

# MULTI-AREA COORDINATED DECENTRALIZED DC OPTIMAL POWER FLOW

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**Abstract** - This paper provides a framework to carry out a multi-area optimal power flow in a coordinated decentralized fashion. A DC nonlinear optimal power flow model is used. Losses are incorporated through additional loads based on cosine approximations. The model makes it possible the independent optimal dispatch of each area while the global economical optimum of the whole electric energy system is achieved. This is possible by means of the Lagrangian Relaxation decomposition procedure. Optimal energy pricing rates for the energy traded through the interconnections are derived. The developed algorithm can be run in parallel either to carry out numerical simulations or in an actual multi-area electric energy system.

**Keywords:** DC-OPF, Decentralization, Energy transaction optimal pricing, Lagrangian relaxation.

## 1 Introduction

This paper provides a framework to carry out a multi-area optimal power flow (OPF) in an electric energy system. This is accomplished in a coordinated but decentralized fashion.

A DC nonlinear OPF model is used [1]. Losses are incorporated through additional loads based on cosine approximations. This approach has proven to be accurate enough for the purpose of cost and price calculations.

The model makes it possible the independent optimal dispatch of each area while the global optimum of the whole system is achieved. This is particularly relevant in a multi-

utility or multi-country setting. In order to achieve an economical optimal dispatch of the whole electric energy system it is not necessary to set up a common control center, it is sufficient to interchange a small amount of information among the involved utilities or countries.

Optimal energy pricing rates for the energy traded through the interconnections are derived.

As an example, the developed algorithm can be applied to the independent but coordinated operation of the Central American countries integrated in the SIEPAC project [2].

The decomposition is not oriented to improve computational efficiency but to preserve dispatching independence of each area in a multi-area electric energy system.

The above algorithm is based on the Lagrangian Relaxation (LR) decomposition procedure [3]. Although the LR decomposition procedure has been extensively used to address the unit commitment problem [4, 5, 6, 7] no reference has been found that applies the LR decomposition procedure to the multi-area OPF problem.

Recent relevant work on unit commitment and economic dispatch includes [8, 9, 10]. Wang and Shahidehpour proposed a multi-area short-term hydro-thermal coordination based on LR [8]. Lee et al. proposed a multi-area unit commitment based on heuristics derived from microeconomics principles [9]. El-Kaib et al. proposed an environmentally constrained economic dispatch solved through LR [10]. Kim and Baldick used an Augmented Lagrangian approach to solve a distributed OPF problem [11]. However, none of these works uses a decentralized multi-area approach based on LR to address the DC-OPF problem.

The developed algorithm can be run in parallel either to carry out numerical experiments or in an actual multi-area (multi-utility) electric energy system.

This paper is organized as follows. Section 2 gives the notation used throughout the paper. Section 3 formulates the multi-area dispatching problem. Section 4 describes the subproblems and the coordinating procedure (multiplier updating). Section 5 is a case study. Section 6 provides conclusions.

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## 2 Notation

The notation used is stated below.

### Variables:

$\delta_i$  angle of bus  $i$ ,  
 $p_i$  power produced by generator  $i$ .

### Multipliers:

$\alpha_{ij}$  multiplier associated to the power balance equation of the fictitious bus of line  $ij$  (one fictitious bus case),  
 $\beta_{ij}$  multiplier associated to the power balance equation of one of the two fictitious buses of line  $ij$  (two fictitious buses case),  
 $\gamma_{ij}$  multiplier associated to the power balance equation of the other one of the two fictitious buses of line  $ij$  (two fictitious buses case),  
 $\theta$  generic multiplier vector.

### Functions:

$f_i(\cdot)$  operating cost of generator  $i$ ,  
 $h_{ij}(\cdot)$  power mismatch at the fictitious bus of interconnecting line  $ij$  (one fictitious bus case),  
 $g_{ij}(\cdot)$  power mismatch at one of the fictitious buses of interconnecting line  $ij$  (two fictitious buses case),  
 $l_{ij}(\cdot)$  power mismatch at the other one of the fictitious buses of interconnecting line  $ij$  (two fictitious buses case).

### Constants:

$D_i$  demand in bus  $i$ ,  
 $R_{ik}$  resistance of line  $ik$ ,  
 $B_{ik}$  the inverse of the reactance of line  $ik$ ,  
 $L_{ik}$  loss coefficient of line  $ik$ ,  
 $\bar{P}_{ij}$  maximum transmission capacity of line  $ij$ ,  
 $\bar{P}_i$  maximum output power of generator  $i$ ,  
 $\underline{P}_i$  minimum output power of generator  $i$ .

### Sets:

$\Lambda_a$  set of generators of area  $a$ ,  
 $\Theta_a$  set of buses of area  $a$ ,  
 $\Omega_i$  set of buses connected to bus  $i$ ,  
 $\Xi_a$  set of interconnecting lines of area  $a$ .

### Operators:

$\cup_a$  set union over sets with subindex  $a$ ,

## 3 Problem Formulation

In this section the multi-area optimal power flow is formulated. Then, fictitious buses are incorporated in this formulation to preserve dispatch independence of each area while allowing area decomposition.

The OPF for the whole electric energy system can be formulated as:

$$\begin{aligned} & \text{Minimize } \sum_{i \in \{\cup_a \Lambda_a\}} f_i(p_i) \\ & \text{subject to} \\ & p_i - D_i + \sum_{k \in \Omega_i} [B_{ik}(\delta_k - \delta_i) \\ & \quad - L_{ik}(1 - \cos(\delta_k - \delta_i))] = 0 \quad \forall i \in \{\cup_a \Theta_a\}, \quad (1) \\ & -\bar{P}_{ij} \leq B_{ij}(\delta_i - \delta_j) \leq \bar{P}_{ij} \\ & \quad \forall i \in \{\cup_a \Theta_a\}, \forall j \in \{\cup_a \Theta_a\}, i \neq j, \\ & \underline{P}_i \leq p_i \leq \bar{P}_i \quad \forall i \in \{\cup_a \Lambda_a\}. \end{aligned}$$

The loss coefficient of line  $ij$  is

$$L_{ij} = \frac{R_{ij}}{R_{ij}^2 + (1/B_{ij})^2}. \quad (2)$$

The objective function is the addition of generator operating costs. The first block of constraints enforces power balance in every bus, the second block enforces transmission capacity limits for every line, and the third block states bounds on power output for every generator.

In order to make the above dispatching problem separable per area either one fictitious bus or two fictitious buses are included per interconnecting line. This is shown in figures 1 and 2.

The purpose of the fictitious buses is to preserve the integrity of the particular dispatching problem of every area while allowing area decomposition.

The one fictitious bus approach allows a simple yet elegant economic interpretation of the Lagrange multipliers. They are interpreted as optimal energy trading prices at interconnecting lines [12]. However, this approach requires a sequential solution of the area subproblems. The variables associated to the fictitious bus per interconnection sequentially concatenates the area subproblems.

The two fictitious bus approach allows a fully independent solution of every area subproblem. This result in a parallel algorithm which can be easily implemented in an actual multi-area electric energy system.

It should be noted that the above two decomposition approaches render identical solution, which is also identical to the solution obtained using a centralized approach.

### 3.1 One fictitious bus

If one fictitious bus  $x$  is included per line interconnecting areas, the equations below should be included in original problem (1).

$$h_{ij} = 2B_{ij}(\delta_i - \delta_x) + 2B_{ij}(\delta_j - \delta_x) = 0 \quad : \alpha_{ij} \quad (3) \\ \forall ij \in \{\cup_a \Xi_a\}.$$

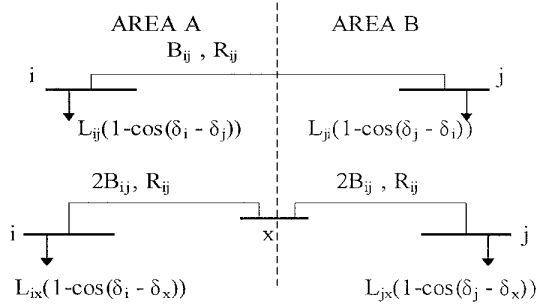


Figure 1: One fictitious bus per interconnecting line.

The above equation enforces power balance in the fictitious bus of every interconnecting line. It should be noted that loads representing losses are allocated to the non-fictitious buses of the interconnecting line  $ij$ . This preserves the linearity of equation (3) and makes it possible the decomposition.

### 3.2 Two fictitious buses

If two fictitious buses  $y$  and  $z$  are included per line interconnecting areas, the equations below should be included in original problem (1).

$$\begin{aligned} g_{ij} &= 3B_{ij}(\delta_i - \delta_y) + 3B_{ij}(\delta_z - \delta_y) = 0 \quad : \beta_{ij} \\ &\quad \forall ij \in \{\cup_a \Xi_a\}, \\ l_{ij} &= 3B_{ij}(\delta_j - \delta_z) + 3B_{ij}(\delta_y - \delta_z) = 0 \quad : \gamma_{ij} \\ &\quad \forall ij \in \{\cup_a \Xi_a\}. \end{aligned} \quad (4)$$

The above equations enforce power balance in the two fictitious buses of every interconnecting line. It should be noted that loads representing losses are allocated to the non-fictitious buses of the interconnecting line  $ij$ .

## 4 Solution Approach

The proposed solution algorithm is based on the LR decomposition procedure [3].

The original (primal) problem (1) has the form:

$$\begin{aligned} &\text{Minimize}_x \quad f(x) \\ &\text{subject to} \quad h(x) = 0 \\ &\quad \quad \quad g_1(x) = 0 \\ &\quad \quad \quad g_2(x) \leq 0, \end{aligned} \quad (5)$$

where  $h(x) = 0$  are complicating constraints.

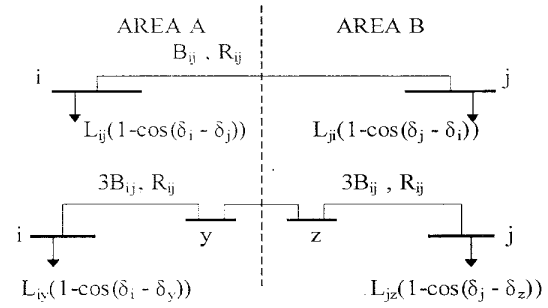


Figure 2: Two fictitious buses per interconnecting line.

The Lagrangian is

$$\mathcal{L}(\theta, x) = f(x) + \theta^T h(x). \quad (6)$$

The dual function is obtained from the Lagrangian as

$$\begin{aligned} \phi(\theta) &= \text{Minimize}_x \quad \mathcal{L}(\theta, x) \\ &\quad \text{subject to} \quad g_1(x) = 0 \\ &\quad \quad \quad g_2(x) \leq 0, \end{aligned} \quad (7)$$

and then the dual problem is

$$\text{Maximize}_\theta \quad \phi(\theta). \quad (8)$$

Under convexity assumptions, it can be shown that the optimal solution for the primal problem is equal to the optimal solution for the dual problem [3], i.e.

$$f(x^*) = \phi(\theta^*), \quad (9)$$

where  $x^*$  is the minimizer for the primal problem and  $\theta^*$  the maximizer for the dual problem.

Based on what is stated above, the LR solution algorithm works as follows:

1. Set initial values for the multiplier vector  $\theta$ .
2. Solve problem (7) for a fixed value of multiplier vector  $\theta$  (this is equivalent to evaluate the dual function).
3. Update multiplier vector  $\theta$  as stated in Subsection 4.3. The updating objective is to increase the dual objective function.
4. Check for convergence: if the dual objective function and the multiplier vector  $\theta$  do not change significantly in 2 consecutive iterations, stop; otherwise go to 2.

The above mechanism is applied to the multi-area OPF problem in what follows.

The complicating constraints are the coupling constraints among areas (either equations (3) or equations (4)). They are incorporated into the objective function through Lagrange multipliers (equation (6)). The resulting problem decomposes by area preserving therefore the dispatching independence of each area (problem (7)).

A mechanism is required to update the Lagrange multipliers so that the dual problem of problem (1) is maximized. This is further developed in Subsection 4.3.

Due to the fact that original problem (1) is "almost" convex the procedure described above achieves the actual optimum of problem (1). Extensive numerical analysis supports this last statement.

Potential nonconvexities arise from the modeling of losses using additional loads based on cosine approximations.

In what follows the problem to be solved by a generic area  $a$  is formulated, and the mechanism to update multipliers is described.

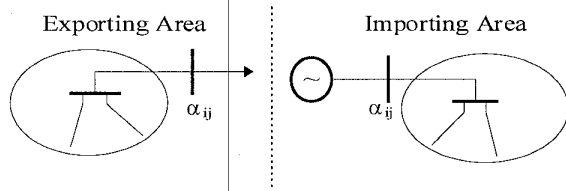


Figure 3: Importing and exporting areas.

#### 4.1 Area problem for one fictitious bus

The independent problem of area  $a$  for the case of one fictitious bus per interconnecting area has the form:

$$\begin{aligned} & \text{Minimize } \sum_{i \in \{\Lambda_a\}} f_i(p_i) + \\ & \quad \sum_{ij \in \Xi_a} \alpha_{ij} (2B_{ij})(\delta_i - \delta_x) \\ & \text{subject to} \\ & p_i - D_i + \sum_{k \in \Omega_i} [B_{ik}(\delta_k - \delta_i) \\ & \quad - L_{ik}(1 - \cos(\delta_k - \delta_i))] = 0 \quad \forall i \in \{\Theta_a\}, \\ & -\bar{P}_{ij} \leq B_{ij}(\delta_i - \delta_j) \leq \bar{P}_{ij} \\ & \quad \forall i \in \{\Theta_a\}, \forall j \in \{\Theta_a\}, i \neq j, \\ & \underline{P}_i \leq p_i \leq \bar{P}_i \quad \forall i \in \{\Lambda_a\}. \end{aligned} \quad (10)$$

It should be noted that  $\alpha_{ij}$  can be interpreted as the buying / selling price of energy at the fictitious bus of interconnecting line  $ij$ . Therefore, the multiplier  $\alpha_{ij}$  is the optimal energy pricing rate for the energy traded through line  $ij$  once the decomposition procedure has converged. Figure 3 illustrates the economic interpretation of multiplier  $\alpha_{ij}$ .

It should also be noted that a sequential solution of area subproblems is required. That is, the solution of the subproblem of area 2 has to be carried out after solving the subproblem of area 1, the subproblem of area 3 has to be solved after solving the subproblem of area 2 and so on. This is a consequence of considering just one fictitious bus per interconnecting line because the variables associated to the fictitious bus sequentially concatenate the area subproblems.

#### 4.2 Area problem for two fictitious buses

The independent problem of area  $a$  for the case of two fictitious buses per interconnecting line has the form:

$$\begin{aligned} & \text{Minimize } \sum_{i \in \{\Lambda_a\}} f_i(p_i) + \\ & \quad \sum_{ij \in \Xi_a} \beta_{ij} (3B_{ij}) \left( \delta_i - \frac{2\beta_{ij} - \gamma_{ij}}{\beta_{ij}} \delta_x \right) \\ & \text{subject to} \\ & p_i - D_i + \sum_{k \in \Omega_i} [B_{ik}(\delta_k - \delta_i) \\ & \quad - L_{ik}(1 - \cos(\delta_k - \delta_i))] = 0 \quad \forall i \in \{\Theta_a\}, \\ & -\bar{P}_{ij} \leq B_{ij}(\delta_i - \delta_j) \leq \bar{P}_{ij} \\ & \quad \forall i \in \{\Theta_a\}, \forall j \in \{\Theta_a\}, i \neq j, \\ & \underline{P}_i \leq p_i \leq \bar{P}_i \quad \forall i \in \{\Lambda_a\}. \end{aligned} \quad (11)$$

It should be noted that area subproblems can be solved in parallel. That is, every area subproblem is solved independently. This is a consequence of considering two fictitious buses per interconnecting line which fully decouples area subproblems.

#### 4.3 Multipliers updating

In order to solve the dual problem, two multiplier updating algorithms have been tried: subgradient method [13] and cutting-plane method [3].

The subgradient algorithm behaved as accurately as the cutting-plane method while achieving the same level of precision in smaller computing time. Therefore, results based on the subgradient algorithm are reported below.

Bundle methods [14, 15, 16] are not used because the subgradient algorithm provides excellent results for this particular application.

The implemented subgradient algorithm is

$$\theta^{(\nu+1)} = \theta^{(\nu)} + k^{(\nu)} \frac{s^{(\nu)}}{|s^{(\nu)}|}, \quad (12)$$

where  $k^{(\nu)}$  is selected in such a way as

$$\lim_{\nu \rightarrow \infty} k^{(\nu)} \rightarrow 0 \quad \text{and} \quad \sum_{\nu=1}^{\infty} k^{(\nu)} \rightarrow \infty, \quad (13)$$

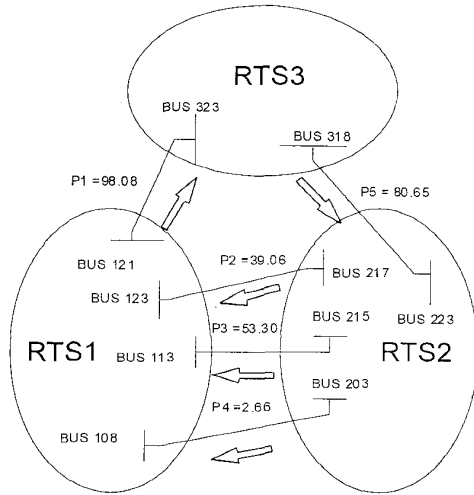


Figure 4: Power interchange among areas in MW.

and where  $s$  is a subgradient and the superindex ( $\nu$ ) indicates iteration  $\nu$ .

An usual choice for  $k^{(\nu)}$  is as follows

$$k^{(\nu)} = 1/(A + B\nu), \quad (14)$$

where  $A$  and  $B$  are positive constants. This selection meets condition (13).

If one fictitious bus per interconnecting line is defined, the subgradient has the form:

$$s^{(\nu)} = h_{ij}^{(\nu)}. \quad (15)$$

If, on the other hand, two fictitious buses per interconnecting line are defined, the subgradient has the form:

$$s^{(\nu)} = \text{column}(g_{ij}^{(\nu)}, l_{ij}^{(\nu)}). \quad (16)$$

It should be noted that a subgradient vector is readily available from power mismatches at fictitious buses [3].

## 5 Case Study

A case study based on the IEEE RTS [17, 18] is presented. Three identical RTS systems are interconnected through 5 tie-lines as shown in figure 4. The resulting system [19] consists of 3 areas, 72 buses, 96 generators, and 119 lines.

Data include (i) quadratic variable cost, maximum output power and minimum output power for each generator;

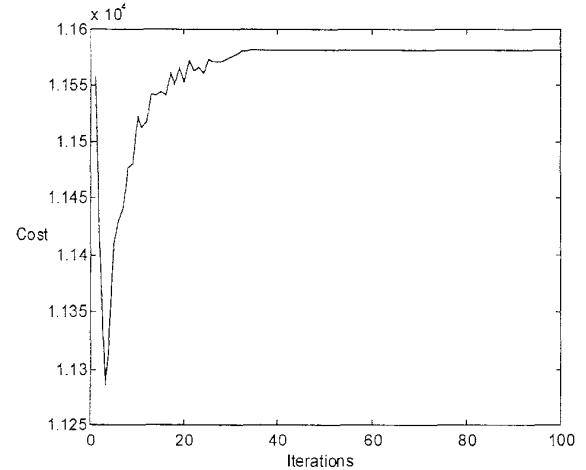


Figure 5: Total cost evolution in US \$ (one fictitious bus case).

(ii) resistance, susceptance and maximum transmission capacity for each line; and (iii) demand in every load bus.

The reported case study was solved in a centralized and decentralized fashion. Results were identical. The decentralized procedure makes it possible an actual decentralized implementation. The centralized procedure is used to validate the results obtained through the decentralized procedure. In what follows, results for the decentralized analysis are reported. A one fictitious bus per interconnection line approach is used.

Figure 4 shows optimal power interchanges among the 3 RTS areas. Area 1 exports to area 3 and imports from area 2. area 2 exports to area 1 and imports from area 3. and area 3 exports to area 2 and imports from area 1.

If no interconnection is operated, total operating cost increases by 0.02 %.

Figure 5 shows the evolution of total operating cost (the addition of the operating costs of the subproblems) as a function of the iteration number. It should be noted that convergence is smoothly attained. It should also be noted that this cost does not represent a completely feasible dispatch of the system due to interconnecting line flow convergence tolerances (0.1 %).

Figure 6 shows the evolution of the interconnecting line optimal energy trading prices as a function of the number of iterations. Convergence is also smoothly attained.

Table 1 provides power flows and optimal energy trading prices for every interconnecting line once the algorithm has converged. The numbers of the two buses defining every interconnecting line are made of three digits. The

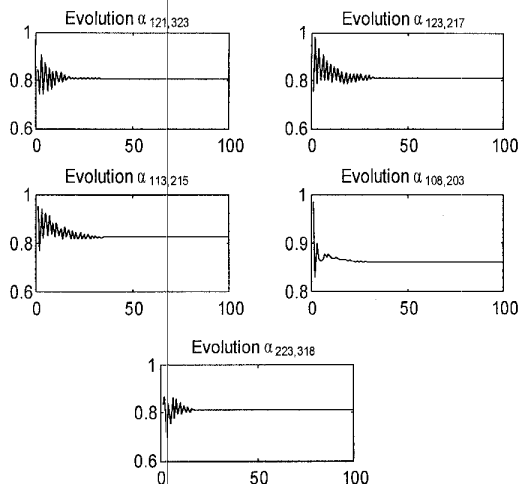


Figure 6: Evolution of interconnecting line prices (one fictitious bus case). In all plots, the horizontal axis represents number of iterations, and the vertical axis represents the corresponding multiplier value in \$/MWh.

first digit indicates area number, and the last two digits indicate the original RTS bus number.

The subgradient constants for the updating of the multipliers were experimentally fixed to  $A = 0.5$  and  $B = 0.25$ .

The model was implemented using the GAMS modeling system [20] and run on a SGI R10000 based computer. The number of required iterations for convergence within a 0.1% interconnecting line flow tolerance was 100. Total required computing time was 18 seconds.

The computing time required by the centralized procedure is smaller than the one required by the decentralized procedure. However, it should be noted that the decomposition is not oriented to improve computational efficiency but to preserve dispatching independence.

Interconnecting Line	Optimal Price [\$/MWh]	Power Flow [MW]
121 - 323	0.8084	98.08
318 - 223	0.8096	80.65
217 - 123	0.8116	39.06
215 - 113	0.8262	53.30
203 - 108	0.8596	02.66

Table 1: Prices and power flows for interconnecting lines (one fictitious bus case).

## 6 Conclusions

This paper presents a multi-area OPF algorithm which makes it possible the independent dispatch of each area while achieving a multi-area optimum.

The algorithm is based on the Lagrangian Relaxation decomposition procedure.

The algorithm is of particular interest in a multi-utility or multi-country setting where coordination achieves substantial savings but where dispatching independence has to be maintained.

A realistic case study based on the IEEE RTS is presented. Results for decentralized numerical studies are shown. Optimal interconnection electric energy trading rates are determined.

Computing time and communication requirements are minimal.

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