Multi-Area Optimal Power Flow with Changeable Transmission Topology

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Outline

- I. Background
- II. Multi-area optimal power flow with changeable transmission topology
- III. Implement static switching security and N-k branch outage analysis on high performance computer
- V. Summary and future work

Introduction

- **Transmission switching: change and control transmission topology during operation**
- **Applications and Benefits**
  - **Alleviate congestion and correct contingencies**
  - **Save production cost through changing the network topology during operations**
- **Switching security**
  - **Static switching security at the moment of switching operation**
  - **Transient state analysis**
- **Computational issue**
  - **Mixed integer programming formulation with big-M constraints, disjunctive programming formulation or nonlinear programming**

Past Work

- **Optimal transmission switching and unit commitment**

O’Neill (2005), Dispatchable transmission in RTO markets, IEEE Trans. Power System.

Hedman (2010), Optimization of generation unit commitment and transmission switching with N-1 reliability, IEEE Trans. Power System.

Khodaei (2010), Transmission switching in security-constrained unit commitment, *IEEE Trans. Power System.*

- **Corrective switching**

Shao (2008), Corrective switching algorithm for relieving overloads and voltage violations, *IEEE Trans. Power System*.

Hedman (2011), Smart Flexible Just-in-Time Transmission and Flowgate Biding, *IEEE Trans. Power System.*

- **Static switching security**

Liu (2012), Static switching security in multi-period transmission switching, *IEEE Trans. Power System*.

Ostrowski , anti-islanding in transmission switching, under revision.

- **Prescreening switchable lines and sequential LP**

Fuller (2012), Fast heuristics for transmission-line switching, *IEEE Trans. Power System*.

Ruiz (2012), Tractable transmission control using sensitivity analysis, *IEEE Trans. Power System*.

Liu (2012), Heuristic prescreening switchable branches in optimal transmission switching, *IEEE Trans. Power System*, In press.

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Multi-area Optimal Power Flow with Changeable Transmission Topology

- **Motivation**
  - **Respect dispatching independence of each area in multi-area power systems. Limited information is exchanged among utilities or operating centers in different areas**
  - **Optimal power flow with transmission switching is intractable even for moderately-sized power systems**
  - **Perform computation in each region in parallel**
  - **Potential use for multi-area network expansion or maintenance coordination**

Multi-area Optimal Power Flow with Changeable Transmission Topology

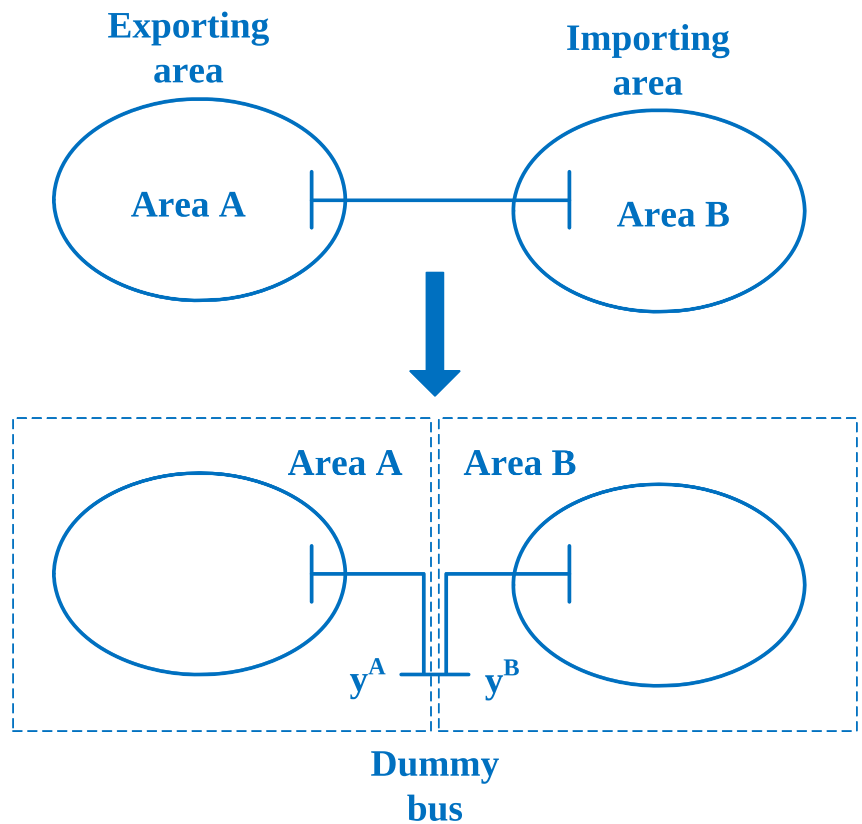
- **Original Problem**

$$Min\ \ f(x^A, y^A) + f(x^B, y^B)$$

$s.t.$

Constraints for area A
Constraints for area B
Coupling constraints $y^A = y^B$

x^A			
	x^B		
		$\ddots$	
			x^N
y^A	y^B	....	y^N



Lagrangian Relaxation

- **Area decomposition by Lagrangian relaxation**

Lagrangian Function

$$\mathcal{L}(\boldsymbol{x},\boldsymbol{y},\boldsymbol{\lambda}) = f(\boldsymbol{x}^A,\boldsymbol{y}^A) + f(\boldsymbol{x}^B,\boldsymbol{y}^B) + \boldsymbol{\lambda}^T(\boldsymbol{y}^A - \boldsymbol{y}^B)$$

dual Function

$$\phi(\boldsymbol{\lambda}) = \underset{\boldsymbol{x},\boldsymbol{y}\in S}{Min}\; f(\boldsymbol{x}^A,\boldsymbol{y}^A) + f(\boldsymbol{x}^B,\boldsymbol{y}^B) + \boldsymbol{\lambda}^T(\boldsymbol{y}^A - \boldsymbol{y}^B)$$

Dual problem

$$\underset{\boldsymbol{\lambda}}{Max}\;\underset{\boldsymbol{x},\boldsymbol{y}\in S}{Min}\; f(\boldsymbol{x}^A,\boldsymbol{y}^A) + f(\boldsymbol{x}^B,\boldsymbol{y}^B) + \boldsymbol{\lambda}^T(\boldsymbol{y}^A - \boldsymbol{y}^B)$$

For given $\boldsymbol{\lambda}$

Dual problem is decomposed

$$\underset{\boldsymbol{x}^A,\boldsymbol{y}^A\in S^A}{Min}\; f(\boldsymbol{x}^A,\boldsymbol{y}^A) + \boldsymbol{\lambda}^T\boldsymbol{y}^A$$

$$\underset{\boldsymbol{x}^B,\boldsymbol{y}^B\in S^B}{Min}\; f(\boldsymbol{x}^B,\boldsymbol{y}^B) - \boldsymbol{\lambda}^T\boldsymbol{y}^B$$

Updated Lagrangian multiplier

$$\boldsymbol{\lambda}^{(k+1)} = \boldsymbol{\lambda}^{(k)} + \eta^{(k)}\cdot(\boldsymbol{y}^A - \boldsymbol{y}^B)$$

Lower bound

$$\phi(\boldsymbol{\lambda}^{(k)}) \le \phi(\boldsymbol{\lambda}^{*}) \le f(\boldsymbol{x}^{A*},\boldsymbol{y}^{A*}) + f(\boldsymbol{x}^{B*},\boldsymbol{y}^{B*})$$

Augmented Lagrangian Relaxation

- **Augmented Lagrangian function**

Introduce quadratic penalty term

$$\mathcal{A}(\boldsymbol{x},\boldsymbol{y},\omega,\boldsymbol{\lambda}) = f(\boldsymbol{x}^A,\boldsymbol{y}^A) + f(\boldsymbol{x}^B,\boldsymbol{y}^B) + \boldsymbol{\lambda}^T(\boldsymbol{y}^A - \boldsymbol{y}^B) + \omega\left\|\boldsymbol{y}^A - \boldsymbol{y}^B\right\|^2$$

- **The augmented Lagrangian function cannot be decomposed as it contains an inseparable cross penalty term**

- **Augmented Lagrangian relaxation + Auxiliary problem principle**
- **Augmented Lagrangian relaxation + Block coordination decent**

Augmented Lagrangian Relaxation

- **Augmented Lagrangian relaxation + Auxiliary Problem Principle**
  - **Use the results in the last iteration**
  - **Update multipliers and penalty factors iteratively**

$$\min_{\boldsymbol{x}^A,\boldsymbol{y}^A} f(\boldsymbol{x}^A,\boldsymbol{y}^A)+\boldsymbol{\lambda}_k^T\boldsymbol{y}^A+\alpha(\boldsymbol{y}_k^A-\boldsymbol{y}_k^B)^T\boldsymbol{y}^A+\beta\left\|\boldsymbol{y}^A-\boldsymbol{y}_k^A\right\|^2$$

$$s.t.\ \text{constraints in area A}$$

$$\min_{\boldsymbol{x}^B,\boldsymbol{y}^B} f(\boldsymbol{x}^B,\boldsymbol{y}^B)-\boldsymbol{\lambda}_k^T\boldsymbol{y}^B+\alpha(\boldsymbol{y}_k^B-\boldsymbol{y}_k^A)^T\boldsymbol{y}^B+\beta\left\|\boldsymbol{y}^B-\boldsymbol{y}_k^B\right\|^2$$

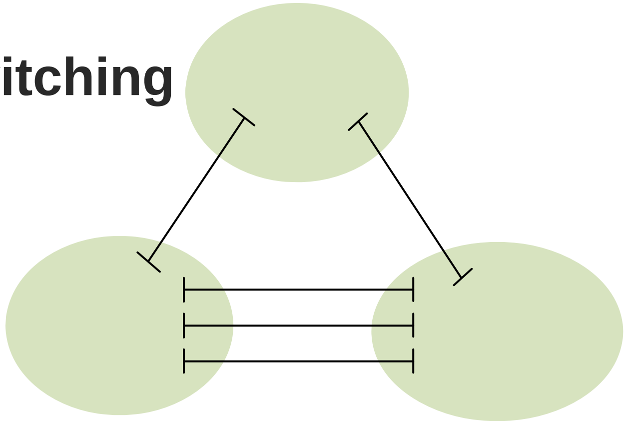
$$s.t.\ \text{constraints in area B}$$

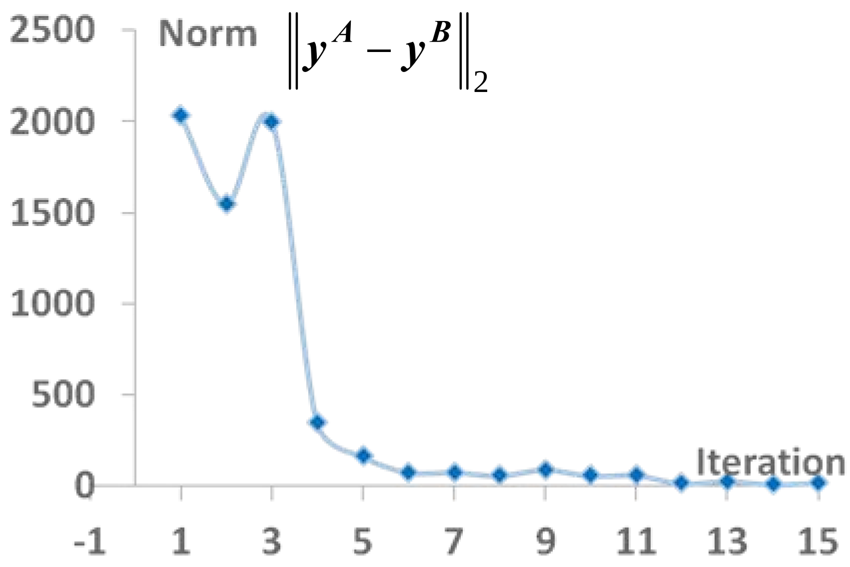
$$\boldsymbol{\lambda}_{k+1}=\boldsymbol{\lambda}_k+\gamma(\boldsymbol{y}_{k+1}^{\boldsymbol{A}}-\boldsymbol{y}_{k+1}^{\boldsymbol{B}})$$

- **The program stops if the norm is less than a given value**

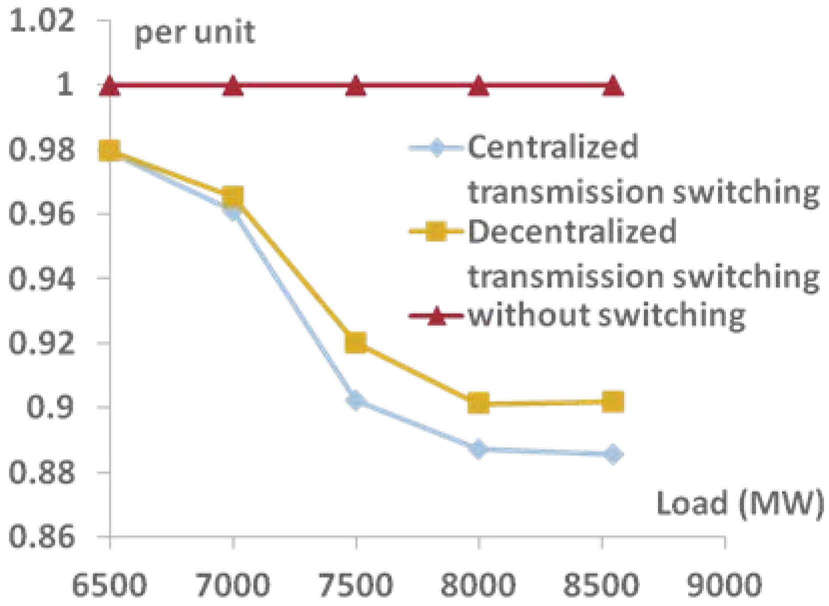
Preliminary Testing Results

- Modified RTS system for transmission switching
- 3 areas, 5 tie-lines
- 117 branches, 111 Units
- No anti-islanding constraints
- Load 6500MW - 8547MW





Norm of violation of constraints in dual solution



Production cost comparison

Preliminary Testing Results

- **Larger systems**
- **Solve the problem with centralized method to optimality**

Case			Decentralized method (ALR)				Centralized method
Areas	Buses	Branches	Load (MW)	Number of tie-lines	Wall-clock time (s)	Operating cost reduction	Operating cost reduction
6	146	236	16600	12	43	7.1%	7.3%
9	219	354	24900	18	79	6.2%	6.3%
12	292	472	33200	24	202	7.4%	7.6%

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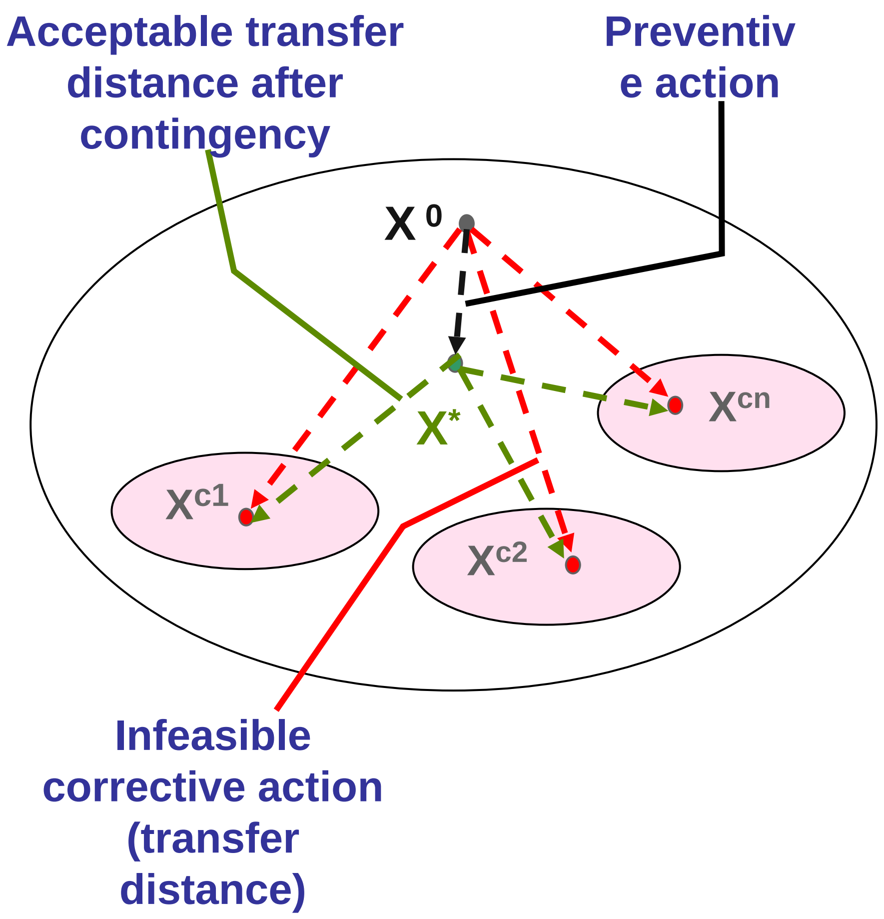
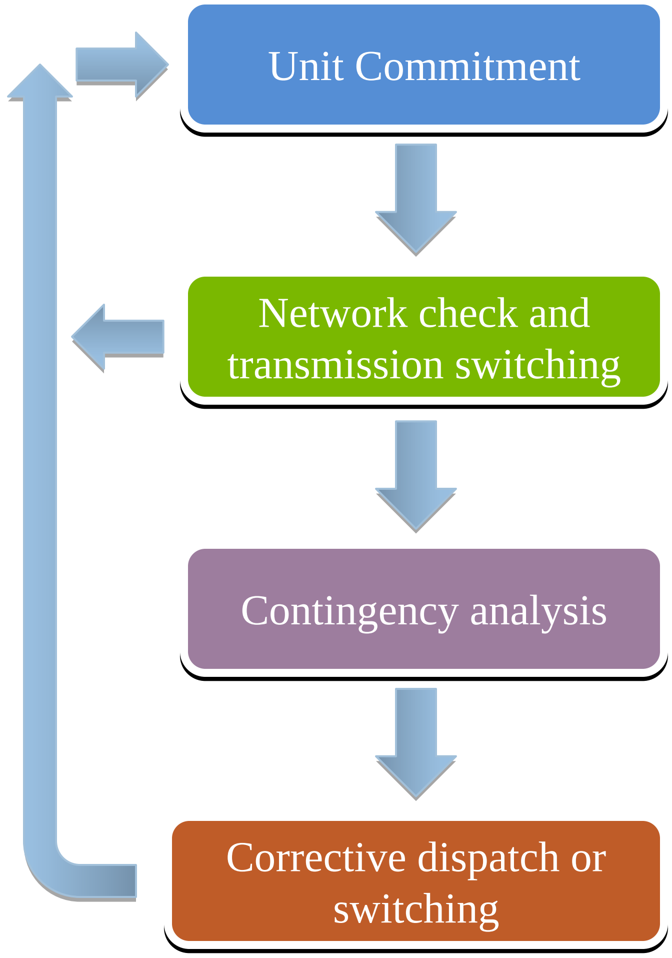
SCOPF with post-contingency correction

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

Expression	Description
$Min \; f(x)$	Objective
$S.t. \; A \cdot x \le b$	Unit commitment and economic dispatch constraints
$g(x, y) \le 0$	Network constraints in normal state
$g(x^c, y^c) \le 0$	Network constraints after each contingency
$\left| x - x^c \right| \le \Delta$	Transfer distance constraints

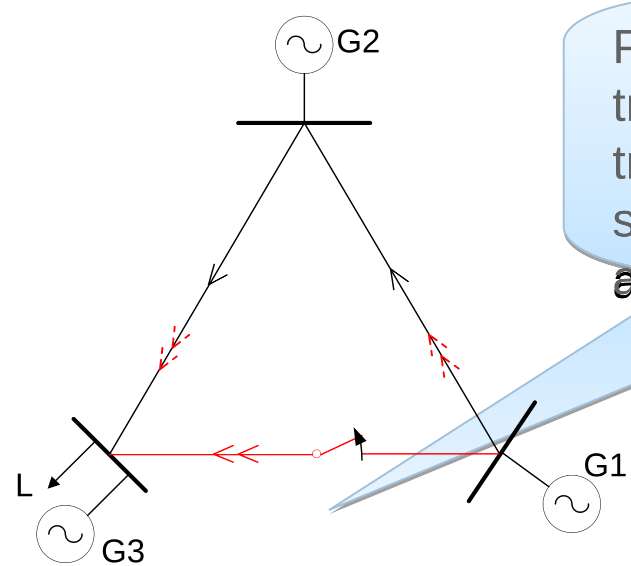
Corrective and preventive actions in power system operations





Static Switching Security of transmission switching

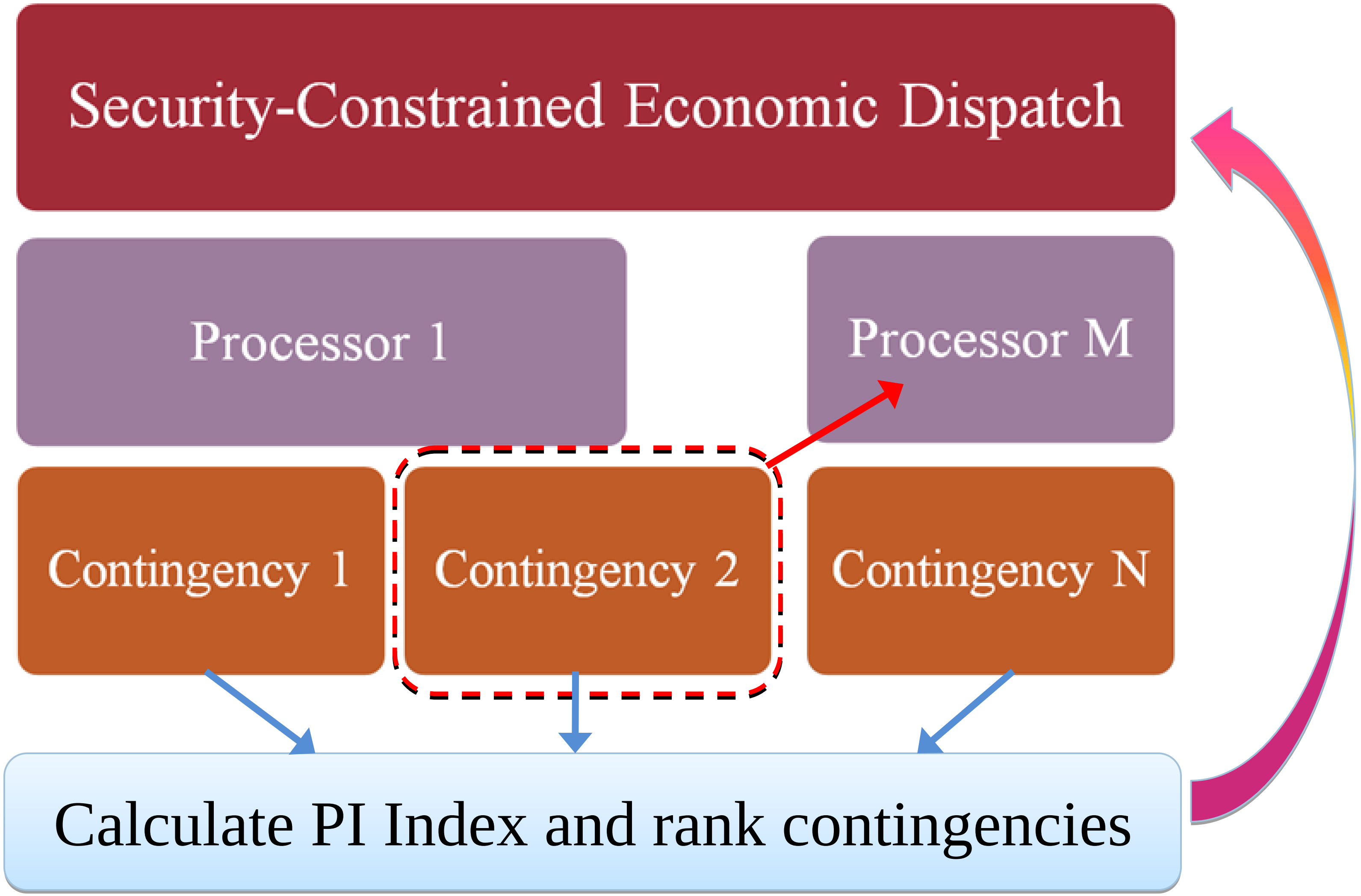
- **Electromagnetic transients process is very fast. The instant redistribution of power flow and voltage during switching operations may violate normal or emergency rates of transmission lines**



Power flow through the transmission line will be transferred into the other path simultaneously after the switching action

- **N-k line open or close operations**

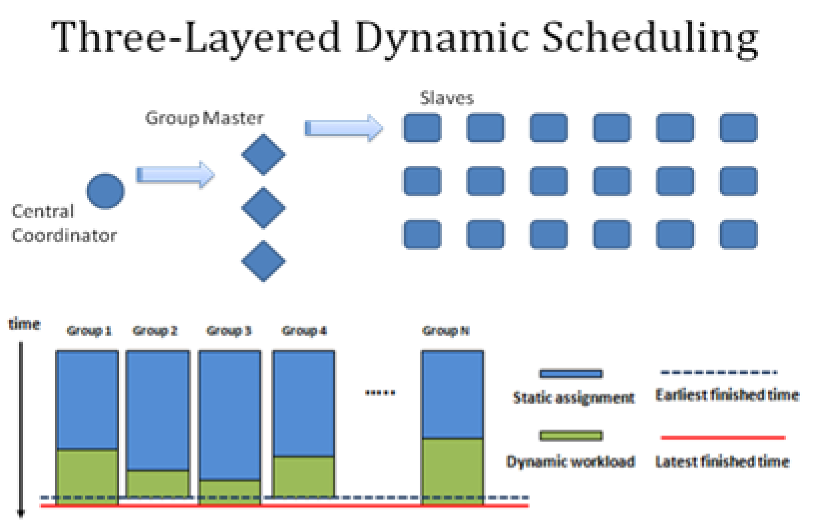
Parallelism for Contingency analysis



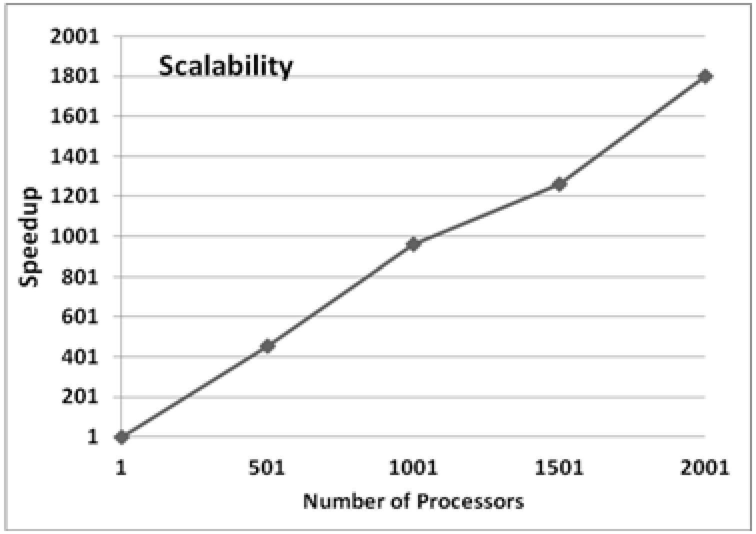
N-k Line Switching and Outage Analysis using HPC

- 1168 bus system
- All N-1 and N-2 cases
- AC power flow

Communication becomes a bottleneck for improving scalability



Working load balance



Scalability of N-k line outage analysis

- We have already tested a 14000-bus system. And we will report the results soon

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Summary and Future Work

- A multi-area optimal power flow with changeable topology is used for coordinating the decision making in each area
- Implement larger case study
- Decentralized scheduling of planning and maintenance in multi-area optimization framework
- Continue implementing contingency analysis on high performance computer
- Link contingency analysis with the parallel implementation of optimal power flow

Thank you! Questions?