Scalable Corrective Security-Constrained Economic Dispatch (SCED) Considering Conflicting Contingencies

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Outline

- Introduction
- Literature review
- Problem formulation
- Solution methodology – Contingency filtering
- Performance enhancements
- Numerical results

Our recent publication

a. Y. Yu and P. B. Luh, "Scalable Corrective Security-constrained Economic Dispatch Considering Conflicting Contingencies," *International Journal of Electrical Power and Energy Systems*, vol. 98, pp. 269-278, June 2018.

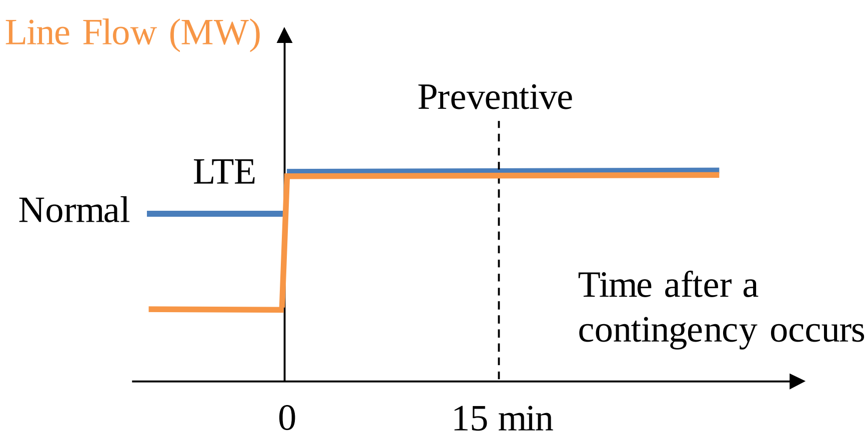
Introduction

- Preventive SCED [1]: One set of ED decisions feasible for the base case and all "N – 1" transmission contingencies
- Corrective SCED [2]: Base-case ED decisions can be adjusted within a unit's ramping capability after each contingency
- Improved corrective SCED [3]
  – Preventive SCED to capture the system status right after a contingency
  – Corrective SCED to model adjustment of post-contingency flows
    - To be within Long-Term Emergency (LTE) ratings in 15 min after a contingency [4] [5]

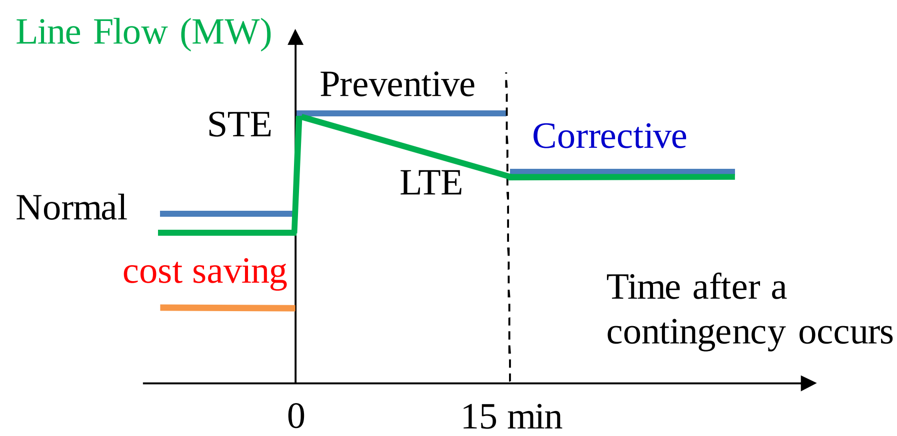
1. Alsac O, Stott B. Optimal load flow with steady-state security. *IEEE Trans Power Ap Syst* 1974;PAS-93(3):745–51.
2. Monticelli A, Pereira MVF, Granville S. Security-constrained optimal power flow with post-contingency corrective rescheduling. *IEEE Trans Power Syst* 1987;2(1):175–80.
3. Capitanescu F, Wehenkel L. Improving the statement of the corrective security constrained optimal power-flow problem. *IEEE Trans Power Syst* 2007;22(2):887–9.
4. NERC, System Operating Limit Definition and Exceedance Clarification, 2015. [Online]. Available: http://www.nerc.com/pa/Stand/Prjct201403RvsnstoTOPandIROStndrds/2014_03_fifth_posting_white_paper_sol_exceedance_20150108_clean.pdf
5. ISO New England Operating Procedure No. 19 – Transmission Operations, 2016. [Online]. Available: http://www.iso-ne.com/rules_proceds/operating/isone/op19/op19_rto_final.pdf

- Advantages of corrective SCED – Higher efficiency
  - More efficient utilization of the transmission grid
  - Explicit modeling of generator contingencies, instead of reserves
- Difficulties
  - Corrective SCED is more complex than preventive SCED
    - Large numbers of post-contingency ED decisions and constraints, one set per contingency
  - Strict time limit of real-time dispatch
  - Different types of infeasible contingencies, especially "conflicting contingencies"

(Pure) Preventive SCED



Improved Corrective SCED



Literature review

- Direct approach
  - Directly solves the problem with all possible contingencies
  - Large numbers of decision variables and constraints
- Contingency filtering [6] [7] [8]
  - Starts the base-case model, and then iteratively adds selected active contingencies to revise the solution
  - Most contingencies were not active at the optimum, so select possibly active ones by ranking all contingencies:
    - Based on the severity index (2-norm of weighted constraint violations) [6]
    - Via the non-dominated contingency (comparing constraint violations) [7]
    - Based on the rescheduling index (the minimum of the maximal controllable redispatch value) [8]

6. Stott B, Alsac O, Monticelli AJ. Security analysis and optimization. *Proc IEEE* Dec. 1987;75(12):1623–44
7. Capitanescu F, Wehenkel L. A new iterative approach to the corrective securityconstrained optimal power flow problem. *IEEE Trans Power Syst* Nov. 2008;23(4):1533–41.
8. Jiang Q, Xu K. A novel iterative contingency filtering approach to corrective security-constrained optimal power flow. *IEEE Trans Power Syst* 2014;29(3):1099–109.

- Benders decomposition [9] [10] [11] [12]
  - Divides the CCED problem into a base-case master problem and multiple contingency subproblems
    - For a given base-case ED, “violated cuts” derived from subproblems and added to the master problem
  - Enhancements including parallel computing
  - Solved the Polish 2383-bus system with all transmission contingencies considering DC power flow within 10 minutes [12]
- Remaining difficulties
  - A faster approach is desired for practical use (< 2~3 minutes)
  - How to manage infeasible contingencies? (To discuss later)

9. Capitanescu F, Ramos JLM, Panciatici P, Kirschen D, Marcolini AM, Platbrood L, et al. State-of-the-art, challenges, and future trends in security constrained optimal power flow. *Electr Power Syst Res* 2011;81(8):1731–41.
10. Peng P and Chang S, “Inclusion of Post-Contingency Actions in Security Constrained Scheduling,” FERC’s 2013 Technical Conference.
11. Chang S, et al., Maximizing transmission efficiency using the National Grid Electricity Balancing System. *2015 IEEE Power & Energy Society General Meeting*, Denver, CO, 2015, pp. 1-5.
12. Liu Y, Ferris MC, Zhao F. Computational study of security constrained economic dispatch with multi-stage rescheduling. *IEEE Trans Power Syst* 2015;30(2):920–9.

Problem Formulation

- SCED
  - A single time period optimization
  - Executed periodically in real-time (e.g., every 5 minutes)
  - Determines the MW level for each online unit
  - Uses DC power flow – Performance tradeoff vs AC power flow
- Model both “N - 1” transmission and generator contingencies
  - L lines, I buses, and K units
  - $L + K + 1$ sets of ED decisions
  - Contingency index: c
    - $c = 0$ – Base case
    - $c = 1, \ldots, L$ – Transmission contingencies
    - $c = L + 1, \ldots, L + K$ – Generator contingencies

- Formulation

To minimize the base-case ED cost

$$\min \sum_k C_k(p_{k,0})$$

s.t.

Transmission

$$-f_{l,c}^{\max} \le f_{l,c} = \frac{\theta_{a(l),c} - \theta_{b(l),c}}{X_l} \le f_{l,c}^{\max}, \forall l, \forall c \ne l$$

When $c = 0$, normal rating; otherwise, LTE rating

Generator capacity

$$p_k^{\min} \le p_{k,c} \le p_k^{\max}, \forall k, \forall c \ne TC + k$$

Nodal flow balance

$$\sum_{k \in \Phi(i): k \ne c - L} p_{k,c} - D_i = \sum_{l: a(l)=i, l \ne c} f_{l,c} - \sum_{l: b(l)=i, l \ne c} f_{l,c}, \forall i, \forall c$$

Contingency-level constraints

(Post-contingency) redispatch

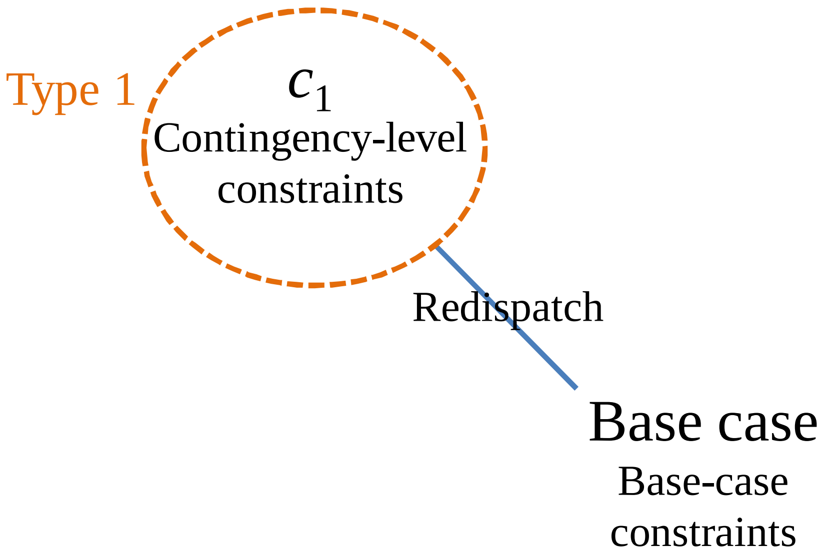
$$p_{k,0} - \Delta_{k,c} \le p_{k,c} \le p_{k,0} + \Delta_{k,c}, \forall k, \forall c \ne L + k$$

Coupling constraints

15-min ramp rate for transmission contingencies
10-min ramp rate for generator contingencies (ISO New England uses 10-min reserves as a buffer)

- A large-sized LP problem
  - A large number of ED decisions and corresponding constraints
  - Post-contingency ED decisions loosely coupled with the base case

- Infeasible contingencies
  - Defined in our paper [a] based on the formulation not on an algorithm



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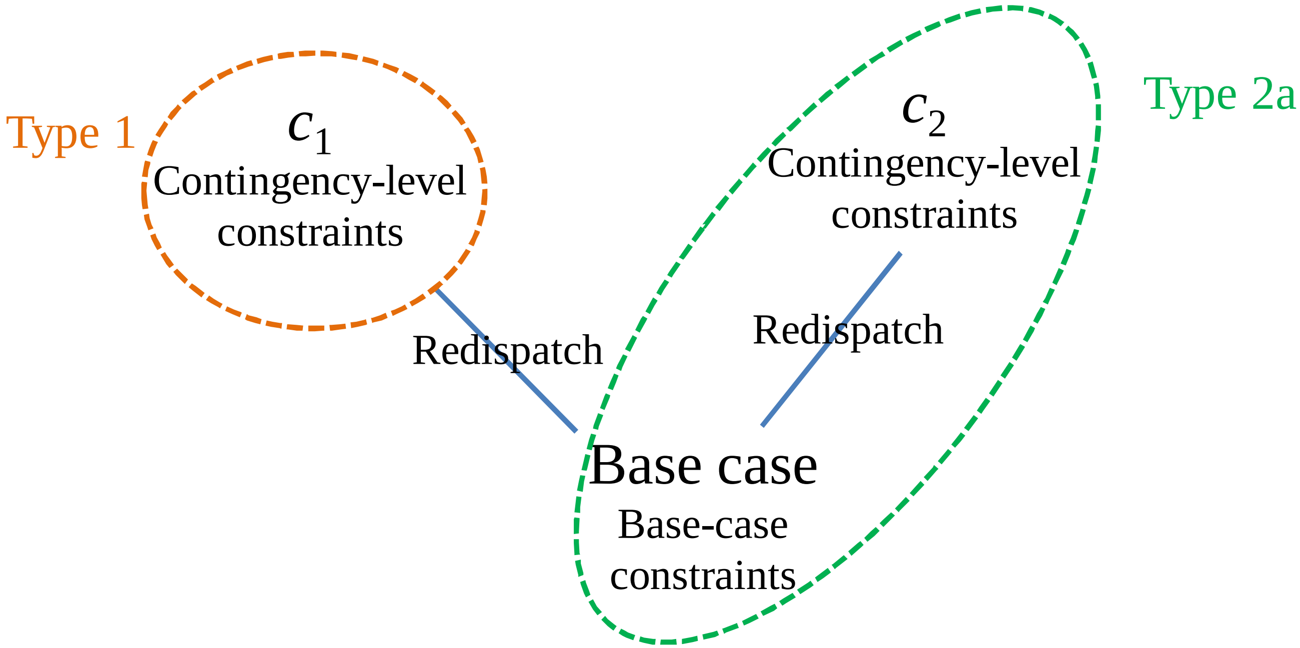

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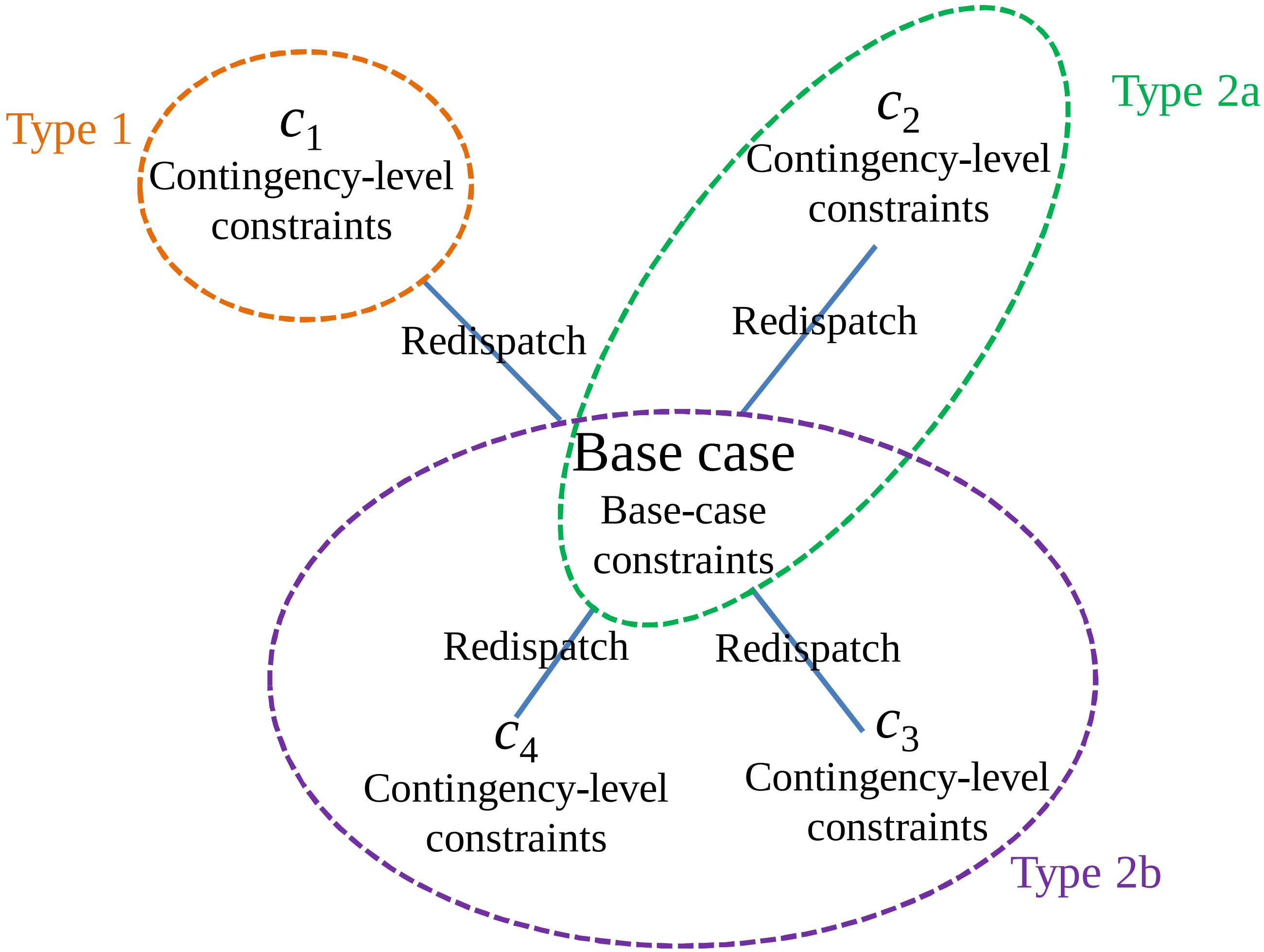

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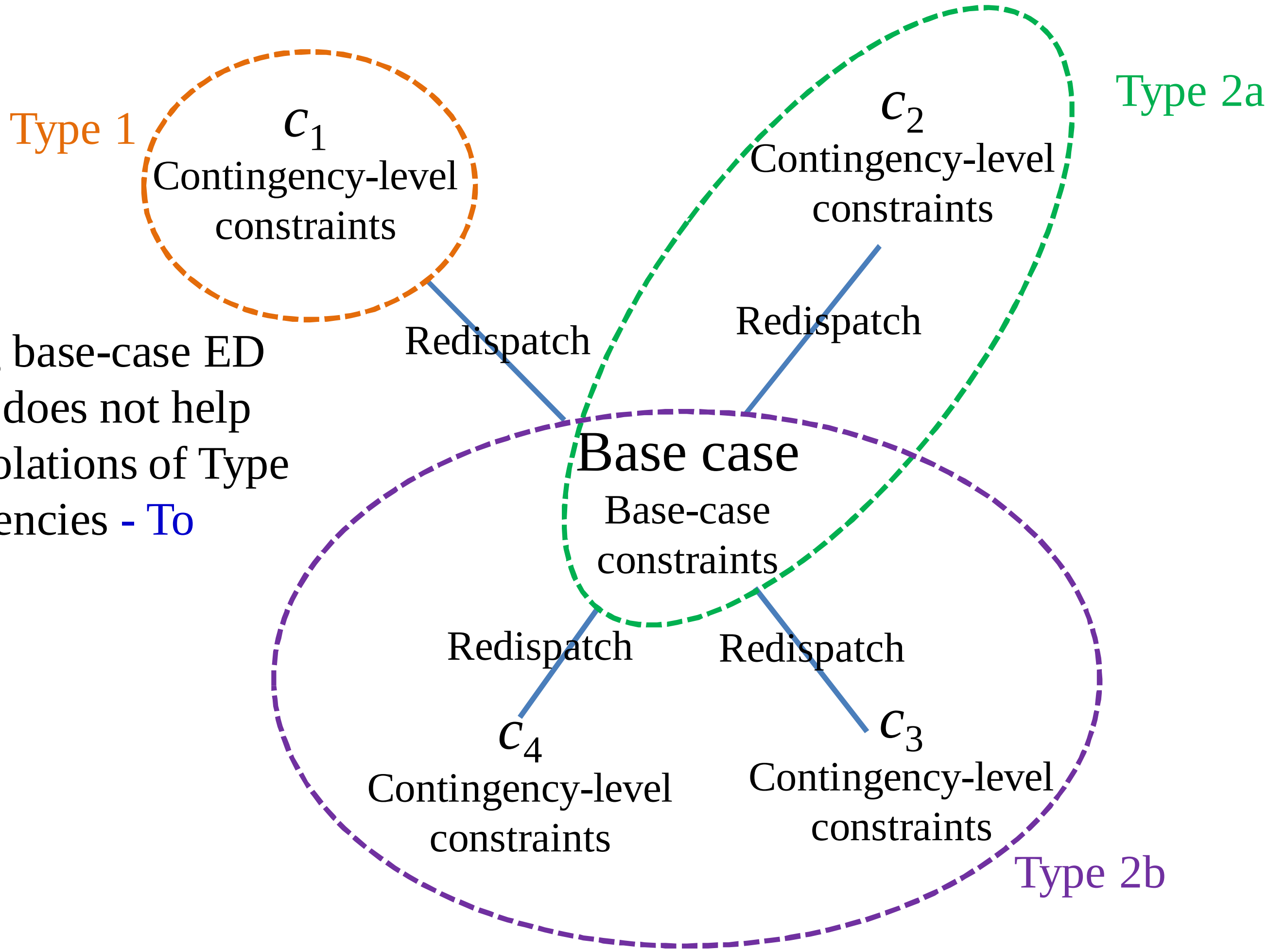
Adjusting base-case ED decisions does not help reduce violations of Type 1 contingencies - To remove



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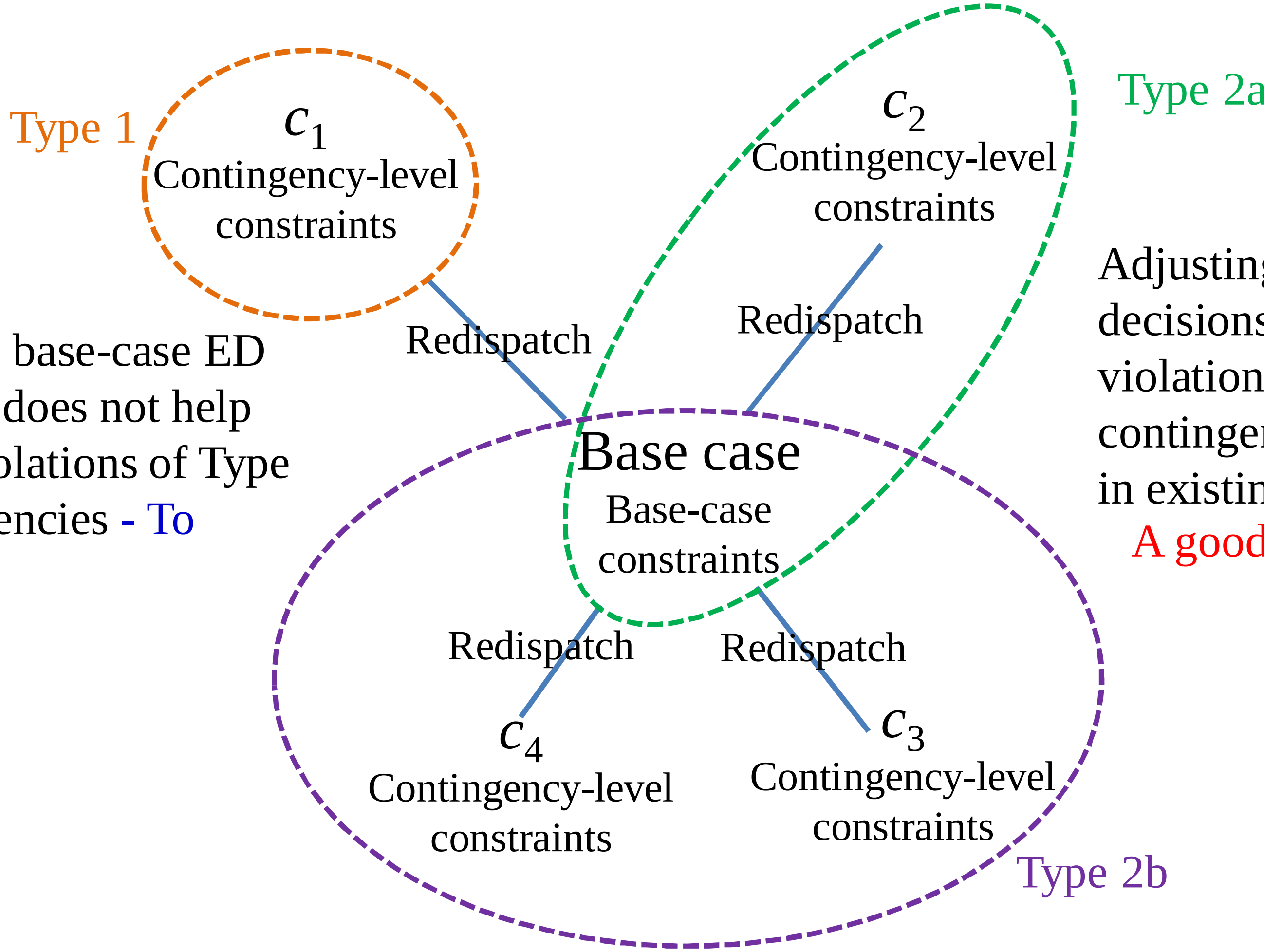


Adjusting base-case ED decisions does not help reduce violations of Type 1 contingencies - To remove

Adjusting base-case ED decisions can help reduce violations of Type 2 contingencies – Removed in existing literature [8][12]

A good treatment?

8. Jiang Q, Xu K. A novel iterative contingency filtering approach to corrective security-constrained optimal power flow. *IEEE Trans Power Syst* 2014;29(3):1099–109.
12. Liu Y, Ferris MC, Zhao F. Computational study of security constrained economic dispatch with multi-stage rescheduling. *IEEE Trans Power Syst* 2015;30(2):920–9.

Methods to overcome the difficulties

Scalable

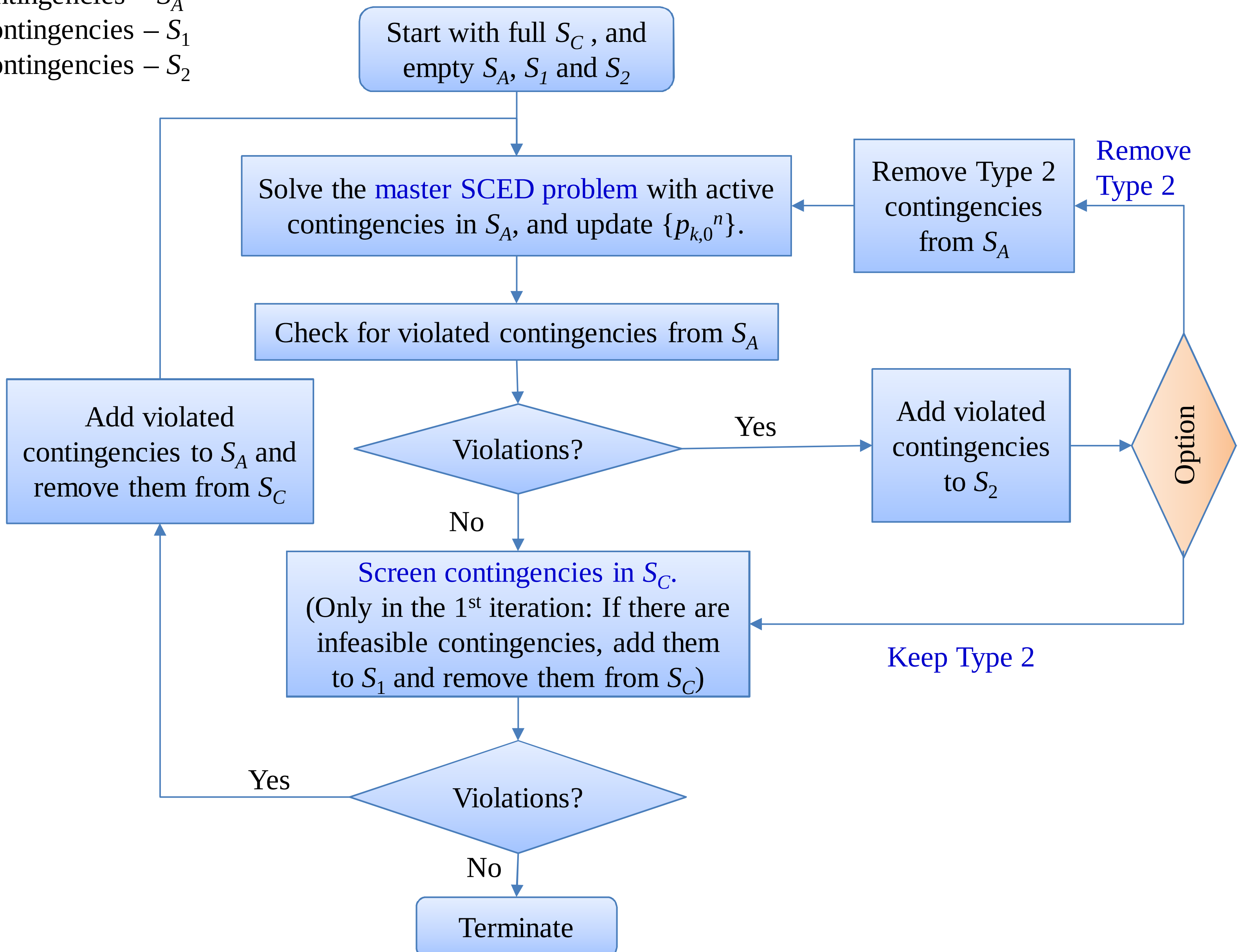
- Decomposition and coordination with contingency filtering
- Warm-start method of creating subproblem models
- Parallel computing

Managing infeasible contingencies

Solution methodology – Contingency filtering

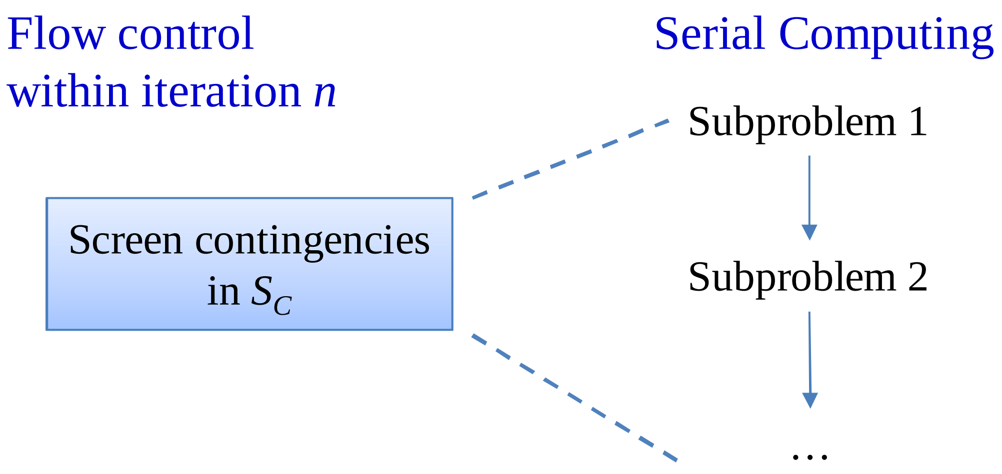
- Decomposition and coordination
  - A master problem with the base case and active contingencies
  - Subproblems for candidate contingencies
  - Starts with the base-case model, and then iteratively adds identified active contingencies to revise the solution
- Key points of our approach
  - The master problem and subproblems are formulated linearly
  - By introducing penalty terms for individual contingencies, multiple conflicting contingencies can be simultaneously identified
  - Keep or remove Type 2 contingencies based on the operator's choice
    - Keep Type 2 contingencies to minimize the overall violation
    - Or remove them for reduced base-case cost
  - Identify active contingencies in subproblems w/o ranking them
    - Linear Programming (LP) should be able to solve the master problem with all active contingencies

Sets:
Set of candidate contingencies – S_C
Set of active contingencies – S_A
Set of Type 1 contingencies – S_1
Set of Type 2 contingencies – S_2



Performance enhancements

- Warm-start method of creating subproblem models between different contingencies
  - Overhead of creating models for all subproblems
    - Thousands of subproblem models at each iteration
    - The overhead time of creating a new model for each subproblem can be comparable to or even more than the CPU time of solving each subproblem
  - Explore the flow control and subproblem structures



- Analyze two transmission contingencies

subproblem c		subproblem c'
$-f_{l,c}^{\max} \le f_{l,c} \le f_{l,c}^{\max}, \forall l \ne c$	Remove (1) of line c' → Include (1) of line c	$-f_{l,c'}^{\max} \le f_{l,c'} \le f_{l,c'}^{\max}, \forall l \ne c'$
$\sum_{k \in \Phi(i)} p_{k,c} - D_i = \sum_{l:\alpha(l)=i, l \ne c} f_{l,c} - \sum_{l:\beta(l)=i, l \ne c} f_{l,c}, \forall i$	Remove $f_{c',c'}$ at $\alpha(c')$ and $\beta(c')$ → Include $f_{c,c}$ at $\alpha(c)$ and $\beta(c)$	$\sum_{k \in \Phi(i)} p_{k,c'} - D_i = \sum_{l:\alpha(l)=i, l \ne c'} f_{l,c'} - \sum_{l:\beta(l)=i, l \ne c'} f_{l,c'}, \forall i$

Other constraints remain the same

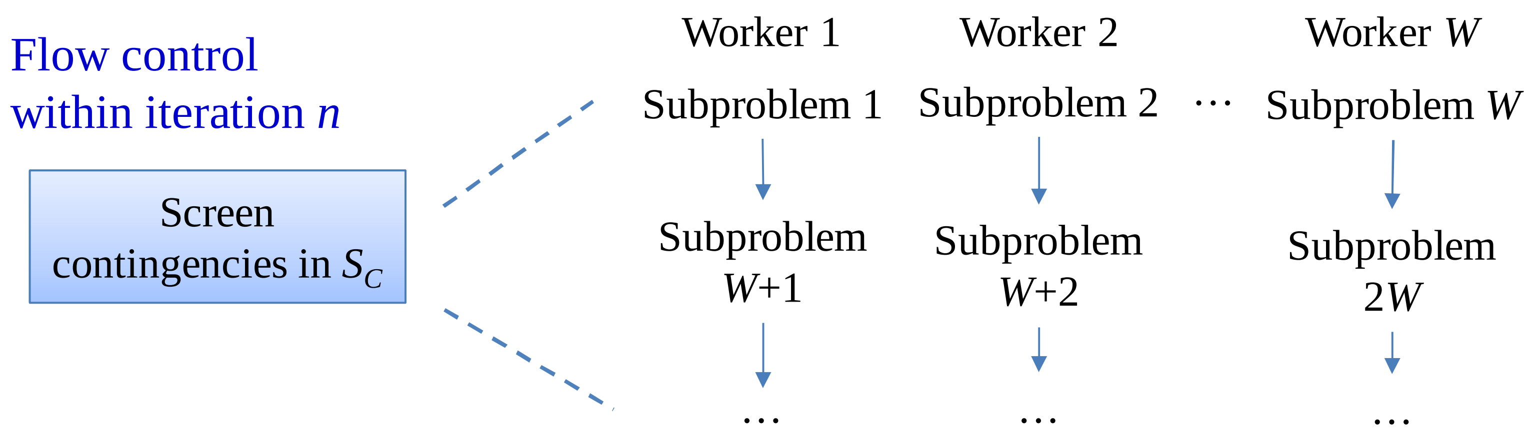
- We create only the first subproblem and then make the fewest possible modifications from one subproblem to another

– Comparison of # of operations
  - Take the 1st iteration for example. The others directly reuse existing models w/o creating new ones in our method

Constraints	Creating all subproblem models	Our warm-start method	
	# of constraints created	# of constraints created	# of constraints modified
Transmission	$2(L-1) \times L$	$2(L-1)$	$4 \times (L-1)$
Generator capacity	$2K \times L$	$2K$	0
Nodal flow balance	$I \times L$	I	$4 \times (L-1)$
Redispatch	$2K \times L$	$2K$	0

– Similar for generator contingencies

- Parallel computing
  - Checking violations of a large number of contingencies in parallel



  - Default multithreaded parallelization in CPLEX or Gurobi can be used to solve each subproblem
  - High-level parallelism via CPLEX remote object [13], [14]
    - Communication through MPI
    - Exchanging a small amount of information $\{p_0^n\}$ and c
  - Warm-start method implemented in a group-wise fashion

13. CPLEX 12.6.1 Manual
14. Rux S. Applications and Use Cases of the CPLEX Remote API. IBM Software Group, 2014. [Online]. Available: http://www-01.ibm.com/support/docview.wss?uid=swg27044403

Example - Polish 2383-bus system at winter peak

- Summary of the realistic Polish 2383-bus system [15]
  - 327 conventional units – All assumed online
    - One price block each
    - 262 of them have zero costs
  - 2896 lines: Normal and LTE ratings
  - Data at the winter peak

15. Polish 2383-bus system at winter peak (case2383wp). [Online]. Available: http://www.neos-guide.org/content/optimal-power-flow

- Improved reliability when keeping Type 2 contingencies
  - With 96 transmission and 4 generator contingencies
  - M = $5,000/MWh
  - Simulation: After optimization, fix the base-case decisions and check violations of all (Type 2) contingencies again
  - Implemented with OPL on a PC laptop

		Keep Type 2	Remove Type 2
Optimization	Wall clock time (s)	36	39
Optimization	Optimization cost (k$)	4,244.24	1,855.99
Optimization	Penalty cost (k$)	2,326.11	0
Optimization / Simulation	Base-case ED cost (k$)	1,918.12	1,855.99
Simulation	Simulation cost (k$)	4,244.24	6,917.39
Simulation	Penalty cost (k$)	2,326.11	5,061.40

Tradeoff between reliability and the base-case ED cost

- Computational performance
  - With all 2896 "N – 1" transmission contingencies
  - UConn High Performance Computing (HPC) cluster
    - Using 1 node with 24 cores; SLURM and Linux
  - CPLEX 12.6.1.0 C++ API

Configuration	a	b	c
Subproblem models	Creating all	Warm-start	Warm-start
Parallelism	Multi-threaded	Multi-threaded	Remote object
Wall clock time	21min42s	7min53s	1min51s
CPU time	16min07s	7min52s	1min45s
Overhead time	5min35s	1s	6s
Overhead/CPU time ratio	34.64%	0.21%	5.71%
Speedup ratio of wall clock time	1	2.75	11.73

  - Overhead is significantly reduced to a negligible level
  - Potential for practical use in real-time operations

Conclusion

- Our new approach is scalable for corrective SCED problems
  - Decomposition and coordination with contingency filtering
  - Warm-start method of creating subproblem models
  - Parallel computing
- Instead of always removing conflicting contingencies as presented in existing literature, we provide system operators with an important option to keep them for increased reliability
  - Validated by simulation results
- Testing against the Polish 2383-bus system demonstrates the computationally efficiency for practical use in real-time

Our recent publication

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Thank you!

For more information:

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Backup slides

- Master problem

$$\min\left[\sum_k C_k(p_{k,0}) + M \sum_{c\in S_A} \sum_{k\neq c-L} \left(s^U_{k,c} + s^D_{k,c}\right)\right] = \min\left[\sum_k C_k(p_{k,0}) + \sum_{c\in S_A} y_c\right],$$

s.t.

Relaxed redispatch constraints

$$p_{k,c} - s^U_{k,c} \le p_{k,0} + \Delta_{k,c}, \forall c \in S_A, \forall k \neq c-L, s^U_{k,c} \ge 0$$

$$p_{k,0} - \Delta_{k,c} - s^D_{k,c} \le p_{k,c}, \forall c \in S_A, \forall k \neq c-L, s^D_{k,c} \ge 0$$

Contingency-level constraints for $c \in \{0\} \cup S_A$

– Penalty cost *M* should be large
  - Otherwise, feasible contingencies identified as Type 2
– Can identify multiple Type 2 contingencies at the same time
  - Penalty terms for individual contingencies (with index *c*)
– Among multiple Type 2b contingencies conflicting with each other, those can be violated with the lowest overall cost will be identified through optimization

- Contingency subproblems
  - Formulated to check for violations in contingencies to identify possibly active ones as well as Type 1 contingencies

Subproblem for transmission contingency c given $p_{k,0}{}^n$

$$v_c = \min \sum_{k} \left(s^U_{k,c} + s^D_{k,c}\right)$$

s.t.

$$p_{k,c} - s^U_{k,c} \le p^n_{k,0} + \Delta_{k,c}, \forall k, s^U_{k,c} \ge 0$$

$$p^n_{k,0} - \Delta_{k,c} - s^D_{k,c} \le p_{k,c}, \forall k, s^D_{k,c} \ge 0$$

Contingency-level constraints for c

Subproblem of generator contingency c given $p_{k,0}{}^n$

$$v_c = \min \sum_{k \ne c-L} \left(s^U_{k,c} + s^D_{k,c}\right)$$

s.t.

$$p_{k,c} - s^U_{k,c} \le p^n_{k,0} + \Delta_{k,c}, \forall k \ne c-L, s^U_{k,c} \ge 0$$

$$p^n_{k,0} - \Delta_{k,c} - s^D_{k,c} \le p_{k,c}, \forall k \ne c-L, s^D_{k,c} \ge 0$$

Contingency-level constraints for c

  - If $v_c{}^* > 0$, c active;
  - If $v_c{}^* = 0$, c inactive;
  - If subproblem infeasible, c is Type 1