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A Marginal Equivalent Algorithm and its Application in Coordinated Multi-Area Dispatch

"Increasing Market and Planning Efficiency through Improved Software"

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Area Coordination

- A large regional power system is often composed of interconnected areas, each operated by a System Operator (SO)
  - An SO has the most accurate information of its own area, but may not have other areas' accurate information
  - Individual area dispatches may *not* achieve the economic efficiency of the *overall* regional system
- The **goal** is to achieve regional economic efficiency through the coordination between area dispatches

Potential Benefits of Coordination

- An area's **reliability problems** may be solved with the assistance of other areas
- An area's **expensive generation** may be replaced by less expensive imports from other areas
- An area's **transmission congestion** may be relieved by the dispatch of other areas' resources

Challenges

- Real-time applications enforce strict time limits for obtaining high-quality solutions
- The **information policy** of each area needs to be respected
- The amount of **information exchange** between areas should be reasonable

Existing Solution Methods

- The problem is mathematically equivalent to the **decomposition** of a *multi-area Optimal Power Flow* (OPF)
- Some existing decomposition **frameworks/algorithms**
  - Lagrange Relaxation
  - Benders Decomposition
  - Parametric Optimization
  - Coordinated Regional Dispatch [1]

1. R. Baldick and D. Chatterjee, Final Phase I Report on Coordinated Regional Dispatch Framework, Jul. 2010. [Online]. Available: http://www.midwestiso.org

Weaknesses of Existing Methods

- Slow convergence
- Need for parameter-tuning
- Involve relaxation of constraints with multipliers
  - Require heuristics to construct a feasible solution in the end
- Rely on specific problem structures

Proposed Algorithm: Marginal Equivalent

- *Assumption*: Dispatch problems are **linear**
- *Key Idea*: Share the information of **marginal units** and **binding constraints** among the areas, and use this information to update each area's dispatch solution
- Such information fully characterizes the **marginal costs** of a dispatch problem, making it an equivalent representation of the area dispatch problem ("**Marginal Equivalent**") at the current interval

The Regional Dispatch Problem

$$\min_{X} \; C^T \cdot X$$

$$\text{S.t.} \quad A \cdot X \le B,$$

$$\underline{X} \le X \le \overline{X}$$

X: vector of dispatch decisions

$\underline{X}, \overline{X}$: vectors of lower and upper bounds

C: vector of cost coefficients

A: shift factors coefficient matrix

B: vector of constraint limits

N: number of areas

$$X = \begin{bmatrix} X_1 \\ \vdots \\ X_i \\ \vdots \\ X_N \end{bmatrix}, \quad C = \begin{bmatrix} C_1 \\ \vdots \\ C_i \\ \vdots \\ C_N \end{bmatrix}, \quad B = \begin{bmatrix} B_1 \\ \vdots \\ B_i \\ \vdots \\ B_N \end{bmatrix}, \quad A = \begin{bmatrix} A_{11} & \cdots & A_{1j} & \cdots & A_{1N} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ A_{i1} & \cdots & A_{ij} & \cdots & A_{iN} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ A_{N1} & \cdots & A_{Nj} & \cdots & A_{NN} \end{bmatrix}$$

Area-i dispatch variables

Area-i cost coeff.

Area-i limits

Shift factors of Area-*i* constraints w.r.t. Area-*j* variables

Area-i's Dispatch Subproblem

$$\min_{X_i,\{X_{j_m}\}_j} \; C_i^T \cdot X_i + \sum_{j \neq i} C_{j_m}^T \cdot \underline{X_{j_m}},$$

Marginal units of Area-j

$$X_j = \begin{bmatrix} X_{j_m} \\ X_{j_{nm}} \end{bmatrix} \begin{matrix} \text{- Marginal} \\ \text{- Nonmarginal} \end{matrix}$$

s.t.

$$A_{i,i} \cdot X_i + \sum_{j \neq i} \left(A_{i,j_m} \cdot X_{j_m} + \underline{A_{i,j_{nm}} \cdot X_{j_{nm}}^*} \right) \leq B_i,$$

$$A_i = \begin{bmatrix} A_{i,i} & A_{i,j_m} & A_{i,j_{nm}} & \cdots \end{bmatrix}$$

Flow contribution of Area-j's non-marginal units to Area-i constraints

$$\underline{A_{j_b,i} \cdot X_i + \sum_{k \neq i} \left(A_{j_b,k_m} \cdot X_{k_m} + A_{j_b,k_{nm}} \cdot X_{k_{nm}}^* \right) \leq B_{j_b}, \; \forall j \neq i,}$$

Binding constraints of Area-j

$$\underline{X_i} \leq X_i \leq \overline{X_i},$$

$$A_j = \begin{bmatrix} A_{j_b,i} & A_{j_b,k_m} & A_{j_b,k_{nm}} & \cdots \\ \cdots & \cdots & \cdots & \cdots \end{bmatrix}$$

$$\underline{X_{j_m}} \leq X_{j_m} \leq \overline{X_{j_m}}, \; \forall j \neq i.$$

Marginal Unit Definition

- In the previous formulation, "marginal unit" is defined as a unit whose dispatch output is not at the boundary
- For Area-*i* subproblem solution

$$X_i^* = \begin{bmatrix} X_{i_m}^* \\ X_{i_{nm}}^* \end{bmatrix}$$

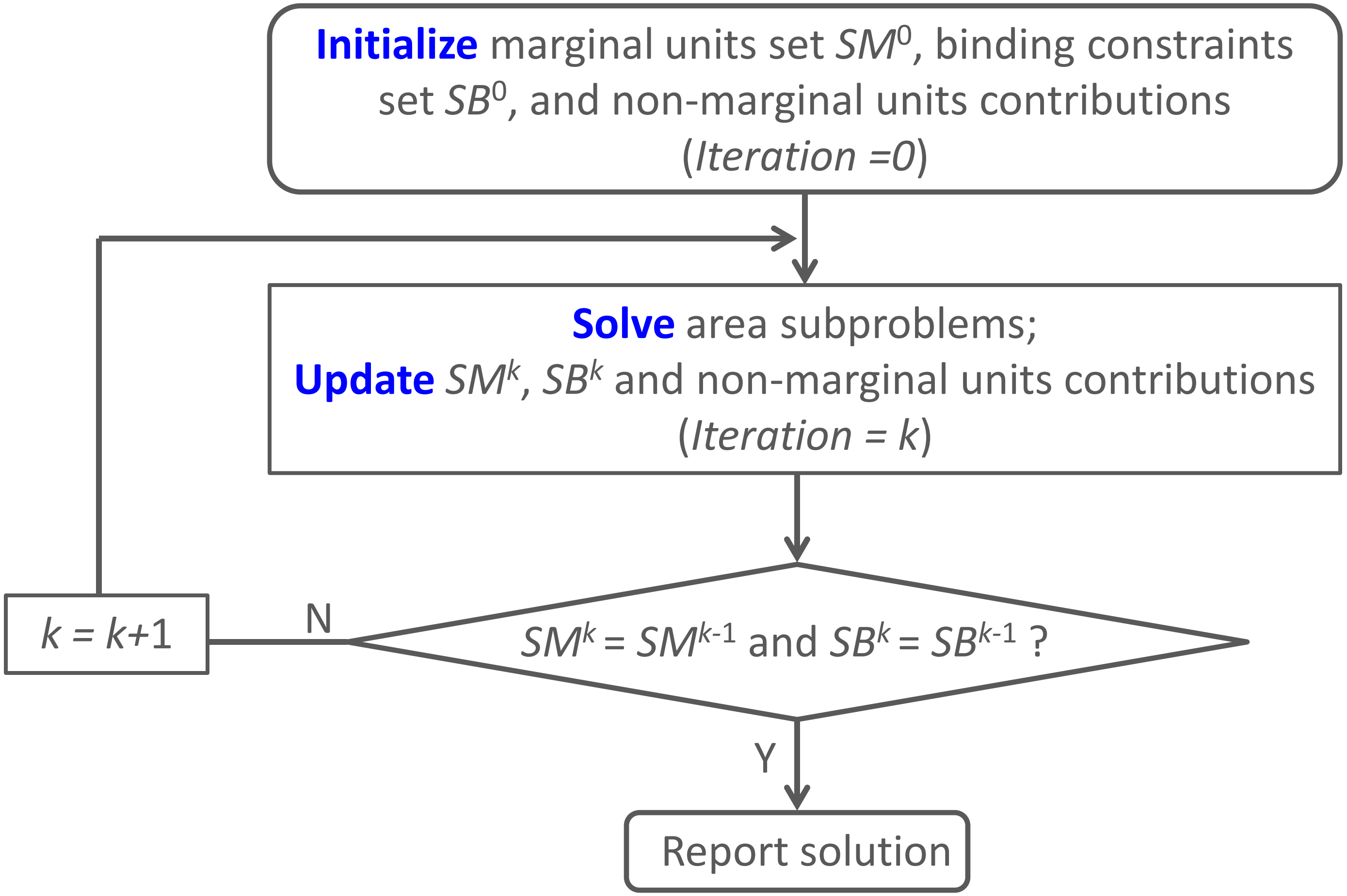
we have

$$\underline{X_{i_m}} < X_{i_m}^* < \overline{X_{i_m}},$$ - **Marginal**

$$X_{i_{nm}}^* = \underline{X_{i_{nm}}} \ or \ \overline{X_{i_{nm}}}$$ - *Non marginal*

- With reserve constraints, marginal units need to be redefined

Marginal Equivalent Algorithm



Information Exchange

Category	Description
Marginal units	Set of marginal units, and their locations, prices and sizes
Binding constraints	Set of binding constraints, and their coefficients and limits
Non-marginal units contributions	Flow contributions of non-marginal units to balance and binding constraints

Convergence

- The algorithm **converges in a finite number of iterations**
  - After a finite number of iterations, the solutions become always **feasible**;
  - After another finite number of iterations, an **optimal** solution will be reached
- Sketch of the proof [1]

  Step 1: Each area subproblem's solution corresponds to a "**basic solution**" of the regional problem

  Step 2: When all subproblems yield the same sets of marginal units and binding constraints (Stopping Criterion), the subproblem solution is **optimal** for the regional problem

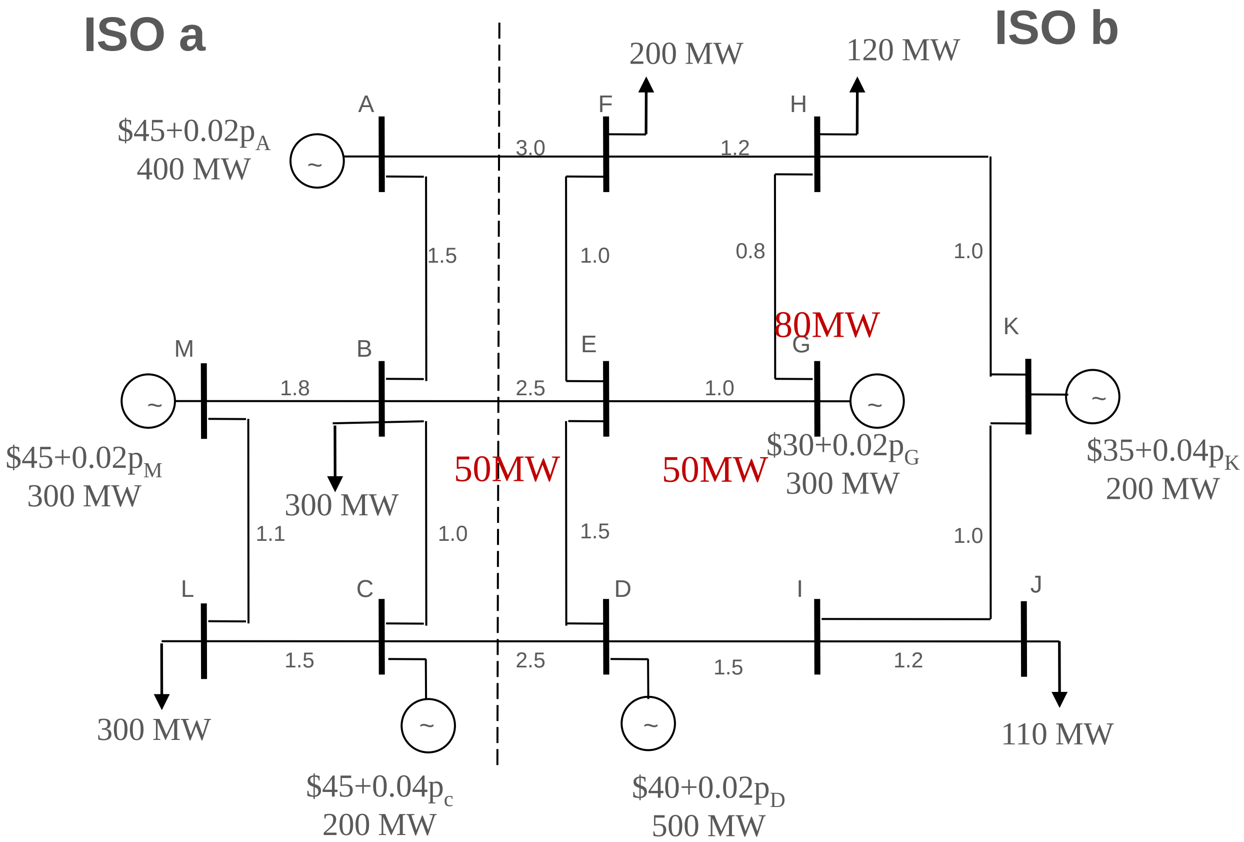
  Step 3: The stopping criterion is reached in a **finite** number of iterations
- The algorithm 'pivots' among basic solutions

[1] See details in F. Zhao, E. Litvinov and T. Zheng, "A Marginal Equivalent Decomposition Method and Its Application to Multi-Area Optimal Power Flow Problems," *IEEE Trans. Power Syst., vol. 29, no. 1, pp.* 53–61, Jan. 2014.

Comparison To Other Methods

- *Pros*:
  - No parameter-tuning
  - No dualization of constraints
  - Fast convergence (based on testing results)
  - No requirement for specific problem structure
- *Cons*:
  - More information exchanged than some methods such as LR

Example 1: 13-bus System[1]



1. R. Baldick and D. Chatterjee, Final Phase I Report on Coordinated Regional Dispatch Framework, Jul. 2010. [Online]. Available: http://www.midwestiso.org

Comparison of Different Methods

Method	N of Iter.	Total Cost ($)	Interchange (MW)	CPU Time ++ (s)
JOD*	-	**4.4019**	**-80.89**	-
LR [a]	44	4.4030	-75.93	51.02
NPC [b]	32	4.4028	-79.93	22.86
CRD [c]	50 +	4.4139	-41.95	26.62
ME**	5	4.4021	-80.21	2.39

* Joint Optimal Dispatch (JOD) for the two areas

** Generator's offer curve is approximated by 20 equal-size blocks

\+ Max iteration number since solution oscillation is observed

++ Implemented in MATLAB using CVX, on PC with Pentium Dual Core 2.80GHz CPU, 3GB RAM

Reference:
[a] B. H. Kim and R. Baldick, "Coarse-Grained distributed optimal power flow," *IEEE Trans. Power Syst.*, vol. 12, pp. 932–939, May 1997.
[b] F. J. Nogales, F. J. Prieto and A. J. Conejo, "A decomposition methodology applied to the multi-area optimal power flow problem," *Annals of Operations Research*, Vol. 120, pp. 99-116, 2003
[c] R. Baldick and D. Chatterjee, "Final Phase I Report on Coordinated Regional Dispatch Framework," July 2010, [Online] www.midwestiso.org

Example 2: NE-NY System

- Description:
  - 402 NE units, 260 NE loads, 582 NY units, and 1026 NY loads
  - Loads are inelastic, with 14,481MW for NE and 19,233MW for NY
  - Generation offers have up to 10 blocks
  - 10 network constraints, 3 in NY and 7 in NE, are activated
  - Sensitivities of the 10 constraints are calculated using off-line network analysis software
  - The ME algorithm was tested under the static and changing system conditions
  - The initialization sets zero interchange between the two areas and empty sets for marginal units and binding constraints.
  - Implemented in GAMS using CPLEX 12.1.0 as the linear solver, and run on a PC with Intel i7 CPU @2.93GHz, 4GB RAM

Convergence Path For Static System

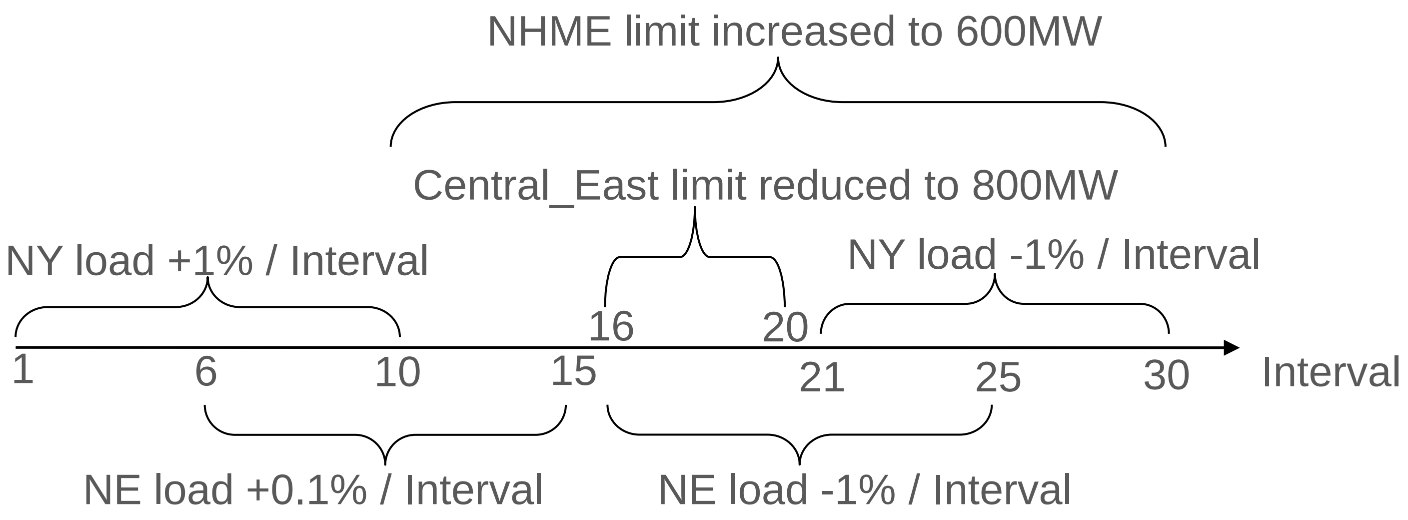
Iter.	Total Cost ($)	Interchange (MW) NE → NY	Marginal Units ID*	Binding Constr.
1	1,561,504	-2	20610_1	(None)
2	1,545,682	-51	2304, 20378_1	NHME
3	1,537,673	-98	195, 20335_1	NHME
4	1,535,189	-130	2304, 20323_1	NHME
5	1,532,955	-167	2304, 20360_1	NHME
6	1,531,535	-213	2304, 20600_1	NHME
7	1,530,622	-254	2304, 20545_5	NHME
8	1,529,737	-313	2043, 20597_2	NHME
9	1,529,519	-351	2043, 20100_1	NHME
10	1,529,519	-351	**1762, 20100_1**	**NHME**
11	**1,529,519**	**-351**	**1762, 20100_1**	**NHME**

* Masked Unit IDs with "_" indicate NY units

Converged!

Changing System Condition

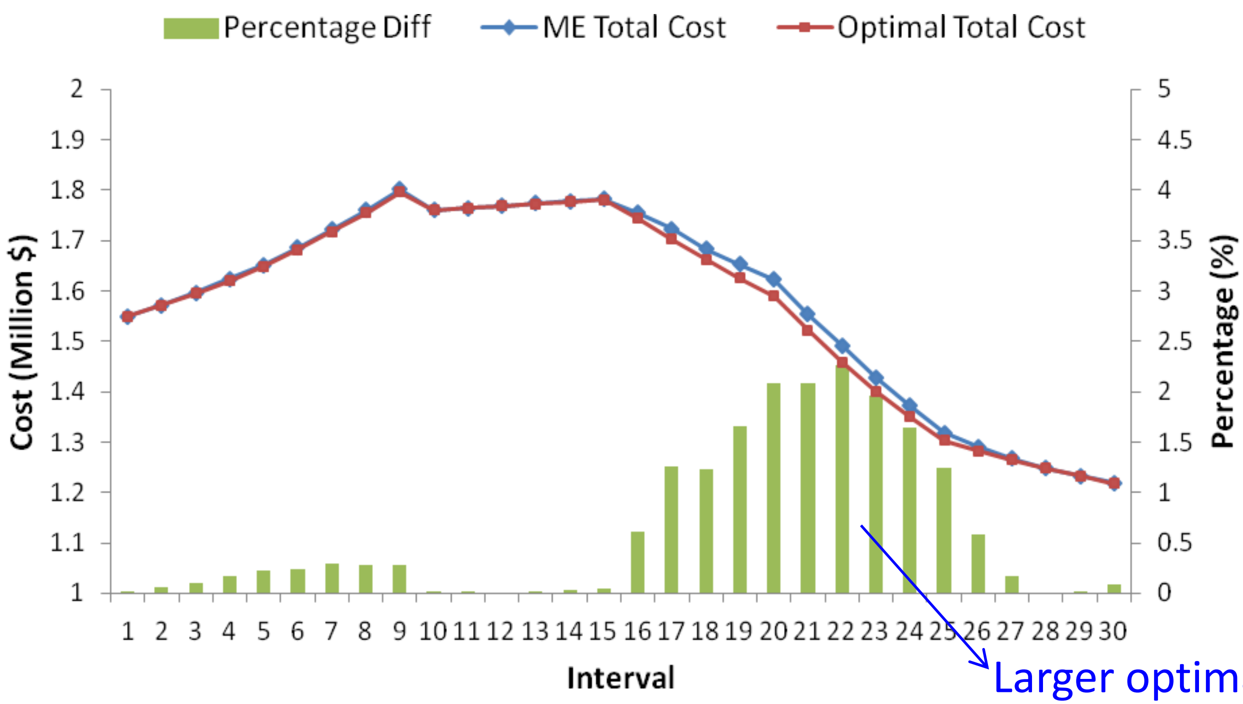
- The ME method is implemented in the non-iterative fashion under varying system conditions for 30 intervals as illustrated below to test the robustness of the algorithm



  - Each interval uses the previous interval solution as initial point, and runs the ME algorithm for one iteration
  - Testing results show that feasible solutions are obtained for each interval

Performance Under Changing System Condition

- Use the joint optimal dispatch cost of two areas for each interval as the benchmark (Percentage difference indicates optimality gap of the ME method)



Larger optimality gap corresponds to larger system condition change

Conclusion

- A Marginal Equivalent (ME) algorithm that uses **the marginal cost information** of local areas is developed for the coordination of multi-area dispatch
- The algorithm is **proven to converge** to the optimal solution in a finite number of iterations
- The algorithm requires **no parameter-tuning**, constraint relaxation or special problem structure
- Testing results demonstrate the effectiveness and robustness of the algorithm, allowing its **practical implementation**

Extension of The Research

Ext-1. How to define "marginal unit" under the energy-reserve co-optimization or the multi-interval dispatch?

– A **Generalized Marginal Unit Concept** has been developed

Ext-2. How to efficiently solve large-scale general linear problems without special structure?

– **Parallel solution** of the ME subproblems (being tested)

Questions