Optimal Power Flow (OPF) in Large-scale Power Grid Simulation

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Outline

- I. Introduction and challenges of optimal power flow
- II. Three topics on optimal power flow
  - Optimal power flow with post-contingency correction
  - Optimal power flow with discrete control variables and two stage MIP
  - Optimal power flow considering other energy infrastructures
- III. Summary and future work

Introduction to optimal power flow

- Applications
  - Optimal production cost simulation with network constraints
  - Minimal network loss in power grid
  - Market clearing and locational marginal price calculation
- Mathematical formulation
  - Continuous linear or nonlinear optimization problem
  - Stochastic optimization
- Algorithms
  - Linear programming and successive linear programming
  - Interior point method
  - Quadratic programming
  - Heuristic method

Three challenges in optimal power flow

- **Optimal power flow with post-contingency correction**
  - **Difficulties: Huge number of contingency cases N-1…N-k**
- **Optimal power flow with discrete control variables and two-stage mixed integer linear and nonlinear problem (MIP)**
  - **Quick start units**
  - **Discrete control variables in networks**
  - **Smart grid operations (energy storages, transmission switching)**
- **Optimal power flow considering other energy infrastructures**
  - **Security interdependency (eg., natural gas network)**
  - **Coordinated operation and planning**

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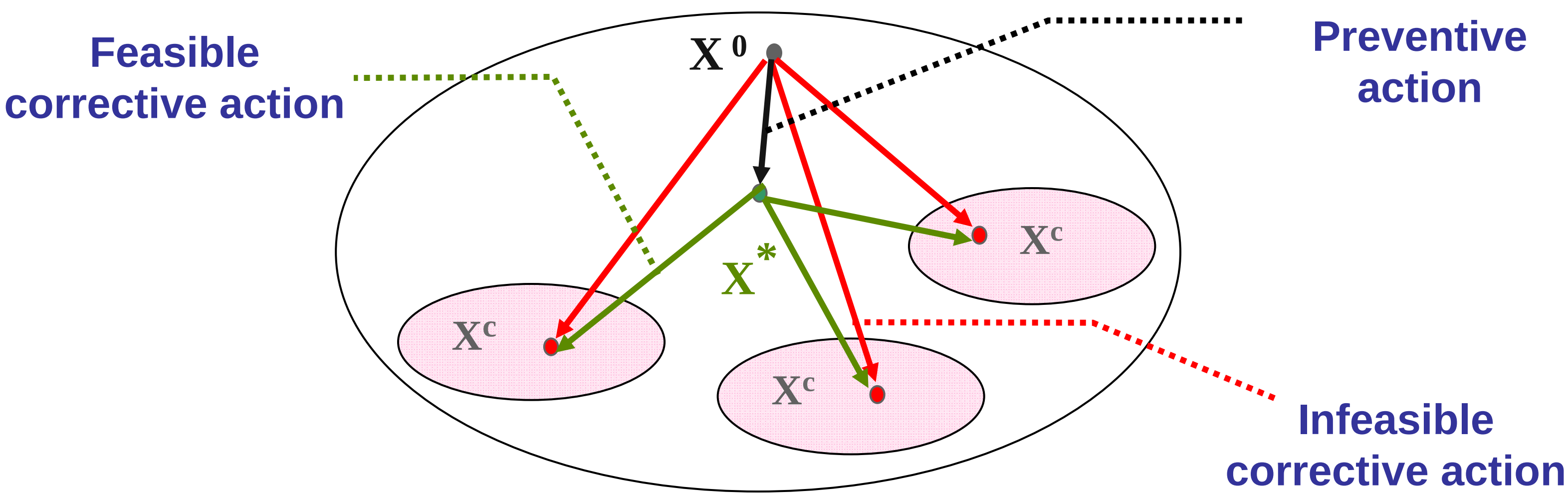
Corrective and preventive actions in power system operations

$$
\boldsymbol{x}^{*}\left\{
\begin{array}{lll}
\boldsymbol{x}^{0}\left\{
\begin{array}{ll}
Min & f(\boldsymbol{x}) \\
S.t. & \boldsymbol{A}\cdot\boldsymbol{x}\le\boldsymbol{b}
\end{array}\right. & & \\
 & g(\boldsymbol{x},\boldsymbol{y})\le 0 & \\
 & g(\boldsymbol{x}^{c},\boldsymbol{y}^{c})\le 0 & \\
 & \left|\boldsymbol{x}-\boldsymbol{x}^{c}\right|\le\Delta &
\end{array}\right.
$$

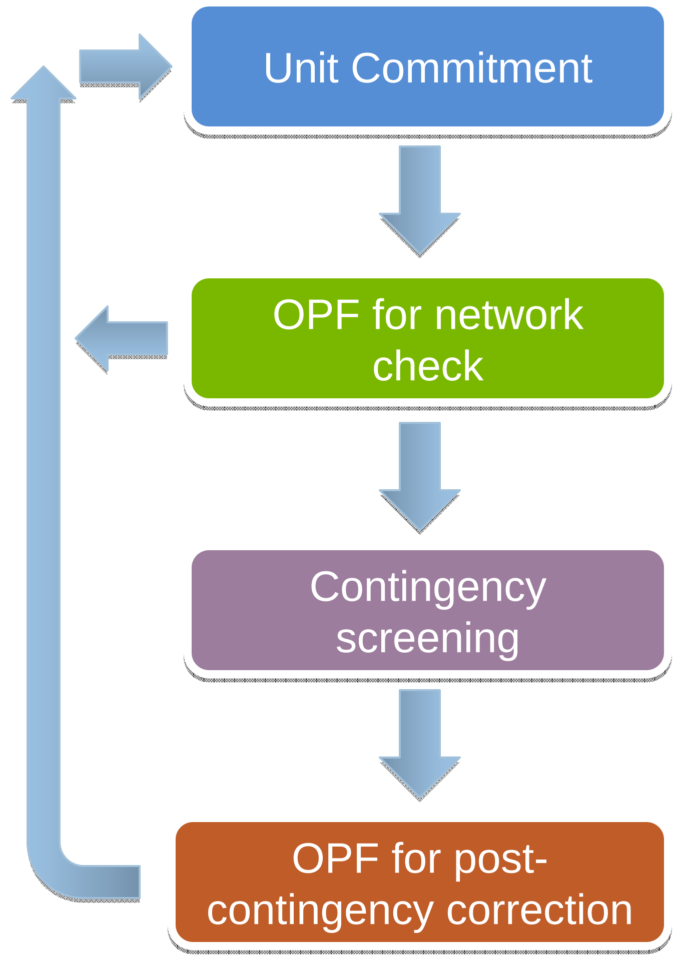
Expression	Meaning
$Min \quad f(\boldsymbol{x})$	Objective
$S.t. \quad \boldsymbol{A}\cdot\boldsymbol{x}\le\boldsymbol{b}$	Unit commitment and economic dispatch constraints
$g(\boldsymbol{x},\boldsymbol{y})\le 0$	Network constraints in normal state
$g(\boldsymbol{x}^{c},\boldsymbol{y}^{c})\le 0$	Network constraints in each contingency
$\left\|\boldsymbol{x}-\boldsymbol{x}^{c}\right\|\le\Delta$	Transfer distance constraints (e.g. ramp rate limit)



Optimal power flow (OPF) with post-contingency correction

Contingency Cases	Number
WECC N-1	~ 20,000
WECC N-2	~154,000
WECC N-3	$\sim 10^8$
WECC N-4	$\sim 10^{12}$

- **Huge number of contingencies**
  - **Contingency screening (CS)**
  - **Degree of severity**
- **Inclusion of probability into CS**
  - **Probability of outage**



Contingency screening

- **Extensive use of sparse linear algebra**

$$Y = LDU$$

- **Fast decoupled AC power flow**

$$\Delta\theta^{(k)} = -[B']^{-1}\frac{\Delta P}{U}, \qquad \Delta U^{(k)} = -[B'']^{-1}\frac{\Delta Q}{U}$$

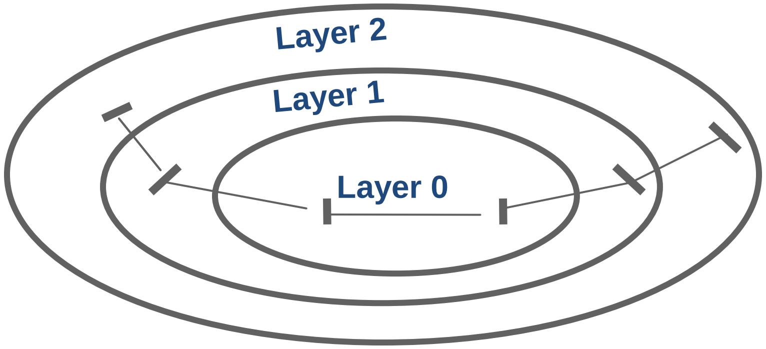
- **Compensation theory**
  - **Branch outages can be considered as minor change of Y (B’ or B’’) matrices. An efficient way is to add additional elements into matrices B’ and B’’.**

$$B' = B' + M\delta y' M^T$$

$$\Delta\theta^{(k)} = [B']^{-1}\frac{\Delta P}{U} + [B']^{-1}M([\delta y']^{-1} + M[B']^{-1}M^T)^{-1}M^T[B']^{-1}\frac{\Delta P}{U}$$

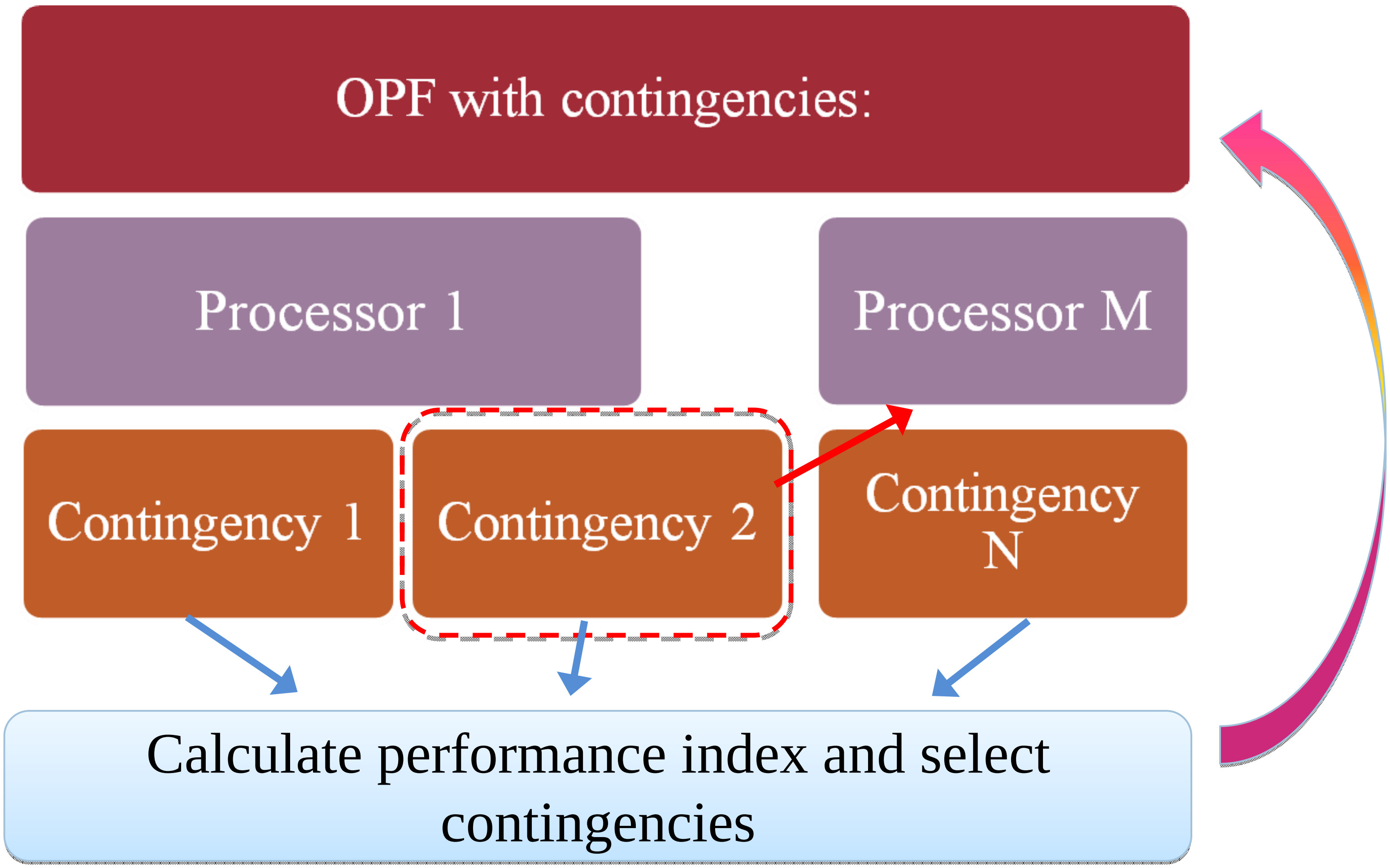
Contingency screening (CS)

- **Concentric relaxation or bounding**
  - **An outage only has a limited geographical effect on steady-state power flow.**



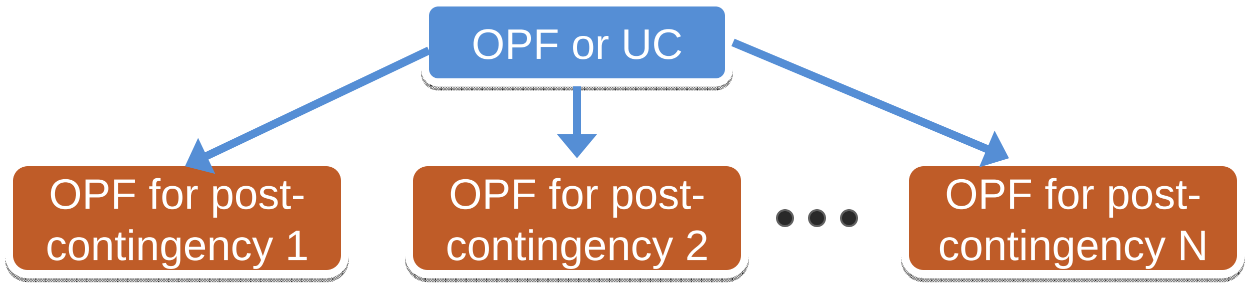
- **1P1Q or 2P2Q method**
- **Multi-area power flow**
  - **Partitioning of admittance matrix**
- **Consider probability of outage into CS**
  - **It is difficult to consider all N-1 to N-k contingencies.**
  - **We can define the better contingency list by considering probability of outage.**
  - **The probability of N-2 may be higher than some N-1 contingency.**

Parallelism for contingency screening

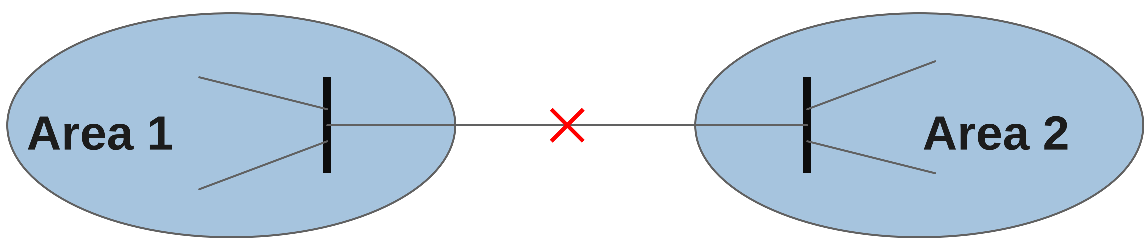


Parallelism of OPF after dual or L-shaped decomposition

- Contingency check can be implemented in a parallel way



- Multi-area optimal power flow
  - Relax power flow in the tie-line or voltage variables in the boundary bus
  - Dual decomposition by Lagrangian relaxation



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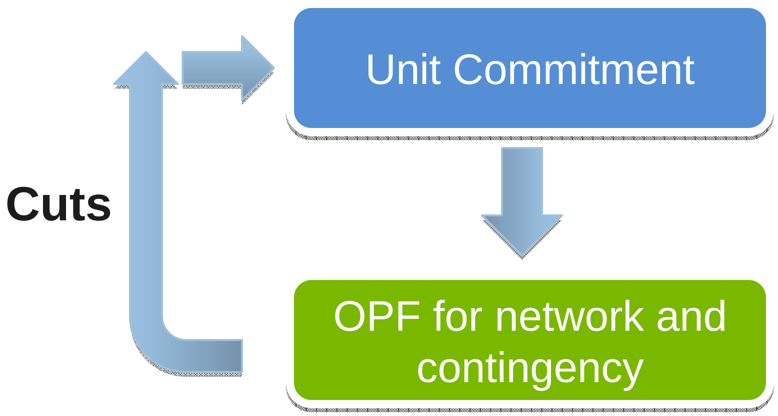
Optimal power flow with discrete variables

- **Discrete control variables in power network**
  - Quick- start unit,
  - Transmission switching, transformer tap-changer, capacitors,
  - Smart grid flexible operations

- **Mixed integer linear or nonlinear programming (MIP)**
  - Optimal power flow with discrete control variables has a similar mathematic structure to the unit commitment problem. Both of them are MIP.
  - Branch and cut method
  - Mathematic decomposition (e.g. Benders decomposition)

Two stage MIP



	Traditional	Current
Unit Commitment	MIP	MIP
OPF for network and contingency	Continuous linear or nonlinear programming	MIP

- **Original Problem**

$$
\begin{aligned}
&Min \quad && \mathbf{c} \cdot \mathbf{x} && \text{Objective} \\
&S.t. \quad && \mathbf{A} \cdot \mathbf{x} \leq \mathbf{b} && \text{First-stage constraints} \\
& && \mathbf{E}^{\mathbf{c}} \cdot \mathbf{x} + \mathbf{F} \cdot \mathbf{y}^{\mathbf{c}} \leq \mathbf{h}^{\mathbf{c}} && \text{Second-stage constraints for each contingency}
\end{aligned}
$$

$$\mathbf{x} \in \mathbf{R}^{\mathbf{m1}} \quad \{0,1\}^{\mathbf{n1}} \qquad \mathbf{y}^{\mathbf{c}} \in \mathbf{R}^{\mathbf{m2}} \quad \{0,1\}^{\mathbf{n2}}$$

L-shaped structure and decomposition

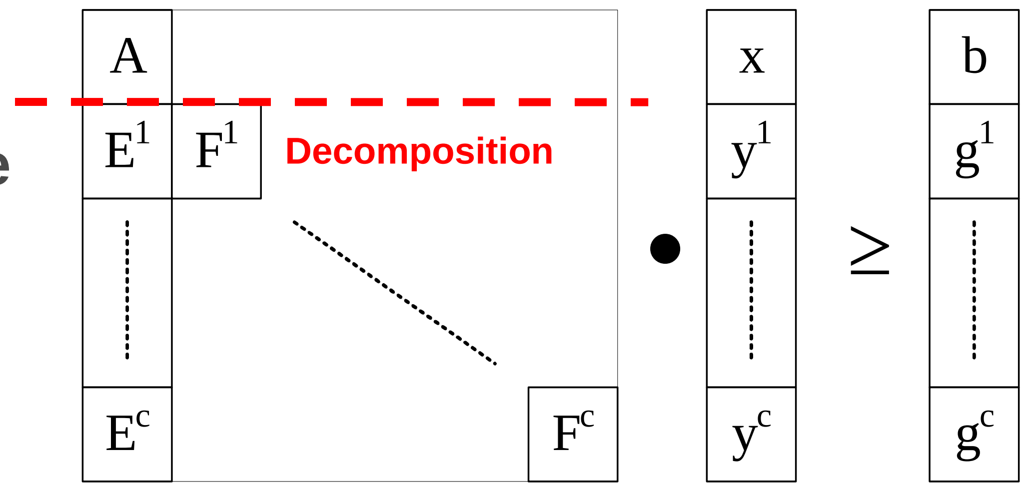
- Initial master problem (MIP)

$$\begin{aligned} &Min \quad \mathbf{c} \cdot \mathbf{x} \\ &S.t. \quad \mathbf{A} \cdot \mathbf{x} \le \mathbf{b} \end{aligned}$$

- Feasibility of corrective action check subproblems for each contingency

$$\begin{aligned} &Min \quad \mathbf{w}^{\mathbf{c}}(\hat{\mathbf{x}}) = \mathbf{1}^{\mathbf{T}} \cdot \mathbf{S}^{\mathbf{c}} \\ &S.t. \quad \mathbf{F}^{\mathbf{c}}\mathbf{y}^{\mathbf{c}} - \mathbf{S}^{\mathbf{c}} \le \mathbf{h}^{\mathbf{c}} - \mathbf{E}^{\mathbf{c}}\hat{\mathbf{x}} \end{aligned}$$

L-shaped structure



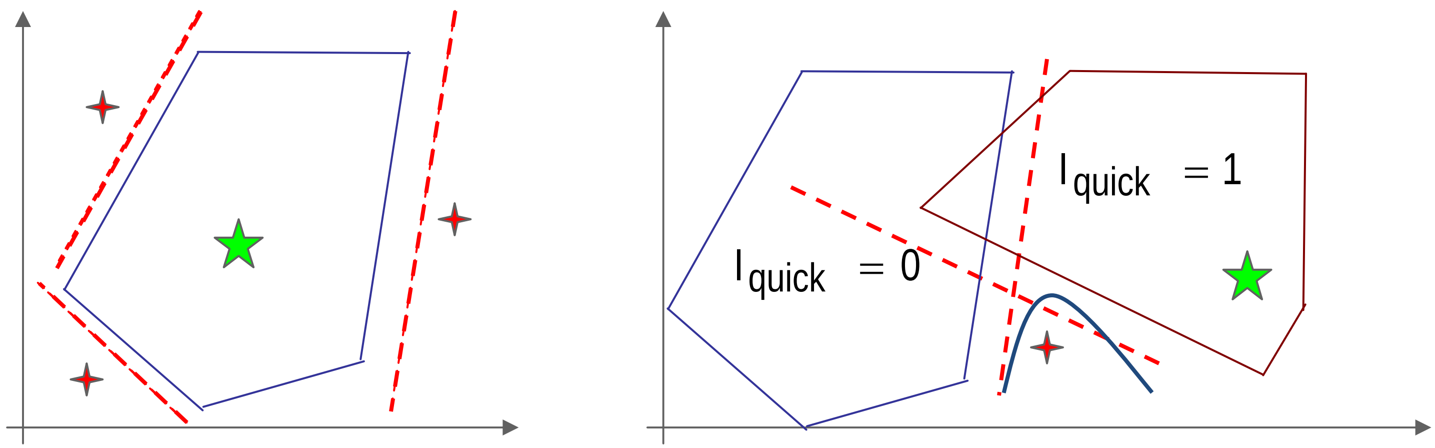
Global optimal solution

- **Without quick-start units, second-stage subproblems are LP (or successive LP)**

$$Min \quad w^{c,k}\left(\hat{x}^k\right) = 1^T \cdot S^c$$

$$S.t. \quad F^c y^c - S^c \le h^c - E^c \hat{x}^k \quad \pi^{c,k} \qquad \underline{w^{c,k}\left(\hat{x}^k\right)} - \underline{\left(\pi^{c,k}\right)^T} \cdot E^c \cdot \left(x - \hat{x}^k\right) \le 0$$

- **With quick-start units, second-stage subproblems are MIP, and its feasible region is non-convex.**



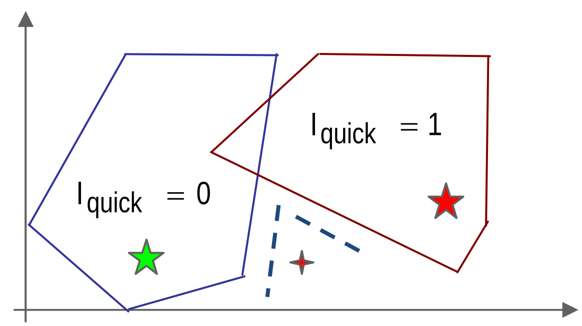
Extended Benders decomposition for SCUC with post-contingency correction

- With quick-start units, second-stage subproblems are MIP
  - A straightforward approach is to enumerate all possible combinations of quick-start units' commitments in each contingency subproblem
    - If the objective value is zero for at least one combination, this subproblem is feasible, and no feasibility cut is necessary
    - If objective values for all combinations are non-zero, this subproblem is infeasible, and feasibility cuts are generated

$$Min \quad w^{c,k}(\hat{x}^k) = 1^T \cdot S^c$$

$$S.t. \quad F^c y^c + S^c \le h^c - E^c \hat{x}^k \qquad \pi^{c,k}$$

$$y_I^c = \hat{y}_I^c \qquad y_I^c \in \{0,1\}^{n2}$$



$$w^{c,k}(\hat{x}^k) - (\pi^{c,k})^T \cdot E^c \cdot (x - \hat{x}^k) - M \cdot (1 - \delta_n) \le 0 \qquad \sum_n \delta_n = 1$$

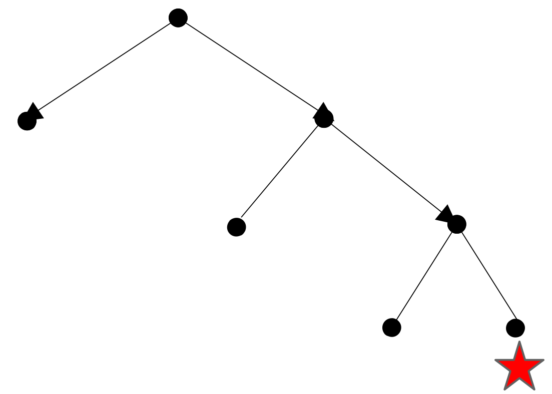
Extended Benders decomposition for SCUC with post-contingency correction (continued)

- Since the second stage subproblems may be feasible after post-contingency corrections, feasibility cuts are formed only in infeasibility case. Optimality cuts are not required in this two-stage MIP.

- The process can be accelerated by using branch and cut method

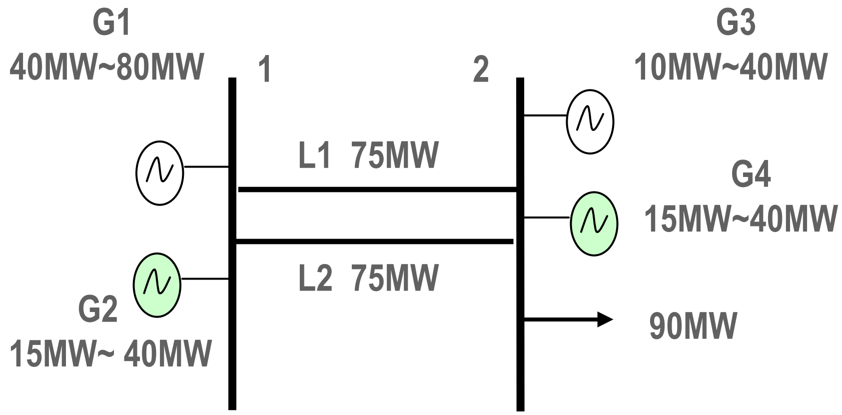
$$w^{c,k}(\hat{x}) - (\pi^{c,k})^T \cdot E^c \cdot (x - \hat{x}^k) - M \cdot (1 - \delta_n) \leq 0$$

$$\sum_n \delta_n = 1$$



A simple example

System



Contingency

Contingency	Equipment Outage	Load (MW)
1	G3	85
2	L2	93

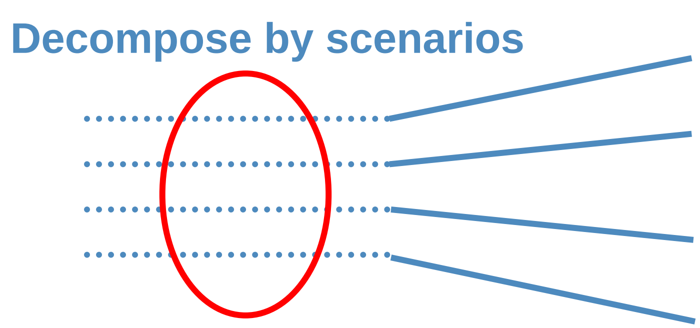
- G1 and G3: they can be re-dispatched by 5 MW
- G2 and G4: 30MW quick-start capability

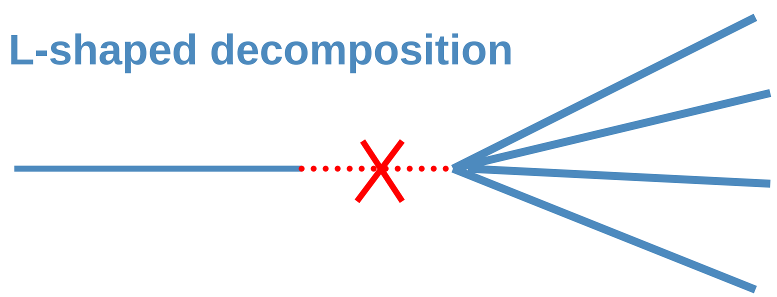
- **Three different models and solutions for quick-start units in post-contingency correction subproblems**
  1) **MIP-LP model**: *Relax integer variables in the second stage (approximation model). G2 and G4 (0~40MW)*
  2) **Two-stage MIP model:** *solve MIP in the second stage. Then fix integer variables in the second stage and form cuts from resulted LP.*
  3) **Two-stage MIP model:** *Extended Benders decomposition*
- **Results:**
  1) **Infeasible for contingency correction** 2) **Suboptimal** 3) **Global optimal**

Other two stage MIP in power grid simulation

Problem	First Stage	Second Stage
UC with network constraints	UC	Transmission constraints
Contingency-based SCUC	UC with pre-contingency transmission constraints	Post- contingency transmission constraints
Two-stage stochastic SCUC	Decision costs and constraints	Recourse costs and constraints
Two stage distribution network expansion	Decision of building new distribution line	Reconfiguration

- **Dual decomposition and L-shaped (Benders) decomposition: pros and cons**





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Optimal power flow with other energy infrastructures

- **Electricity infrastructure**
  - Smart grid
  - Renewable energy

- **Natural gas transmission system**
  - Texas: 70% electricity are generated by natural gas units
  - Coordination between peaking units and renewable energy
- **River and cascaded hydropower station**
  - Hydrothermal coordinated scheduling
- **Transportation**
  - PHEV, Vehicle to Grid
  - Coal, Oil transportation

Coupled energy flow

- **Steady-state integrated model have been proposed in the last decade**
- **Different energy flows travel via different speed through infrastructures**
  - Power flow: very small time constant
  - Water flow: large time constant
  - Natural gas flow: medium time constant
  - transportation flow: medium time constant
- **Use dynamic model instead of steady-state linear or nonlinear algebraic equations**
- **Potential application: security monitoring, reliability evaluation, planning**

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Summary and future work at Argonne

- Three challenges of optimal power flow in power grid simulation are addressed.

- Contingency screening method is nested into unit commitment and optimal power flow with post-corrective action. Contingency analysis and optimal power flow study can be extended to a large-scale power system with parallel computing. Probability of outage cloud be included into contingency screening process.

Summary and future work at Argonne

- Discrete variables will bring more difficulties in solving optimal power flow especially for two-stage MIP problems. Dual decomposition and L-shaped (Benders) decomposition techniques can be used to divide the original problem into several small-scale subproblems.

- Energy infrastructures are highly coupled, it is envisioned that using an integrated method to model optimal power flow and other energy flows together is necessary.

Reference

[1] Jianhui Wang, Mohammad Shahidehpour, and Zuyi Li, “Contingency- Constrained Reserve Requirements in Joint Energy and Ancillary Services Auction,” *IEEE Transactions on Power Systems*, Vol.24, No.3, pp.1457-1468, Aug. 2009

[2] Cong Liu, Mohammad Shahidehpour, Yong Fu and Zuyi Li “Security-Constrained Unit Commitment with Natural Gas Transmission Constraints,” *IEEE Transactions on Power Systems*, Vol. 24, No. 3, Aug. 2009.

[3] Lei Wu, Mohammad Shahidehpour, and Cong Liu “MIP-based Post-Contingency Corrective Action with Quick-Start Units,” *IEEE Transactions on Power Systems*, Vol. 24, No. 4, Nov. 2009.

[4] Cong Liu, Mohammad Shahidehpour, and Lei Wu, “Extended Benders Decomposition for Two-Stage SCUC,” *IEEE Transactions on Power Systems*, Vol. 25, No. 2, May. 2010.

Thank You for Attention!

Question?

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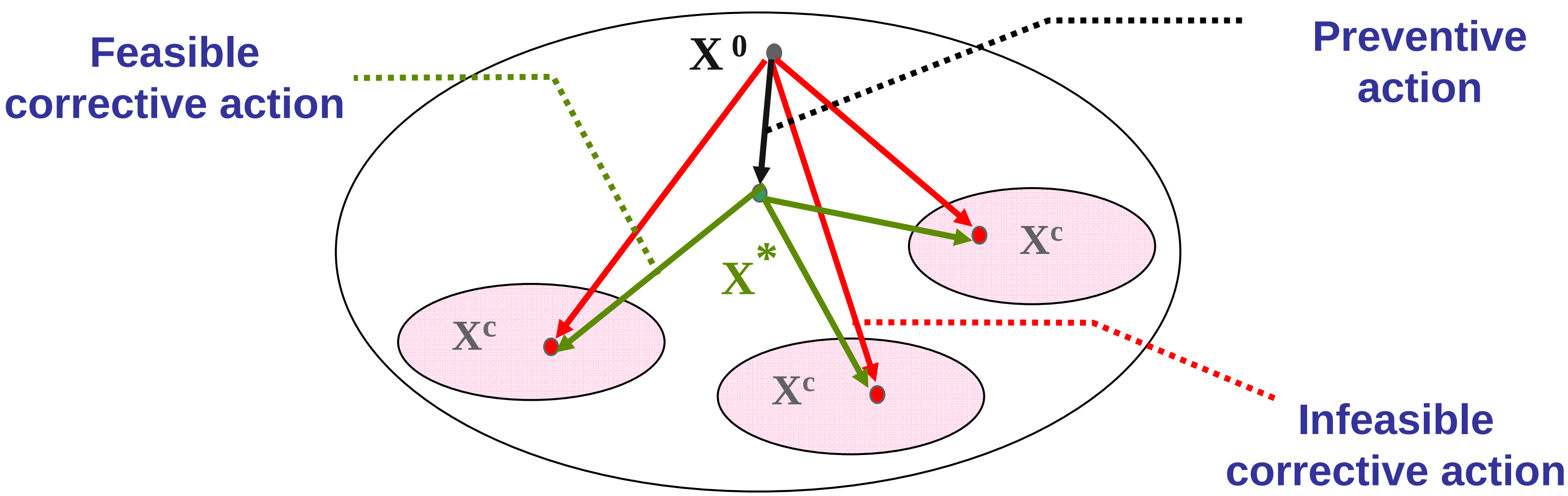

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  - **Degree of severity**
- **Inclusion of probability into CS**
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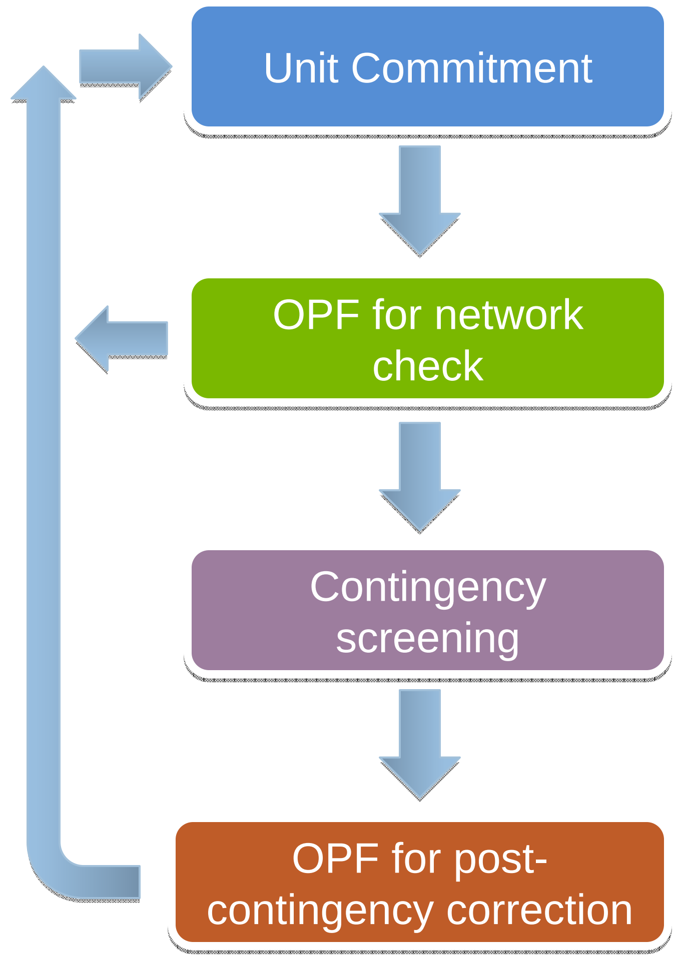

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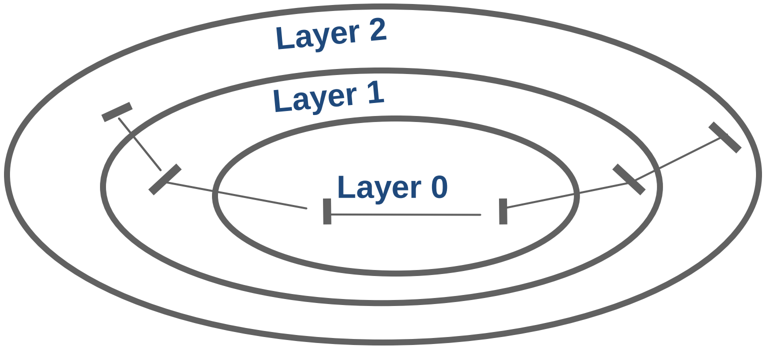

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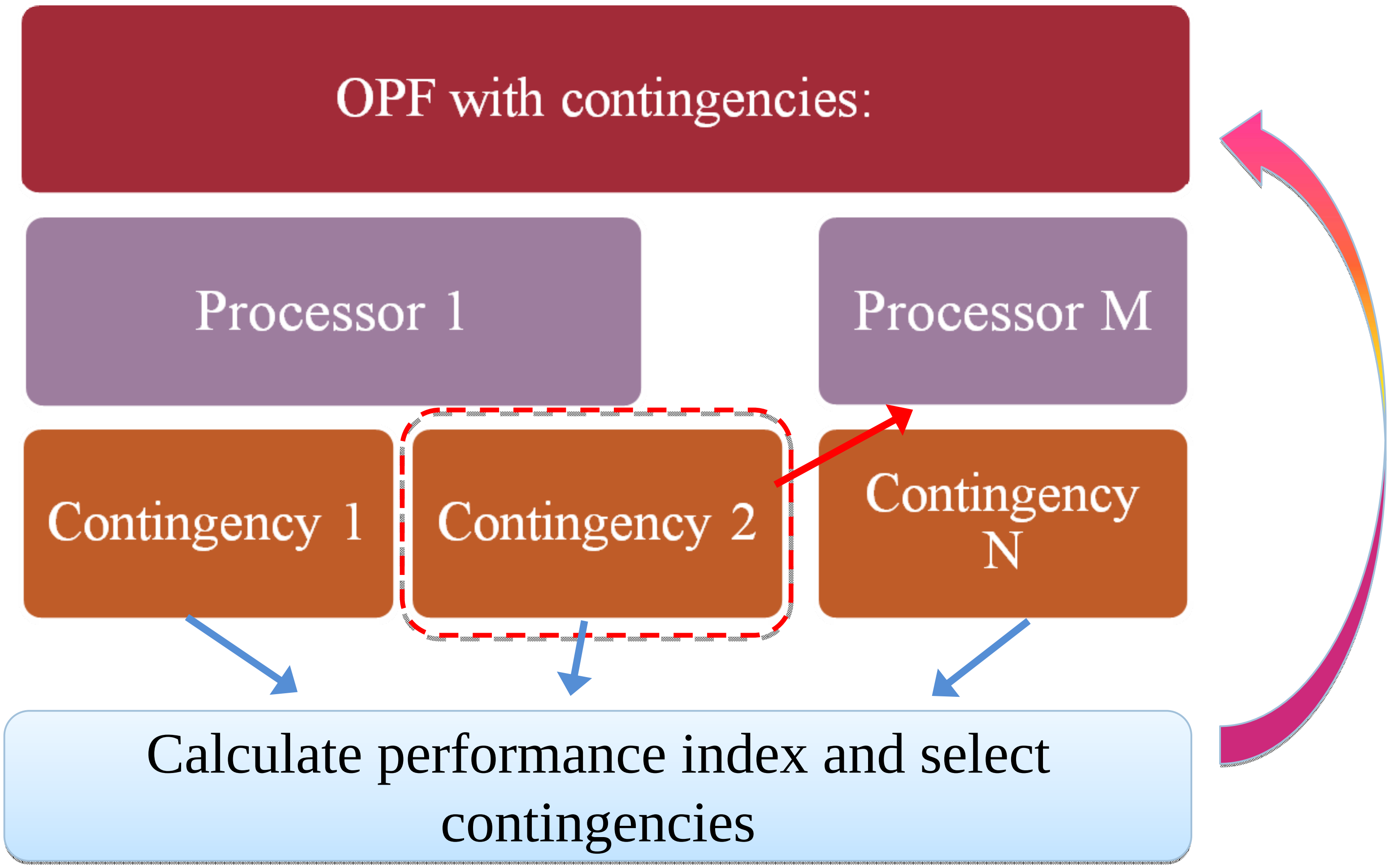
Parallelism for contingency screening



Parallelism of OPF after dual or L-shaped decomposition

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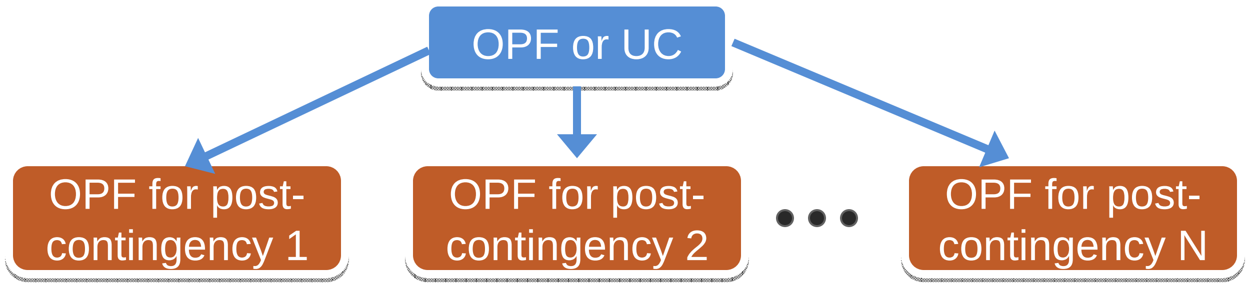

- Multi-area optimal power flow
  - Relax power flow in the tie-line or voltage variables in the boundary bus
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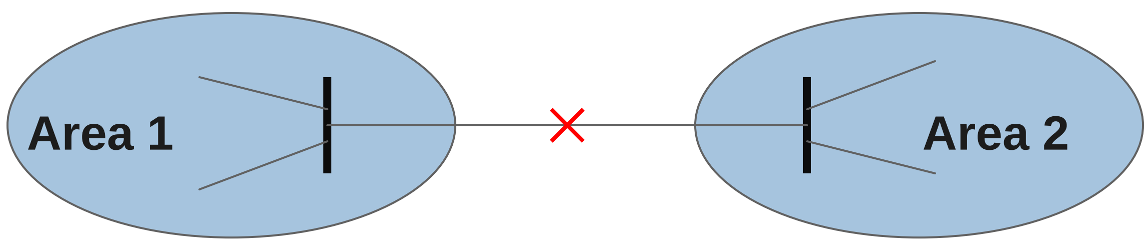

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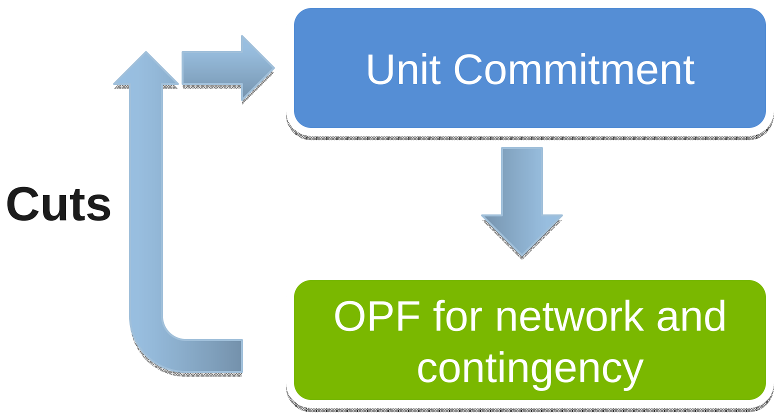
- **Discrete control variables in power network**
  - **Quick- start unit,**
  - **Transmission switching, transformer tap-changer, capacitors,**
  - **Smart grid flexible operations**

- **Mixed integer linear or nonlinear programming (MIP)**
  - **Optimal power flow with discrete control variables has a similar mathematic structure to the unit commitment problem. Both of them are MIP.**
  - **Branch and cut method**
  - **Mathematic decomposition (e.g. Benders decomposition)**

Two stage MIP



	Traditional	Current
	MIP	MIP
	Continuous linear or nonlinear programming	MIP

- **Original Problem**

Min	$\mathbf{c} \cdot \mathbf{x}$	Objective
$S.t.$	$\mathbf{A} \cdot \mathbf{x} \le \mathbf{b}$	First-stage constraints
	$\mathbf{E}^{\mathbf{c}} \cdot \mathbf{x} + \mathbf{F} \cdot \mathbf{y}^{\mathbf{c}} \le \mathbf{h}^{\mathbf{c}}$	Second-stage constraints for each contingency

$$\mathbf{x} \in \mathbf{R}^{m1} \quad \{0,1\}^{n1} \qquad \mathbf{y}^{\mathbf{c}} \in \mathbf{R}^{m2} \quad \{0,1\}^{n2}$$

L-shaped structure and decomposition

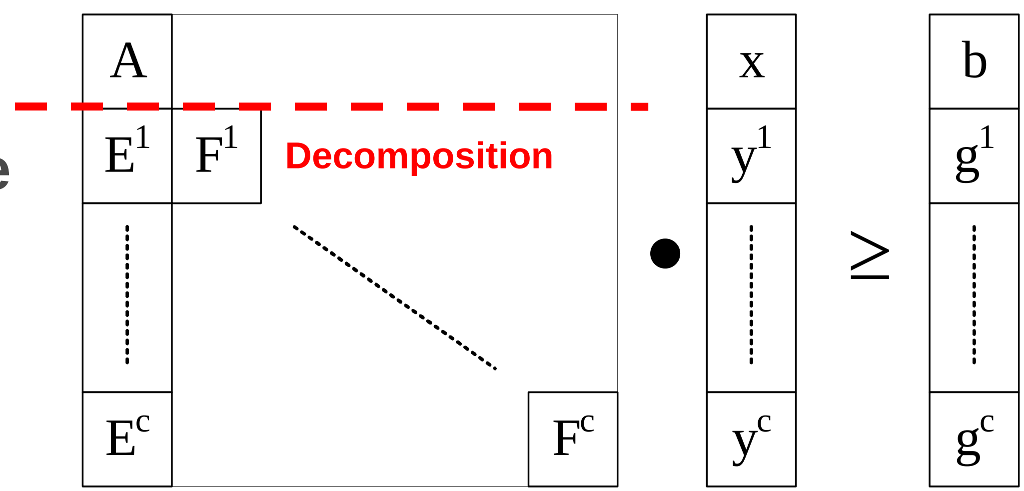
- Initial master problem (MIP)

$$\begin{aligned} &Min && \mathbf{c} \cdot \mathbf{x} \\ &S.t. && \mathbf{A} \cdot \mathbf{x} \le \mathbf{b} \end{aligned}$$

- Feasibility of corrective action check subproblems for each contingency

$$\begin{aligned} &Min && \mathbf{w}^{c}(\hat{\mathbf{x}}) = \mathbf{1}^{T} \cdot \mathbf{S}^{c} \\ &S.t. && \mathbf{F}^{c}\mathbf{y}^{c} - \mathbf{S}^{c} \le \mathbf{h}^{c} - \mathbf{E}^{c}\hat{\mathbf{x}} \end{aligned}$$

L-shaped structure



Global optimal solution

- **Without quick-start units, second-stage subproblems are LP (or successive LP)**

$$Min \quad w^{c,k}\left(\hat{x}^k\right) = 1^T \cdot S^c$$

$$S.t. \quad F^c y^c - S^c \le h^c - E^c \hat{x}^k \quad \pi^{c,k} \qquad w^{c,k}\left(\hat{x}^k\right) - \left(\pi^{c,k}\right)^T \cdot E^c \cdot \left(x - \hat{x}^k\right) \le 0$$

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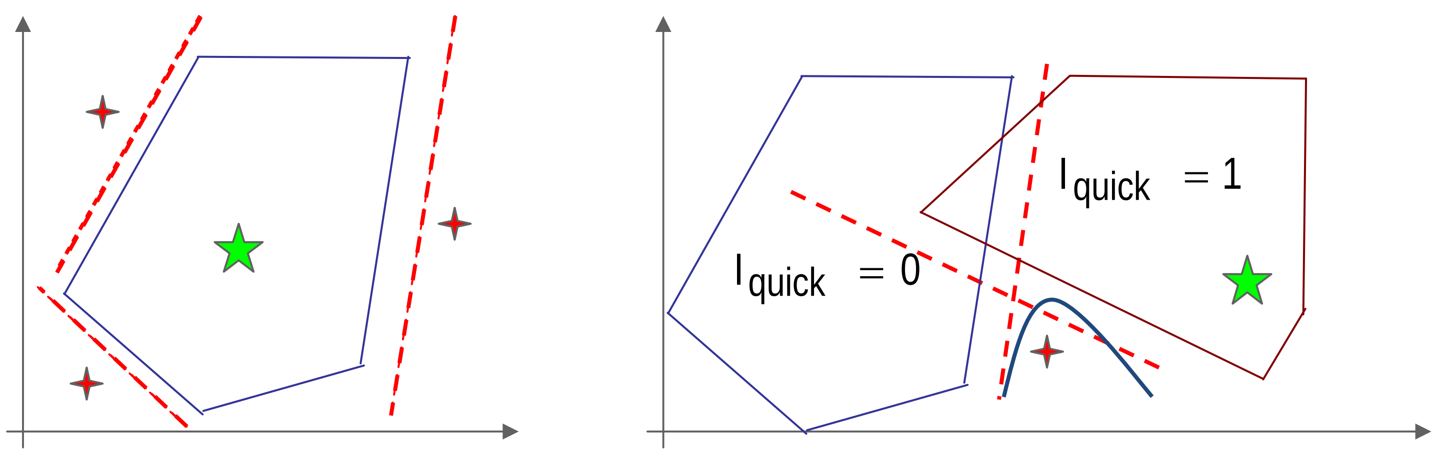

Extended Benders decomposition for SCUC with post-contingency correction

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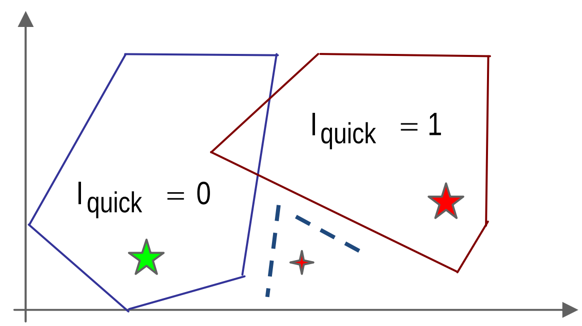
    - If objective values for all combinations are non-zero, this subproblem is infeasible, and feasibility cuts are generated

$$\mathit{Min} \quad w^{c,k}\left(\hat{x}^k\right) = 1^T \cdot S^c$$

$$\mathit{S.t.} \quad F^c y^c + S^c \le h^c - E^c \hat{x}^k \qquad \pi^{c,k}$$

$$y_l^c = \hat{y}_l^c \qquad y_l^c \in \{0,1\}^{n2}$$



$$w^{c,k}\left(\hat{x}^k\right) - \left(\pi^{c,k}\right)^T \cdot E^c \cdot \left(x - \hat{x}^k\right) - M \cdot \left(1 - \delta_n\right) \le 0 \qquad \sum_n \delta_n = 1$$

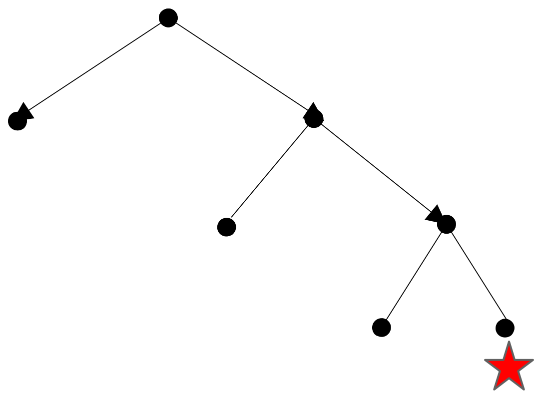
Extended Benders decomposition for SCUC with post-contingency correction (continued)

- Since the second stage subproblems may be feasible after post-contingency corrections, feasibility cuts are formed only in infeasibility case. Optimality cuts are not required in this two-stage MIP.

- The process can be accelerated by using branch and cut method

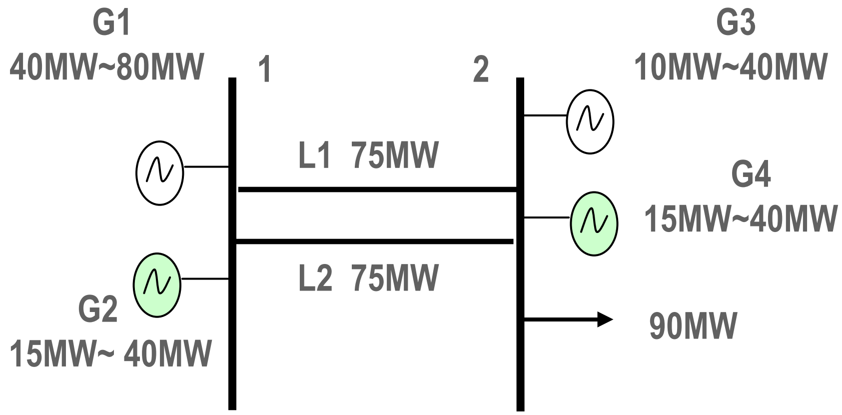
$$w^{c,k}(\hat{x}) - (\pi^{c,k})^T \cdot E^c \cdot (x - \hat{x}^k) - M \cdot (1 - \delta_n) \leq 0$$

$$\sum_n \delta_n = 1$$



A simple example

System



Contingency

Contingency	Equipment Outage	Load (MW)
1	G3	85
2	L2	93

- G1 and G3: they can be re-dispatched by 5 MW
- G2 and G4: 30MW quick-start capability

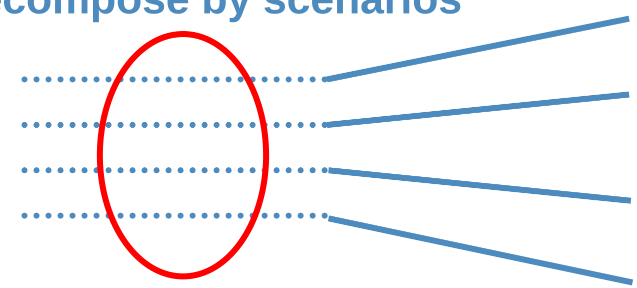
- **Three different models and solutions for quick-start units in post-contingency correction subproblems**
  1) **MIP-LP model**: *Relax integer variables in the second stage (approximation model). G2 and G4 (0~40MW)*
  2) **Two-stage MIP model:** *solve MIP in the second stage. Then fix integer variables in the second stage and form cuts from resulted LP.*
  3) **Two-stage MIP model:** *Extended Benders decomposition*
- **Results:**
  1) **Infeasible for contingency correction** 2) **Suboptimal** 3) **Global optimal**

Other two stage MIP in power grid simulation

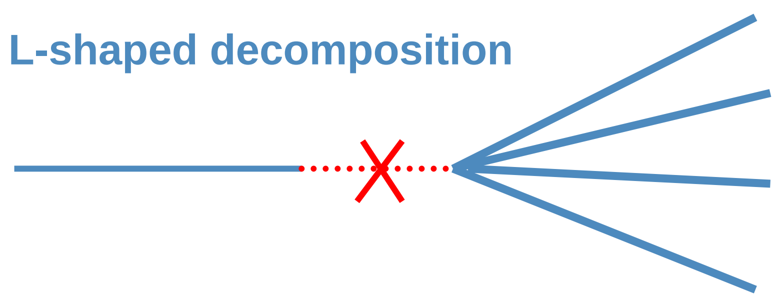
Problem	First Stage	Second Stage
UC with network constraints	UC	Transmission constraints
Contingency-based SCUC	UC with pre-contingency transmission constraints	Post- contingency transmission constraints
Two-stage stochastic SCUC	Decision costs and constraints	Recourse costs and constraints
Two stage distribution network expansion	Decision of building new distribution line	Reconfiguration

- **Dual decomposition and L-shaped (Benders) decomposition: pros and cons**

Decompose by scenarios



L-shaped decomposition

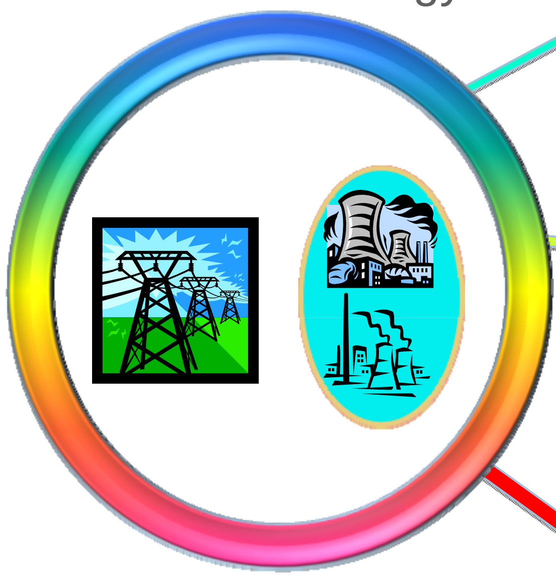


Outline

- I. Introduction and challenges of optimal power flow
- II. Three topics on optimal power flow
  - Optimal power flow with post-contingency correction
  - Optimal power flow with discrete control variables and two stage MIP
  - Optimal power flow considering other energy infrastructures
- III. Summary and future work

Optimal power flow with other energy infrastructures

- **Electricity infrastructure**
  - Smart grid
  - Renewable energy



- **Natural gas transmission system**
  - Texas: 70% electricity are generated by natural gas units
  - Coordination between peaking units and renewable energy
- **River and cascaded hydropower station**
  - Hydrothermal coordinated scheduling
- **Transportation**
  - PHEV, Vehicle to Grid
  - Coal, Oil transportation

Coupled energy flow

- **Steady-state integrated model have been proposed in the last decade**
- **Different energy flows travel via different speed through infrastructures**
  - Power flow: very small time constant
  - Water flow: large time constant
  - Natural gas flow: medium time constant
  - transportation flow: medium time constant
- **Use dynamic model instead of steady-state linear or nonlinear algebraic equations**
- **Potential application: security monitoring, reliability evaluation, planning**

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Summary and future work at Argonne

- **Three challenges of optimal power flow in power grid simulation are addressed.**

- **Contingency screening method is nested into unit commitment and optimal power flow with post-corrective action. Contingency analysis and optimal power flow study can be extended to a large-scale power system with parallel computing. Probability of outage cloud be included into contingency screening process.**

Summary and future work at Argonne

- Discrete variables will bring more difficulties in solving optimal power flow especially for two-stage MIP problems. Dual decomposition and L-shaped (Benders) decomposition techniques can be used to divide the original problem into several small-scale subproblems.

- Energy infrastructures are highly coupled, it is envisioned that using an integrated method to model optimal power flow and other energy flows together is necessary.

Reference

[1] Jianhui Wang, Mohammad Shahidehpour, and Zuyi Li, "Contingency- Constrained Reserve Requirements in Joint Energy and Ancillary Services Auction," *IEEE Transactions on Power Systems*, Vol.24, No.3, pp.1457-1468, Aug. 2009

[2] Cong Liu, Mohammad Shahidehpour, Yong Fu and Zuyi Li "Security-Constrained Unit Commitment with Natural Gas Transmission Constraints," *IEEE Transactions on Power Systems*, Vol. 24, No. 3, Aug. 2009.

[3] Lei Wu, Mohammad Shahidehpour, and Cong Liu "MIP-based Post-Contingency Corrective Action with Quick-Start Units," *IEEE Transactions on Power Systems*, Vol. 24, No. 4, Nov. 2009.

[4] Cong Liu, Mohammad Shahidehpour, and Lei Wu, "Extended Benders Decomposition for Two-Stage SCUC," *IEEE Transactions on Power Systems*, Vol. 25, No. 2, May. 2010.

Thank You for Attention!

Question?