - power flow (Salmeron et al. 2004, Arroya 2010, Fan et al. 2010)
  - survivable power system design (Chen et al. 2012)
  - contingency-constrained unit commitment (Chen et al. 2013)
  - robust unit commitment (Street et al. 2011, Wang et al. 2012)

Contingency Analysis

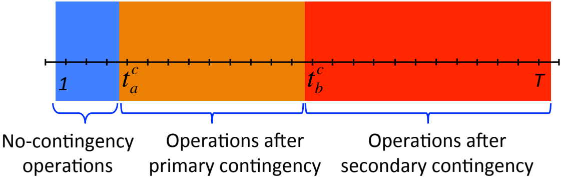
- Contingency analysis: a key function in the Energy Management System
- N-1-1 contingency analysis:
  - a category B event followed by a category C event per TPL-001-1
  - simulation analysis: PowerWorld, Mathwork, Siemens Energy (2011), Chatterjee et al. (2010) for midwest ISO
  - optimal power flow (Fan et al. 2012)

N-1-1 Contingency-Constrained Unit Commitment

- Baseline UC: find least cost on/off schedule of generating units and economic dispatch (DCOPF) to meet electrical loads
- N-1-1 CCUC: find expected, least-cost on/off schedule of generating units, economic dispatch (DCOPF) such that a feasible recourse DC PF exist for any N-1-1 contingency state
- Modeled as a three-stage stochastic mixed-integer program (SMIP)

Time periods

- given a N-1-1 contingency state c
- planning horizon T
- t_a^c, t_b^c, times of the primary and secondary contingencies, respectively



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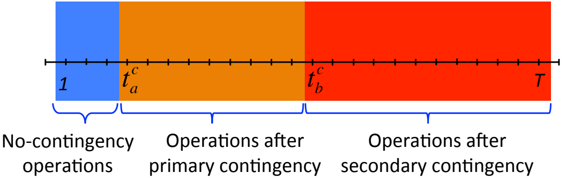

- non-anticipativity during no-contingency operations

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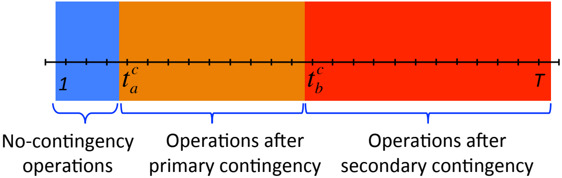
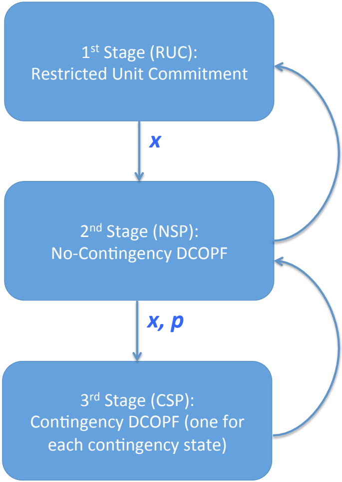


- non-anticipativity during no-contingency operations
- line overload and loss-of-load permitted during secondary contingency state

Three-Stage *N*-1-1 UC Model

Three-stage model/Nested Benders decomposition



Adjust Unit Commitment:

- Optimality cut (o-cut)
- Feasibility cut (f-cut1)

Adjust No-Contingency DCOPF:

- Feasibility cut (f-cut2)

Nomenclatures

Indices and parameters:

- Planning horizon, $\mathcal{T} = \{1, \cdots, T\}$
- Power system $(i \in N, g \in G, e \in E)$:
  - T_g^{u0}, T_g^{d0}, initial online and offline
  - T_g^{u}, T_g^{d}, minimum online and offline

Decision variables:

- $x_g^t \in \{0, 1\}$, generator on/off

Three-Stage Formulation: 1^{st} stage (RUC)

- objective: minimize startup, shutdown costs, and no-contingency state generation cost
- constraints:
  - minimum online/offline requirements (initial periods)
  - minimum online/offline requirements
  - startup/shutdown costs
- variables: $x_g^t \in \{0,1\} \quad \forall, g \in G, t \in \mathcal{T}$
- UC formulation based on Carrion and Arroyo (2006) and Wu and Shahidehpour (2010)

Nomenclatures

Indices and parameters:

- Power system ($i \in N, g \in G, e \in E$):
  - i_e, j_e, tail and head bus of line e
  - D_i^t, demand
  - $\underline{P}_g$, $\overline{P}_g$, generation bounds
  - R_g^u, R_g^d, $\bar{R}_g^u, \bar{R}_g^d$, ramp rates
  - B_e, F_e, susceptance and capacity

Decision variables:

- p_g^t, f_e^t, θ_i^t, no-contingency state generation level, flow, and voltage phase angle

Three-Stage Formulation: 2^{nd} stage (NSP)

$$\min \sum_{t\in\mathcal{T}}\sum_{g\in G} C^p_g(p^t_g)$$

- minimize generation cost

$$\text{s.t.} \sum_{g\in G_i} p^t_g + \sum_{e\in E_{.i}} f^t_e - \sum_{e\in E_{i.}} f^t_e = D^t_i,\ \forall i,t$$

- power balance at each bus

$$B_e(\theta^t_{i_e} - \theta^t_{j_e}) - f^t_e = 0,\ \forall e,t$$

- power flow w.r.t. phase angles

$$-F_e \le f^t_e \le F_e,\ \forall e,t$$

- line capacity bounds

$$\underline{P}_g \tilde{x}^t_g \le p^t_g \le \overline{P}_g \tilde{x}^t_g,\ \forall g,t$$

- generation capacity bounds

$$p^t_g - p^{s,t-1}_g \le R^u_g \tilde{x}^{t-1}_g + \bar{R}^u_g(\tilde{x}^t_g - \tilde{x}^{t-1}_g) + \overline{P}_g(1-\tilde{x}^t_g),\ \forall g,t$$

- generation ramp-up

$$p^{s,t-1}_g - p^t_g \le R^d_g \tilde{x}^t_g + \bar{R}^d_g(\tilde{x}^{t-1}_g - \tilde{x}^t_g) + \overline{P}_g(1-\tilde{x}^{t-1}_g),\ \forall g,t$$

- generation ramp-down

Nomenclatures

Indices and parameters:

- Power system ($i \in N, g \in G, e \in E$):
  - $\mathcal{C}$, set of all N-1-1 contingencies (indexed by c)
  - $\tilde{d}_e^{ct}, \tilde{d}_g^{ct}$, contingency element indicators
  - t_a^c, t_b^c, times of the primary and secondary contingency for c, respectively
  - $\tilde{v}_2^{ct}$, in secondary contingency indicator, $\tilde{v}_2^{ct}$ equal 1 for all $t > t_b$ and 0 otherwise
  - o_e, allowable line overload factor during secondary contingency state

Decision variables:

- $p_g^{ct}, f_e^{ct}, \theta_i^{ct}, q_i^{ct}$, contingency state c generation level, flow, voltage phase angle, loss-of-load

N-1-1 contingency set ($\mathcal{C}$)

- refers to the loss of a system element followed by a loss of another system element in a subsequent time period
- in a given time period at most one element in $G \cup E$ can fail
- there are $\binom{T}{2} = \frac{T(T-1)}{2}$ possible pairs of periods for primary and secondary losses
- $|G| + |E|$ possible losses for primary contingency
- $|G| + |E| - 1$ possible losses for secondary contingency
- $|\mathcal{C}| = \frac{T(T-1)}{2}(|G| + |E|)(|G| + |E| - 1)$
- number of N-2 contingencies $= \frac{(|G|+|E|)(|G|+|E|-1)}{2}$

Three-Stage Formulation: 3^{rd} stage (CSP)

Recourse operations in contingency state c, for all $c \in \mathcal{C}$ and $t = t_a^c, \cdots, T$,

$$\sum_{g \in G_i} p_g^{ct} + \sum_{e \in E_{.i}} f_e^{ct} - \sum_{e \in E_{i.}} f_e^{ct} + q_i^{ct} = D_i^t, \ \forall i, t$$

- power balance at each bus

$$B_e(\theta_{i_e}^{ct} - \theta_{j_e}^{ct})(1 - \sum_{t'=t_a^c}^{t} \tilde{d}_e^{ct'}) - f_e^{ct} = 0, \ \forall e, t$$

- power flow w.r.t. phase angles

$$-f_e^{ct} \leq F_e(1 - \sum_{t'=t_a^c}^{t} \tilde{d}_e^{ct'})(1 + o_e \tilde{v}_2^{ct}), \ \forall e, t$$

$$f_e^{ct} \leq F_e(1 - \sum_{t'=t_a^c}^{t} \tilde{d}_e^{ct'})(1 + o_e \tilde{v}_2^{ct}), \ \forall e, t$$

- line capacity bounds

$$-p_g^{ct} \leq \underline{P}_g \tilde{x}_g^t (1 - \sum_{t'=t_a^c}^{t} \tilde{d}_g^{ct'}), \ \forall g, t$$

$$p_g^{ct} \leq \overline{P}_g \tilde{x}_g^t (1 - \sum_{t'=t_a^c}^{t} \tilde{d}_g^{ct'}), \ \forall g, t$$

- generation capacity bounds

Three-Stage Formulation: 3^{rd} stage (CSP)

$$p_g^{ct} - p_g^{c,t-1} \leq R_g^u \tilde{x}_g^{t-1} + \bar{R}_g^u(\tilde{x}_g^t - \tilde{x}_g^{t-1}) + \overline{P}_g(1 - \tilde{x}_g^t), \ \forall g, t$$

- generation ramp-up

$$p_g^{c,t-1}(1 - \textstyle\sum_{t'=t_a^c}^{t} \tilde{d}_g^{ct'}) - p_g^{ct} \leq R_g^d \tilde{x}_g^t + \bar{R}_g^d(\tilde{x}_g^{t-1} - \tilde{x}_g^t) + \overline{P}_g(1 - \tilde{x}_g^{t-1}), \ \forall g, t$$

- generation ramp-down

$$0 \leq q_i^{ct} \leq D_i^t, \ \forall i, t$$
$$\textstyle\sum_{i \in V} q_i^{ct} \leq (\varepsilon \sum_{i \in V} D_i^t)\tilde{v}_2^{ct}, \ \forall i, t$$

- load shedding threshold

$$p_g^{c,t_a^c-1} = \tilde{p}_g^{t_a^c-1}, \ \forall g \in G | \tilde{d}_g^{t_a^c} = 0$$

- non-anticipativity

Dualize constraints above to form a maximization problem. If infeasible the dual is unbounded.

Optimality and Feasibility Cuts

If NSP($\tilde{x}$) is feasible, an optimality cut can be generated.

$$[\text{o-cut}] : \boldsymbol{\delta}^T x + \gamma_1 \leq Q$$

If NSP($\tilde{x}$) is infeasible, the dual problem is unbounded and a feasibility cut can be generated.

$$[\text{f-cut1}] : \boldsymbol{\delta}^T x + \gamma_1 \leq 0$$

If CSP($\tilde{x}, \tilde{p}, c$) is infeasible, the dual problem is unbounded and a feasibility cut can be generated.

$$[\text{f-cut2}] : \boldsymbol{\alpha}^T p + \gamma_2 \leq 0$$

Power System Inhibition Problem - PSIP($\tilde{x}, \tilde{p}, t_a, t_b$)

For $t = t_a, \cdots, T$,

$$\max_{d^{t_a}, d^{t_b}} \min_{f,p,q,r,s,\theta} \sum_t \sum_g r_g^t + \sum_t s^t$$

- minimize load and generation shedding above allowable threshold

$$\text{s.t. } \sum_e d_e^{t_a} + \sum_g d_g^{t_a} = 1$$
$$\sum_e d_e^{t_b} + \sum_g d_g^{t_b} = 1$$
$$\sum_t d_e^t = 1, \ \forall e$$
$$\sum_t d_g^t = 1, \ \forall g$$

- contingency constraints

$$\sum_{g \in G_i} (p_g^t - r_g^t) + \sum_{e \in E_{\cdot i}} f_e^t - \sum_{e \in E_{i \cdot}} f_e^t + q_i^t = D_i^t, \ \forall i, t$$

- power balance at each bus

$$B_e(\theta_{i_e}^t - \theta_{j_e}^t)(1 - \sum_{t'=t_a}^{t} d_e^{t'}) - f_e^t = 0, \ \forall e, t$$

- power flow w.r.t. phase angles

$$-f_e^t \le F_e(1 - \sum_{t'=t_a}^{t} d_e^{t'})(1 + o_e \tilde{v}_2^t), \ \forall e, t$$
$$f_e^t \le F_e(1 - \sum_{t'=t_a}^{t} d_e^{t'})(1 + o_e \tilde{v}_2^t), \ \forall e, t$$

- line capacity bounds

Power System Inhibition Problem (PSIP)

$$-p_g^t \leq \underline{P}_g \tilde{x}_g^t (1 - \textstyle\sum_{t'=t_a}^{t} d_g^{t'}), \ \forall g, t$$
$$p_g^t \leq \overline{P}_g \tilde{x}_g^t (1 - \textstyle\sum_{t'=t_a}^{t} d_g^{t'}), \ \forall g, t$$

- generation capacity bounds

$$p_g^t - p_g^{t-1} \leq R_g^u \tilde{x}_g^{t-1} + \bar{R}_g^u (\tilde{x}_g^t - \tilde{x}_g^{t-1}) + \overline{P}_g (1 - \tilde{x}_g^t), \ \forall g, t$$

- generation ramp-up

$$p_g^{t-1} - p_g^t \leq R_g^d \tilde{x}_g^t + \bar{R}_g^d (\tilde{x}_g^{t-1} - \tilde{x}_g^t) + \overline{P}_g (1 - \tilde{x}_g^{t-1}), \ \forall g, t$$

- generation ramp-down

$$0 \leq q_i^t \leq D_i^t, \ \forall i, t$$
$$\textstyle\sum_{i \in V} q_i^t - (\varepsilon \sum_{i \in V} D_i^t) \tilde{v}_2^t \leq s^t, \ \forall i, t$$
$$r_g^t \leq p_g^t, \ \forall g, t$$

- load and generation shedding

$$p_g^{t_a - 1} = \tilde{p}_g^{t_a - 1} (1 - d_g^{t_a}), \ \forall g$$

- non-anticipativity

$$d_e^t \in \{0, 1\}, d_g^t \in \{0, 1\}, \ \forall t \in \{t_a, t_b\}$$
$$d_e^t = 0, d_g^t = 0, \ \forall t \notin \{t_a, t_b\}$$

- integrality restrictions

$$p_g^t \geq 0, r_g^t \geq 0, s^t \geq 0, \ \forall g, t$$

- non-negativity restrictions

PSIP Reformulation

- PSIP is a bilevel program and cannot be solved directly.
- PSIP can reformulated as a MILP
  - bilinear terms in the objective
  - product of d^{t_a}, d^{t_b} and continuous lower level variables
  - mixed-integer linear reformulation refer to as PSIP-M

Cutting Plane Algorithm 2 (CPA2)

0: Initialize LB, UB
1: Solve RUC
2:     If infeasible, EXIT
3:     Else, update LB and solutions $\tilde{x}$, $\tilde{Q}$
4: Solve a NSP($\tilde{x}$),
5:     If infeasible, add [f-cut1] to RUC and go to (1)
6:     Else, let $\tilde{p}$ be the optimal generation schedule and z be the ofv
7: For each (t_a, t_b) pairs, solve PSIP-M$(\tilde{x}, \tilde{p}, t_a, t_b)$ and let w be the ofv
8:     If $w > 0$, add [f-cut2] to NSP($\tilde{x}$) and go to (4)
9: If $z > Q$, add [o-cut] to RUC
10: Update UB
11: If (UB$-$LB$< \varepsilon$), EXIT
12: Else, go to (1)

CPA2 Discussion

- At each iteration of CPA2:
  - Instead of solving $|\mathcal{C}|$ linear programs (CSP)

    For $c \in \mathcal{C}$, solve $\text{CSP}(\tilde{x}, \tilde{p}, c)$
  - We now solve $\frac{1}{2}(T)(T-1)$ mixed-integer linear programs (PSIP-M)

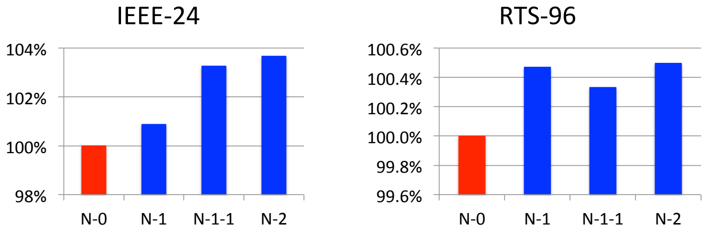
    For each (t_a, t_b) pairs, solve $\text{PSIP-M}(\tilde{x}, \tilde{p}, t_a, t_b)$
- Number of contingencies identified is extremely small

Preliminary Study Setup

- Test Systems: modified IEEE-24 and RTS-96
- Time periods: $T = 6$
- Implementation C++, CPLEX 12.1 and Concert 2.9
- ε values of 0.08, and 0.05 for IEEE-24 and RTS-96, respectively
- Line overload factor $o_e = 0.25$

Preliminary Observations (1 of 3)

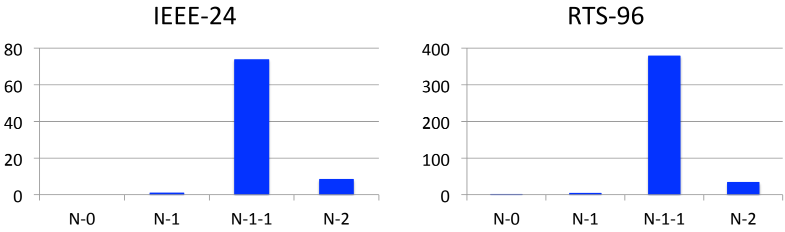
Cost comparison using N-0 as baseline



- Modest increases in costs
- Small number of contingencies identified (3 to 7)
- Contingencies mostly correspond to failures in consecutive periods

Preliminary Observations (2 of 3)

Runtime comparison (min.)



- Order of magnitude increase in runtimes from N-2 to N-1-1
- Scalability is an issue (PSIP for each time-period pairs)

Preliminary Observations (3 of 3)

- detailed relations between N-2 and N-1-1?
- Need more comprehensive studies on larger (and more realistic) systems to draw conclusion

Current and Next Steps

- Model refinements
  - enforcing non-anticipativity between primary and secondary contingency
- Algorithmic refinements
  - HPC implementation
- Further testing and analysis
  - Larger and more realistic instances
  - Longer time periods (e.g. $T = 8, 12, 24$)
  - Rolling horizons
  - N-2 and N-1-1?

Thank you

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