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Optimal Multi-area Generation Schedule Considering Renewable Resources Mix: a Real-Time Approach

Alireza Soroudi, Abbas Rabiee

Abstract

This paper proposes a new model for multi-area dynamic economic dispatch (MA-DED) problem, taking into account hydro-thermal generating units, wind power generation and power pool market, for supplying the overall demand of the system for a given horizon. The uncertainties in wind power generations, energy prices and demand of the system are also modeled to make the proposed approach more practical in case of real-time operation of practical power systems. Scenario based approach is adopted for uncertainty modeling. In order to make the proposed MA-DED applicable in real-time operation of power systems, optimality condition decomposition technique is employed along with parallel computation ability. The proposed approach is examined on a three-area interconnected power network, to demonstrate its applicability for real-time scheduling of joint thermal and undispatchable renewable energy resources.

Index Terms

Dynamic economic dispatch (DED), Multi-area, Optimality condition decomposition (OCD), Real-time, Uncertainty modeling, Scenario based approach.

NOMENCLATURE

s	Scenario s.

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i	Thermal generation unit i.
h	Hydro generation unit h.
a	Area a.
t	Time interval t.
v_{in}^{c}	Cut-in speed of wind turbine (m/s).
v_{out}^{c}	Cut-out speed of wind turbine (m/s).
$\lambda_{t,s}$	Electricity price in time t and scenario s $(\$/MWhr)$.
P_i^{min}	Minimum limit of power generation of i^{th} thermal unit, (MW).
P_i^{max}	Maximum limit of power generation of i^{th} thermal unit, (MW).
π_s	Probability of scenario s.
$P_i^a(t)$	Power produced by thermal unit i in area a and time t, (MW).
$P_h^a(t)$	Power produced by hydro unit h in area a and time t, (MW).
$Pp_s^a(t)$	Power purchased from pool market in area a, time t and scenario s, (MW).
wp_s	Percent of wind turbine capacity produced by wind turbine in scenario s.
$Pw_s^a(t)$	Power produced by wind turbine in area a, time t and scenario s, (MW).
$P_{D,s}^a(t)$	Power demand in area a, time t and scenario s (MW).
UR_i	Ramp-up limit of power generation of i^{th} thermal unit, (MW/hr).
$Tie_s^{a\acute{a}}(t)$	Flow of tie-line between areas a and $\acute{a}$, (MW).
$Cap_{a\acute{a}}$	Flow limit of tie-line between areas a and $\acute{a}$, (MW).
DR_i	Ramp-down limit of power generation of i^{th} thermal unit, (MW/hr).
v_{rated}	Rated speed of wind turbine (m/s).
P_r^w	Rated power of wind turbine, (MW).
Ω_s^w	Set of wind speed scenarios.
Ω_s^λ	Set of price scenarios.
v_s	Wind speed in scenario s.

$L_h^a(t)$	Reservoir volume of hydro unit h at time t and in area a, (in million m^3).
$I_h^a(t)$	Water inflow for the reservoir of hydro unit h at time t and in area a, (in million m^3).
$R_h^a(t)$	Released water for the reservoir of hydro unit h at time t and in area a, (in million m^3).
$S_h^a(t)$	Spilled water for the reservoir of hydro unit h at time t and in area a, (in million m^3).
$R_{h,max}^a$	Maximum released capacity per hour for the reservoir of hydro unit h, (in million m^3).
TC	Total costs ($).
OF	Total benefit ($).

I. INTRODUCTION

Electric power networks are usually large-scale and multi-area systems with several tie-lines. The purpose of multi-area dynamic economic dispatch (MA-DED) is to find the optimal schedule of power generation resources for a given horizon, while the demand of each area is supplied as well as satisfying the technical constraints. Different approaches have been proposed for solving the MA-DED problem in the literature. The approach introduced in [1], presents a method for solving the MA-DED, which considers various constraints like, tie line flow limits, area demand and reserve requirement constraints. In [2], the proposed adaptive Lagrange relaxation approach incorporates the power contracts and reliability must-run contracts, into the problem. Another Lagrange relaxation approach is proposed in [3] which considers the transmission network using a DC-flow model. The impact of transmission losses are considered in [4]. Heuristic based methods [5]–[7], and generalized Benders decomposition [8] have been proposed to deal with multi-area unit commitment problem. MA-DEDs usually include constraints like power balance in each area, tie-lines capacity constraints, tie-lines security [9] and reserve constraints [6].

A. *Motivations*

In recent years, the use of renewable energy resources is given a great deal of attention due to environmental concerns. With the increased penetration of renewable energy in electric power systems, more operating issues are revealed [10]. Most of these issues are related to the uncertain primary sources of these technologies [11] like wind speed, solar radiations and etc.

The volatile nature of wind power generation is an important issue which should be considered in DED formulation properly. On the other hand, there are other uncertain parameters such as pool market prices and load profile, which make the MA-DED a complicated stochastic optimization problem. A comprehensive method is needed to model the aforementioned uncertainties which should be able to solve the DED problem in a real-time environment. This is the shortage that this work tries to overcome.

B. Contributions

In this paper, a new model for MA-DED problem is proposed by considering uncertainties in wind power generation, pool market prices and demand of each area. Thermal and hydro generation units, wind power generation, and pool market are considered in the proposed MA-DED. Uncertainties are modeled by scenario based approach [12] (see Appendix A-A). In order to make the proposed MA-DED approach applicable in real-time environment, optimality condition decomposition (OCD) technique [13] is utilized to decompose the overall MA-DED problem into several area-based DEDs (i.e. one DED for each area) with lower dimensions. The main feature of the OCD approach is that the resultant DED problems are independent, and hence by utilizing parallel computation ability the solution-time reduces considerably, such that the proposed approach would be suitable for real-time operation of practical multi-area power systems.

C. Paper organization

The rest of this paper is organized as follows: Section II presents the probabilistic MA-DED problem formulation. The OCD technique is explained in Section III. Simulation results are given in section IV and finally, Section V concludes the paper.

II. PROBABILISTIC MA-DED PROBLEM FORMULATION

A. Assumptions

The retailer is paid a fixed price for each MWh which sells to the customers. It has four options for supplying the demand of its customers namely: pool market, hydro power generation, thermal generating units and finally the wind power generation.

B. Uncertainty modeling of wind power generation, electricity demand and electricity price

The output power schedule of a wind turbine basically depends on wind speed in the area which wind turbine is installed. The variations of wind speed make the generated power volatile. In this paper, the variation of wind speed is stochastically modeled. It is assumed that the probability density function of wind speed is known and then using the approach proposed by [14], it is divided into several discrete scenarios with known probabilities (see Appendix A-B for more details). The price of energy purchased from the power pool, i.e. $\lambda_s(t)$, is also an uncertain parameter. The variation of this quantity along with the demand values in area a, $P^a_{D,s}(t)$, are modeled on a scenario based approach in this paper. The aim of MA-DED is to find the optimal schedule of power generation resources for a given horizon, while the demand of each area is supplied as well as satisfying the technical constraints. Uncertainties in wind power generation, pool market prices and load profile of the system, emerge into a probabilistic MA-DED which is formulated as follows:

C. Total cost of energy procurement

The production cost of i^{th} thermal unit located in area a is defined as:

$$C^a_i(P^a_i(t)) = a_i(P^a_i(t))^2 + b_i P^a_i(t) + c_i \tag{1}$$

where a_i, b_i and c_i are the fuel cost coefficients of the i^{th} unit. The total cost paid by the retailer is calculated as follows:

$$TC = \sum_{s,t,a} \pi_s * Pp^a_s(t) * \lambda_s(t) + \sum_{i,t,a} C^a_i(P^a_i(t)) \tag{2}$$

where π_s is the probability of scenario s. $Pp_s^a(t)$ is the purchased power from the pool market in time t, scenario s and area a.

D. Thermal unit constraints

1) Generation limits of units

$$P_i^{min} \leq P_i^a(t) \leq P_i^{max} \tag{3}$$

where $P_i^{max/min}$ are the maximum/minimum power outputs of i-th thermal unit.

2) Ramp up and ramp down constraints The variation of output power in thermal generating units is limited in transition from time $t-1$ to t. This limitation is called ramp rate limit which is stated as follows:

$$P_i^a(t-1) - DR_i \leq P_i^a(t) \leq P_i^a(t-1) + UR_i \tag{4}$$

where UR_i and DR_i are the ramp up/down limits of the i-th thermal unit (MW/hr).

E. Hydro unit constraints

1) Water Balance: The water balance equations that should be satisfied in each period for hydro unit h at area a are as follows:

$$\begin{aligned} L_h^a(t+1) =& L_h^a(t) + I_h^a(t+1) - R_h^a(t+1) - S_h^a(t+1) \\ &+ \sum_{\hat{h}} [R_{\hat{h}}^a(t-\tau_{\hat{h}}) + S_{\hat{h}}^a(t-\tau_{\hat{h}})] \\ & L_{h,min}^a \leq L_h^a(t) \leq L_{h,max}^a, \hat{h} \in up\{h\} \\ & R_h^a(t) \leq R_{h,max}^a \\ & L_h^a(t_0) = L_{h,ini}^a, L_h^a(t_{24}) = L_{h,fin}^a \end{aligned} \tag{5}$$

where $L_h^a(t)$ is reservoir volume , $I_h^a(t+1)$ is the water inflow, $R_h^a(t)$ is the released water and $S_h^a(t)$ is the spilled water is at the end of period t in million m^3. R_{max} is the maximum released capacity per hour in million m^3. $L_{h,ini}^a$ and $L_{h,fin}^a$ are the volume of the water in dam at beginning and the end of the considered horizon, respectively. This constraint means that the volume of water in a reservoir of hydro turbine h in time $t+1$ will be equal to its value in the previous period plus the water inflow to its reservoir in time $t+1$ minus its own released/spilled water and in time $t+1$ plus the released/spilled water of all reservoirs in its upstream in previous hours (with considering time delays $\tau_{\hat{h}}$).

2) Water to Power Conversion:

$$\begin{aligned}P_h^a(t) =& c_{h,1}^a L_h^a(t) * L_h^a(t) + c_{h,2}^a * R_h^a(t) * R_h^a(t) + \\ & c_{h,3}^a * R_h^a(t) * L_h^a(t) + c_{h,4}^a * L_h^a(t) + c_{h,5}^a * R_h^a(t) + c_{h,6}^a\end{aligned} \tag{6}$$

where $c_{h,1\rightarrow 6}^a$ are the characteristics factors of hydro turbine h in area a. Also, $P_h^a(t)$ is the generated power of unit h in area a and time t.

F. Power balance in each area

For hour t and scenario s within area a, the power balance constraints should be satisfied as follows:

$$\begin{aligned}&\sum_i P_i^a(t) + Pw_s^a(t) + Pp_s^a(t) + \sum_h P_h^a(t) \\ &= P_{D,s}^a(t) + \sum_{\acute{a}} Tie_s^{a\acute{a}}(t)\end{aligned} \tag{7}$$

$$0 \leq Pw_s^a(t) \leq wp_s * P_r^w \tag{8}$$

$$-Cap_{a\acute{a}} \leq Tie_s^{a\acute{a}}(t) \leq Cap_{a\acute{a}} \tag{9}$$

where $P_{D,s}^a(t)$ and $Pw_s^a(t)$ are the load demand and wind power generation level in area a at time t and scenario s, respectively. Also, $Tie_s^{a\acute{a}}(t)$ and $Cap_{a\acute{a}}$ are the flow and limit of the flow for tie-line connecting the areas a & $\acute{a}$, respectively. The concept of (7) is depicted in Fig.1. The values of power demand in each area as well as price values are obtained using the expected and variance values of demand in each area. It is assumed that these values are known using forecasting methods [15].

$$P^{a}_{D,s}(t) = Normal(\Delta^{a}_{D}(t), \sigma^{a}_{D}(t)) \tag{10}$$

$$\lambda_s(t) = Normal(\Lambda(t), \sigma_{\lambda}(t)) \tag{11}$$

where $Normal$ operator generates random samples using the given expected and variance parameters with normal probability density distribution. $\Delta^{a}_{D}(t)$ & $\sigma^{a}_{D}(t)$ are the expected and variance of demand values in area a and time t, respectively. Similarly, $\Lambda(t)$ & $\sigma_{\lambda}(t)$ are the expected and variance of price values in time t, respectively.

The power exchanges between connected areas are equal with opposite signs as follows:

$$Tie^{a\acute{a}}_{s}(t) = -Tie^{\acute{a}a}_{s}(t) \tag{12}$$

G. Objective function

The retailer in a deregulated electricity market is a profit seeker entity. It tries to maximize its benefits with making proper decisions regarding energy purchase and selling. Thus, the objective function of a rational retailer to be maximized is defined as the total money received from the customers minus the total costs, as follows:

$$OF = \sum_{a,t,s} \pi_s * P^{a}_{D,s}(t) * \lambda_c - TC \tag{13}$$

where λ_c is the price of energy sold to customers.

III. Optimality Condition Decomposition (OCD)

In large-scale and multi-area power systems, the dimension of the DED problem is very large and hence the solution-time is very critical for real-time implementation. To speed up the solution process, the MA-DED problem is decomposed to a few simpler subproblems with lower dimensions (i.e. one subproblem for each area), and hence with less computational burden. In this paper, optimality condition decomposition (OCD) [13] is employed for this aim. OCD is a mathematical approach for decomposing a large-scale but decomposable NLP optimization problem to several simpler and independent subproblems. The decomposition is based on relaxing complicating constraints of the original NLP problem. Complicating constraints are those that if relaxed, the resulting problem decomposes into several simpler problems [13]. In MA-DED problem, tie-line power exchange constraints (i.e. (12)) are the complicating constraints. By relaxing these constraints, the objective function corresponding to $a-th$ subproblem (i.e. subproblem of $a-th$ area) in $k-th$ iteration of the OCD is described as follows:

$$OF_a^{(k)} = \sum_{t,s} \pi_s * P_{D,s}^a(t) * \lambda_c - TC_a^{(k)} \tag{14}$$

$$\begin{aligned} TC_a^{(k)} = &\sum_{s,t} \pi_s * Pp_s^{a,(k)}(t) * \lambda_s(t) + \\ &\sum_{s,t} C_i(P_i^{a,(k)}(t)) + \sum_{\acute{a},t} \delta_{\acute{a}}^{(k)}(t) \end{aligned} \tag{15}$$

where,

$$\delta_{\acute{a}}^{(k)}(t) = \bar{\mu}_s^{a\acute{a},(k-1)}(t) \times (\bar{Tie}_s^{a\acute{a},(k-1)}(t) + Tie_s^{a\acute{a},(k)}(t)) \tag{16}$$

where, $\bar{\mu}_s^{a\acute{a},(k-1)}(t)$ are Lagrange multipliers corresponding to the complicating constrains (12) of $a-th$ subproblem at time t, scenario s and iteration $k-1$. The dashed parameters (like $\bar{Tie}_s^{a\acute{a},(k-1)}(t)$) are the obtained values of the corresponding variables at the previous iteration (i.e. iteration $k-1$) of the OCD. It is evidently observed that utilization of the OCD leads to independent relaxed subproblems (RSPs) with much less dimension than the original one, which can be solved quickly by parallel computation. In other words, the subproblem of $a-th$ area contains only the variables of that area, and the variables of neighbor areas are treated as constant parameters both in the objective function and the constraints of area a. The steps of the algorithm are as follows:

- Step 0: Initialization. In this step, all variables and Lagrange multipliers of complicating constrains (12) are initialized. In this paper, the initial values for variables are chosen by independently solving the RSPs (i.e. the area based DEDs), with zero initial values for Lagrange multipliers of complicating constraints (i.e. $\forall t,\ \bar{\mu}_s^{a\acute{a},(k-1)}(t)$), and neglecting constraints (12). Therefore, $\forall t,\ \ Pp_s^{a,(0)}(t)$ and $P_i^{a,(0)}(t)$,are known.

- Step 1: Independently solving of the RSPs in iteration k: In this phase, the RSPs are solved independently, by parallel computation, and the optimal values for all variables are obtained, along with the Lagrange multipliers of complicating constraints (12).
- Step 2: Stopping criterion. The algorithm stops if the objective functions for all RSPs do not change significantly in two consecutive iterations [13]. In other words:

$$\left| \frac{OF_a^{(k)} - OF_a^{(k-1)}}{OF_a^{(k)}} \right| \leq \epsilon \tag{17}$$

  Otherwise, it continues in Step 1.

The flowchart of the proposed OCD algorithm is depicted in Fig. 2.

IV. SIMULATION RESULTS

The proposed approach is implemented in GAMS [16] environment. It is applied on a 33-units three-areas system [17]. Area 1 consists of 10 thermal generation units, and the total wind generation capacity is assumed to be 250MW in this area. There are 13 thermal generation units in Area 2, and the total wind power generation capacity is assumed to be 150MW for this area. In Area 3, there are 10 thermal generation units, which are the same with those located in Area 1. The technical and economical data of 10 and 13 thermal units are given in tables VII and VIII (in Appendix B),respectively. Also, power pool and hydro generation are available in Area 3. These three areas are interconnected by 3 tie-lines, one tie-line between each pair of areas. The tie-lines' flow limits are as follows: $Cap_{a_1,a_2} = 120MW$, $Cap_{a_1,a_3} = 630MW$ and $Cap_{a_3,a_2} = 500MW$.

The hourly price data for scenarios $s_{1\rightarrow 10}$ is given in Table. IX (Appendix B). These values are repeated in the upcoming scenarios from $s_{11\rightarrow 120}$. The expected hourly load data in each area is given in Table. X (Appendix B). The $\sigma_D^a(t)$ is considered to be 1% of $\Delta_D^a(t)$.

The reservoir inflows into hydro reservoirs are available in Table.XI. The technical characteristics of hydro units are given in Table.XII [18] (see Appendix B).

The v_{in}^{c},v_{rated},v_{out}^{c} are 4, 14, 25 (m/s), respectively.

The percent of producible wind power in each scenario are given in Table I obtained using the method described in Appendix. A.

Table. II shows the variations of OF according to iterations of the OCD algorithm. As it is observed from this figure, total number of iterations is 17. Also, the overall CPU-time for this MA-DED problem using parallel computation ability is 71.915 seconds. By solving the above model without using the OCD algorithm, the CPU-time equals to 672.609 seconds. This study implies the fact that utilization of the OCD approach with parallel computation will reduce the CPU-time, drastically (89.3% in this study).

The values of purchased power from pool market in different scenarios are given in Table. III. As it is observed from this table, only in some scenarios the purchased power is non-zero, which are mainly corresponds to scenarios with low wind power generation.

Tables. IV and V presents the hourly schedule of thermal and hydro generation units, respectively. Besides, the hourly schedule for the volume of released water, water head and water spillage are given in Table. VI.

V. CONCLUSION

This paper presents a probabilistic model for multi-area dynamic economic dispatch (MA-DED) problem. The aim of the proposed MA-DED is to find the optimal schedule of thermal and hydro generation units, by considering uncertain wind power generation. The technical constraints of hydro and thermal units as well as tie-lines' capacity limits are taken into account. The uncertainties in wind power generation, electricity prices and load profile of the system are included in the proposed model. In order to make the proposed MA-DED applicable in real-time operation of practical power systems, Optimality condition decomposition (OCD) technique is utilized. The proposed approach is tested on a three-area interconnected system to demonstrate its applicability for real-time operation of power systems.

APPENDIX A

UNCERTAINTY MODELING

A. Scenario based uncertainty modeling [19]

Consider a multivariate function, $y = F(X)$, where X is vector containing the uncertain input values. The scenario based uncertainty modeling approach is a method for finding the expected value of y which is described as follows: a set of scenarios, Ω_s is generated for describing the probable values of X.

$$y = \sum_{s \in \Omega_s} \pi_s * F(X_s) \tag{18}$$

where π_s is the probability of state s.

B. Wind turbine power generation modeling [14]

Suppose that the probability density function (PDF) of wind speed is known in the region under study and it is described as follows:

$$PDF(v) = (\frac{2v}{c^2})\ exp[-(\frac{v}{c})^2] \tag{19}$$

The producible power of wind turbine in wind speed v denoted by $P^w(v)$ is calculated using (20).

$$P^w(v) = \begin{cases} 0 & \text{if } v \leq v^c_{in} \text{ or } v \geq v^c_{out} \\ \frac{v - v^c_{in}}{v^c_r - v^c_{in}} P^w_r & \text{if } v^c_{in} \leq v \leq v_r \\ P^w_r & \text{else} \end{cases} \tag{20}$$

Where, P^w_r is the rated power of wind turbine.

The characteristic curve of a wind turbine is depicted in Fig. 3. The probability that wind speed is in scenario s ($\in [v_{1,s}\ v_{2,s}]$) is calculated as follows:

$$\pi_s = \int_{v_{1,s}}^{v_{2,s}} (\frac{2v}{c^2})\ exp[-(\frac{v}{c})^2] dv \tag{21}$$

$$v_s = \frac{v_{2,s} + v_{1,s}}{2}$$

where $v_{1,s}, v_{2,s}$ are the limits of wind speed's interval in state s. The generated power of wind turbine in state t is calculated using the obtained v_s and (20).

APPENDIX B

SIMULATION DATA

The simulation data of hydro-thermal units along with price and demand values are given in Table VII to Table XII.

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TABLE I

WIND TURBINE AVAILABLE PERCENT OF POWER IN DIFFERENT SCENARIOS

States (Ω_s)	wp_s (%)	π_s
1	0	0.2059
2	5	0.0661
3	15	0.1123
4	20	0.1037
5	35	0.1122
6	45	0.0912
7	55	0.0773
8	65	0.0501
9	75	0.0451
10	85	0.0326
11	95	0.0250
12	100	0.0784

TABLE II

THE VARIATION OF OF VERSUS THE ITERATIONS OF THE OCD

Iteration	CPU time (s)	Benefit ($)
1	17.703	2097038.76
2	5.406	2072806.81
3	5.640	2106325.00
4	2.125	2072806.81
5	4.485	2106382.94
6	1.516	2072806.81
7	1.608	2076300.00
8	1.047	2072312.93
9	4.157	2078748.18
10	0.907	2072325.17
11	11.375	2080088.44
12	3.985	2072281.67
13	4.719	2080090.44
14	1.000	2072344.33
15	4.313	2080078.96
16	0.953	2072285.76
17	0.977	2075812.00

TABLE III

THE PURCHASED POWER FROM POOL MARKET IN DIFFERENT SCENARIOS IN (MW)

Scenario	$Ppool_s(t)$	Scenario	$Ppool_s(t)$	Scenario	$Ppool_s(t)$	Scenario	$Ppool_s(t)$
s_{29}	9.13	s_{62}	168.22	s_{82}	1224.17	s_{102}	2488.85
s_{37}	30.38	s_{63}	145.17	s_{83}	1284.26	s_{103}	2662.42
s_{42}	9.26	s_{64}	359.94	s_{84}	1785.70	s_{104}	2339.59
s_{44}	4.11	s_{65}	256.75	s_{85}	1456.72	s_{105}	2393.16
s_{46}	4.60	s_{66}	102.09	s_{86}	1299.43	s_{106}	2350.73
s_{47}	39.18	s_{67}	100.60	s_{87}	1368.32	s_{107}	2640.20
s_{48}	6.41	s_{68}	225.26	s_{88}	1434.63	s_{108}	2858.52
s_{49}	6.70	s_{69}	280.74	s_{89}	1373.53	s_{109}	2548.64
s_{50}	4.20	s_{70}	299.18	s_{90}	1479.37	s_{110}	2233.24
s_{51}	48.62	s_{71}	534.84	s_{91}	1572.53	s_{111}	2905.71
s_{52}	34.70	s_{72}	526.17	s_{92}	1637.99	s_{112}	3081.36
s_{53}	15.87	s_{73}	537.12	s_{93}	1742.69	s_{113}	2951.50
s_{54}	41.59	s_{74}	325.33	s_{94}	1831.13	s_{114}	2855.19
s_{55}	54.55	s_{75}	669.92	s_{95}	1808.91	s_{115}	2891.38
s_{56}	61.07	s_{76}	677.77	s_{96}	1726.99	s_{116}	3156.41
s_{57}	131.59	s_{77}	550.34	s_{97}	1696.99	s_{117}	2950.95
s_{58}	40.93	s_{78}	707.86	s_{98}	1820.87	s_{118}	2913.25
s_{59}	124.92	s_{79}	715.71	s_{99}	1849.95	s_{119}	3052.83
s_{60}	18.27	s_{80}	610.88	s_{100}	1801.21	s_{120}	2905.30
s_{61}	175.32	s_{81}	1525.26	s_{101}	2655.79		

TABLE IV

THE HOURLY PRODUCED POWER BY THERMAL UNITS IN (MW)

Unit #	Time (t)																							
i	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	150.0	150.0	173.8	150.0	150.0	150.4	200.3	178.4	223.9	210.4	150.0	150.0	150.0	150.0	150.0	150.0	150.0	150.0	150.0	150.0	193.1	273.1	230.0	150.0
2	135.0	135.0	215.0	184.8	135.0	215.0	295.0	375.0	422.3	342.3	262.3	182.3	167.0	135.0	135.0	135.0	135.0	135.0	135.0	209.4	289.4	295.0	215.0	135.0
3	73.0	147.9	227.9	180.0	100.0	180.0	260.0	340.0	340.0	340.0	340.0	260.0	221.0	141.0	73.0	73.0	73.0	95.1	147.5	227.5	307.5	330.6	250.6	170.6
4	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0
5	73.0	73.0	81.9	73.0	73.0	73.0	96.4	84.5	109.2	101.9	73.0	73.0	73.0	73.0	73.0	73.0	73.0	73.0	73.0	73.0	89.2	139.2	113.4	73.0
6	110.0	160.0	160.0	160.0	160.0	160.0	160.0	160.0	160.0	160.0	160.0	160.0	160.0	160.0	114.3	71.1	57.0	107.0	157.0	160.0	160.0	160.0	160.0	160.0
7	117.9	130.0	130.0	130.0	130.0	130.0	130.0	130.0	130.0	130.0	130.0	130.0	130.0	130.0	130.0	100.0	70.0	100.0	130.0	130.0	130.0	130.0	130.0	130.0
8	47.0	47.0	47.0	47.0	47.0	47.0	47.0	47.0	47.0	47.0	47.0	47.0	47.0	47.0	47.0	47.0	47.0	47.0	47.0	47.0	47.0	47.0	47.0	47.0
9	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
10	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0
11	362.7	385.1	434.2	480.2	500.9	551.3	570.1	594.1	643.4	680.0	680.0	680.0	680.0	644.4	595.4	525.7	495.2	549.7	597.7	680.0	644.2	551.1	456.8	409.5
12	181.3	192.5	217.1	240.1	250.5	275.7	285.1	297.0	321.7	351.7	360.0	360.0	349.9	322.2	297.7	262.8	247.6	274.9	298.8	347.5	322.1	275.6	228.4	204.8
13	181.3	192.5	217.1	240.1	250.5	275.7	285.1	297.0	321.7	351.7	360.0	360.0	349.9	322.2	297.7	262.8	247.6	274.9	298.8	347.5	322.1	275.6	228.4	204.8
14	86.9	88.8	93.1	97.1	98.8	103.2	104.8	106.9	111.2	116.3	123.3	132.8	116.0	111.2	107.0	101.0	98.3	103.1	107.2	115.6	111.2	103.2	95.0	90.9
15	86.9	88.8	93.1	97.1	98.8	103.2	104.8	106.9	111.2	116.3	123.3	132.8	116.0	111.2	107.0	101.0	98.3	103.1	107.2	115.6	111.2	103.2	95.0	90.9
16	86.9	88.8	93.1	97.1	98.8	103.2	104.8	106.9	111.2	116.3	123.3	132.8	116.0	111.2	107.0	101.0	98.3	103.1	107.2	115.6	111.2	103.2	95.0	90.9
17	86.9	88.8	93.1	97.1	98.8	103.2	104.8	106.9	111.2	116.3	123.3	132.8	116.0	111.2	107.0	101.0	98.3	103.1	107.2	115.6	111.2	103.2	95.0	90.9
18	86.9	88.8	93.1	97.1	98.8	103.2	104.8	106.9	111.2	116.3	123.3	132.8	116.0	111.2	107.0	101.0	98.3	103.1	107.2	115.6	111.2	103.2	95.0	90.9
19	86.9	88.8	93.1	97.1	98.8	103.2	104.8	106.9	111.2	116.3	123.3	132.8	116.0	111.2	107.0	101.0	98.3	103.1	107.2	115.6	111.2	103.2	95.0	90.9
20	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0
21	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0
22	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0
23	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0
24	150.0	150.0	169.3	150.0	150.0	150.5	168.0	150.0	182.9	205.6	150.0	150.0	150.0	150.0	150.0	150.0	150.0	150.0	150.0	150.0	150.0	230.0	207.6	150.0
25	135.0	135.0	215.0	184.8	135.0	215.0	295.0	336.9	389.3	309.3	229.3	149.3	167.0	135.0	135.0	135.0	135.0	135.0	135.0	173.8	253.8	295.0	215.0	135.0
26	73.0	145.4	225.4	173.8	93.8	173.8	253.8	333.8	340.0	340.0	292.9	224.2	201.8	121.8	73.0	73.0	73.0	95.1	109.2	189.2	269.2	286.6	206.6	126.6
27	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0
28	73.0	73.0	79.5	73.0	73.0	73.0	78.8	73.0	86.9	99.2	73.0	73.0	73.0	73.0	73.0	73.0	73.0	73.0	73.0	73.0	73.0	123.0	100.3	73.0
29	110.0	160.0	160.0	160.0	160.0	160.0	160.0	160.0	160.0	160.0	160.0	160.0	160.0	160.0	114.3	71.1	57.0	107.0	157.0	160.0	160.0	160.0	160.0	160.0
30	117.9	130.0	130.0	130.0	130.0	130.0	130.0	130.0	130.0	130.0	130.0	130.0	130.0	130.0	130.0	100.0	70.0	100.0	130.0	130.0	130.0	130.0	130.0	130.0
31	47.0	47.0	47.0	47.0	47.0	47.0	47.0	47.0	47.0	47.0	47.0	47.0	47.0	47.0	47.0	47.0	47.0	47.0	47.0	47.0	47.0	47.0	47.0	47.0
32	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
33	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0

TABLE V

THE HOURLY POWER PRODUCED BY HYDRO UNITS IN (MW)

	Hydro unit #			
Time	1	2	3	4
t_1	98.50	88.60	59.01	260.40
t_2	60.40	50.16	56.92	306.00
t_3	68.26	51.85	53.04	306.00
t_4	68.79	53.46	47.81	306.00
t_5	61.19	54.50	42.00	306.00
t_6	72.47	55.01	65.26	306.00
t_7	74.12	55.01	65.28	306.00
t_8	75.40	55.50	65.22	306.00
t_9	78.14	56.48	65.05	306.00
t_{10}	80.47	61.29	64.73	306.00
t_{11}	81.49	64.37	64.37	306.00
t_{12}	82.72	68.56	64.03	306.00
t_{13}	85.18	73.58	63.84	306.00
t_{14}	85.52	75.60	63.57	306.00
t_{15}	80.07	71.67	63.35	306.00
t_{16}	80.19	74.40	63.06	306.00
t_{17}	55.06	59.90	62.83	306.00
t_{18}	87.00	82.72	62.73	306.00
t_{19}	84.55	82.38	62.53	306.00
t_{20}	86.20	85.32	62.12	306.00
t_{21}	87.36	87.09	61.88	306.00
t_{22}	88.58	87.34	60.83	306.00
t_{23}	89.25	85.12	61.82	306.00
t_{24}	86.00	80.95	59.01	284.40

TABLE VI

The hourly schedule of hydro units

Time	$L_h^a(t)$				$S_h^a(t)$			$R_h^a(t)$			
	1	2	3	4	1	3	4	1	2	3	4
t_1	100.00	80.00	170.00	120.00	117.20	44.47		15.00	15.00	13.13	20.00
t_2	103.15	82.00	159.80	160.00		5.50		5.85	6.00	12.90	20.00
t_3	104.32	85.00	143.80	160.00		7.48		6.83	6.00	12.52	20.00
t_4	104.42	88.00	125.80	160.00		7.90		6.90	6.00	12.10	20.00
t_5	104.50	90.00	108.80	160.00		8.29		5.92	6.00	11.71	20.00
t_6	104.08	91.00	240.00	160.00		5.23		7.43	6.00	14.77	20.00
t_7	104.42	91.00	234.85	160.00		5.35		7.66	6.00	14.65	20.00
t_8	105.61	92.00	229.68	160.00		5.47		7.81	6.00	14.53	20.00
t_9	107.45	94.00	223.58	160.00		5.62		8.16	6.00	14.38	20.00
t_{10}	110.02	96.49	216.50	160.00		5.78		8.43	6.51	14.22	20.00
t_{11}	113.55	98.69	210.92	160.00		5.91		8.47	6.80	14.09	20.00
t_{12}	114.92	99.30	206.58	160.00		6.01		8.63	7.39	13.99	20.00
t_{13}	116.95	99.11	204.39	160.00		6.06		8.97	8.19	13.94	20.00
t_{14}	120.01	99.62	201.55	160.00		6.13		8.94	8.49	13.87	20.00
t_{15}	122.98	100.86	199.49	160.00		6.18		8.04	7.76	13.82	20.00
t_{16}	124.95	100.65	196.76	160.00		6.24		8.03	8.21	13.76	20.00
t_{17}	128.95	101.65	194.78	160.00		6.29		5.00	6.00	13.71	20.00
t_{18}	127.94	97.67	193.94	160.00		6.31		9.01	9.98	13.69	20.00
t_{19}	126.28	94.41	192.37	160.00		6.34		8.65	10.26	13.66	20.00
t_{20}	123.31	91.06	189.17	160.00		6.42		8.97	11.35	13.58	20.00
t_{21}	121.10	87.70	187.41	160.00		6.46		9.21	12.37	13.54	20.00
t_{22}	119.63	83.32	180.41	160.00		6.43		9.47	13.38	13.38	20.00
t_{23}	119.02	77.00	187.09	160.00		6.62		9.61	14.32	13.30	20.00
t_{24}	120.00	70.00	170.00	140.00		22.87	13.30	9.02	15.00	13.13	20.00

TABLE VII

THERMAL UNITS TECHNICAL AND ECONOMICAL CHARACTERISTICS OF 10-UNIT SYSTEM [20]

$Gen\#$	a_i	b_i	c_i	P_i^{min}	P_i^{max}	UR_i	DR_i
1	0.00043	21.60	958.20	150	470	80	80
2	0.00063	21.05	1313.60	135	460	80	80
3	0.00039	20.81	604.97	73	340	80	80
4	0.00070	23.90	471.60	60	300	50	50
5	0.00079	21.62	480.29	73	243	50	50
6	0.00056	17.87	601.75	57	160	50	50
7	0.00211	16.51	502.70	20	130	30	30
8	0.00480	23.23	639.40	47	120	30	30
9	0.10908	19.58	455.60	20	80	30	30
10	0.00951	22.54	692.40	55	55	30	30

TABLE VIII

THERMAL UNITS TECHNICAL AND ECONOMICAL CHARACTERISTICS OF 13-UNIT SYSTEM [21]

$Gen\#$	a_i	b_i	c_i	P_i^{min}	P_i^{max}	UR_i	DR_i
11	0.00028	8.1	550	0	680	335	360
12	0.00056	8.1	309	0	360	250	290
13	0.00056	8.1	307	0	360	250	290
14	0.00324	7.74	240	60	180	80	130
15	0.00324	7.74	240	60	180	80	130
16	0.00324	7.74	240	60	180	80	130
17	0.00324	7.74	240	60	180	80	130
18	0.00324	7.74	240	60	180	80	130
19	0.00324	7.74	240	60	180	80	130
20	0.00284	8.6	126	40	120	120	120
21	0.00284	8.6	126	40	120	120	120
22	0.00284	8.6	126	55	120	120	120
23	0.00284	8.6	126	55	120	120	120

TABLE IX

THE HOURLY ELECTRICITY PRICE VALUES IN SCENARIO $1 \rightarrow 10$ (\$/MWh)

	s_1	s_2	s_3	s_4	s_5	s_6	s_7	s_8	s_9	s_{10}
t_1	39.09	37.80	34.52	29.75	38.59	31.77	32.64	35.06	37.88	34.86
t_2	29.60	34.40	32.82	31.37	26.66	30.03	35.66	27.74	26.21	25.00
t_3	27.58	32.90	29.44	38.50	36.89	28.59	30.47	40.59	25.06	39.66
t_4	40.30	28.10	30.02	37.33	33.64	34.78	40.77	33.57	29.65	31.25
t_5	25.03	27.54	40.65	28.92	35.40	28.62	39.14	35.98	28.04	38.19
t_6	32.51	37.14	27.25	40.23	36.92	32.09	38.11	31.83	31.58	39.21
t_7	34.47	36.82	26.06	26.51	37.48	28.58	31.54	25.90	32.19	25.94
t_8	36.36	25.10	33.59	28.56	25.36	29.07	30.92	29.93	32.24	40.60
t_9	33.41	31.44	33.06	28.31	37.49	33.88	32.10	31.08	28.63	32.11
t_{10}	30.06	31.82	32.67	40.68	40.14	35.40	35.09	38.93	31.44	34.66
t_{11}	29.39	32.55	28.98	40.17	27.98	31.66	29.07	33.48	37.01	28.71
t_{12}	28.55	30.02	29.68	35.19	30.78	34.14	33.48	38.23	40.91	36.43
t_{13}	35.17	40.48	38.03	37.70	37.91	32.31	33.63	34.98	32.16	35.55
t_{14}	26.74	35.24	37.22	40.53	30.05	37.88	28.65	35.63	40.64	35.48
t_{15}	27.00	27.29	30.51	29.50	32.14	40.32	27.77	39.48	28.93	27.45
t_{16}	40.79	30.65	30.79	31.41	36.94	32.20	27.38	28.50	29.98	36.23
t_{17}	32.74	25.62	33.25	38.70	34.93	34.06	34.19	40.44	26.05	35.53
t_{18}	40.28	34.51	31.28	28.69	38.23	36.37	28.61	33.74	32.81	29.75
t_{19}	25.89	33.01	29.40	37.44	40.14	38.28	35.74	25.44	35.93	34.57
t_{20}	36.91	31.98	33.79	30.06	29.54	26.96	40.30	40.57	25.52	36.19
t_{21}	40.03	40.92	28.02	28.74	30.36	26.00	39.10	37.97	29.48	38.96
t_{22}	29.59	29.50	38.33	27.78	26.36	38.70	34.51	32.84	38.47	28.80
t_{23}	28.65	32.37	30.41	40.18	29.03	26.58	34.83	37.37	35.85	31.18
t_{24}	34.08	33.56	29.94	26.72	39.44	30.43	34.00	26.87	40.64	36.39

TABLE X

THE HOURLY EXPECTED VALUES OF DEMAND IN EACH AREA $\Delta_D^a(t)$(MW)

	a_1	a_2	a_3
t_1	1524.6	828.8	1355.2
t_2	1681.2	888	1494.4
t_3	1877.4	1006.4	1668.8
t_4	1759.5	1124.8	1564
t_5	1602.9	1184	1424.8
t_6	1799.1	1302.4	1599.2
t_7	2033.1	1361.6	1807.2
t_8	2151	1420.8	1912
t_9	2268	1539.2	2016
t_{10}	2189.7	1657.6	1946.4
t_{11}	1994.4	1716.8	1772.8
t_{12}	1837.8	1776	1633.6
t_{13}	1799.1	1657.6	1599.2
t_{14}	1681.2	1539.2	1494.4
t_{15}	1564.2	1420.8	1390.4
t_{16}	1485.9	1243.2	1320.8
t_{17}	1368.9	1184	1216.8
t_{18}	1564.2	1302.4	1390.4
t_{19}	1681.2	1420.8	1494.4
t_{20}	1837.8	1657.6	1633.6
t_{21}	2033.1	1539.2	1807.2
t_{22}	2229.3	1302.4	1981.6
t_{23}	1994.4	1065.6	1772.8
t_{24}	1681.2	947.2	1494.4

TABLE XI

THE VALUES OF WATER INFLOW OVER THE HOURS

Period	$Reservoir_{1,t}$	$Reservoir_{2,t}$	$Reservoir_{3,t}$	$Reservoir_{4,t}$
t_1	10	8	8.10	2.80
t_2	9	8	8.20	2.40
t_3	8	9	4.00	1.60
t_4	7	9	2.00	0
t_5	6	8	3.00	0
t_6	7	7	4.00	0
t_7	8	6	3.00	0
t_8	9	7	2.00	0
t_9	10	8	1.00	0
t_{10}	11	9	1.00	0
t_{11}	12	9	1.00	0
t_{12}	10	8	2.00	0
t_{13}	11	8	4	0
t_{14}	12	9	3	0
t_{15}	11	9	3	0
t_{16}	10	8	2	0
t_{17}	9	7	2	0
t_{18}	8	6	2	0
t_{19}	7	7	1	0
t_{20}	6	8	1	0
t_{21}	7	9	2	0
t_{22}	8	9	2	0
t_{23}	9	8	1	0
t_{24}	10	8	0	0

TABLE XII

THE CHARACTERISTICS OF HYDRO POWER GENERATORS

h	L^h_{min}	L^h_{max}	L^h_{ini}	L^h_{fin}	R^h_{min}	R^h_{max}	P^{min}_h	P^{max}_h
1	80	150	100	120	5	15	0	500
2	60	120	80	70	6	15	0	500
3	100	240	170	170	10	30	0	500
4	70	160	120	140	6	20	0	500
h	c^h_1	c^h_2	c^h_3	c^h_4	c^h_5	c^h_6	τ_h(h)	Upstream reservoir
1	-0.0042	-0.42	0.03	0.9	10	-50	2	-
2	-0.004	-0.3	0.015	1.14	9.5	-70	3	-
3	-0.0016	-0.3	0.014	0.55	5.5	-40	4	1,2
4	-0.003	-0.31	0.027	1.44	14	-90	0	3

List of figure Captions:

- Figure 1. The concept of multi area DED
- Figure 2. The flowchart of the OCD algorithm
- Figure 3. The power curve of a wind turbine

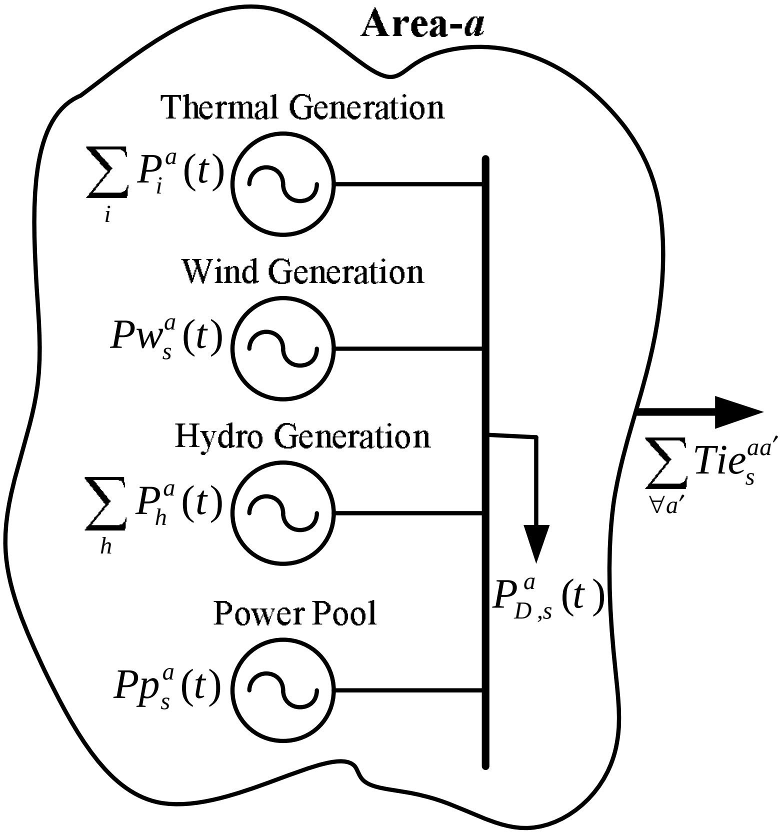

Fig. 1. The concept of multi area DED

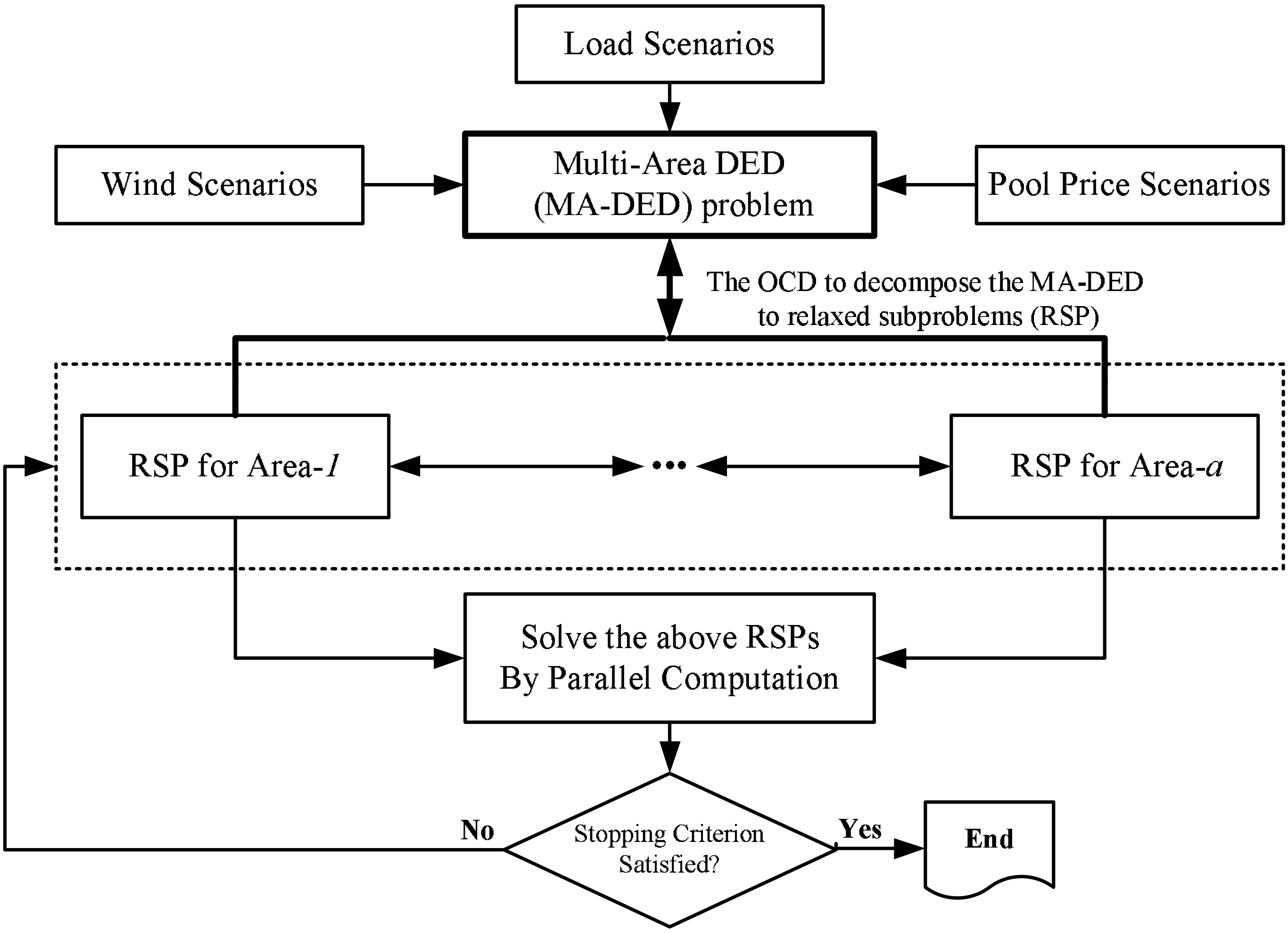

Fig. 2. The flowchart of the OCD algorithm

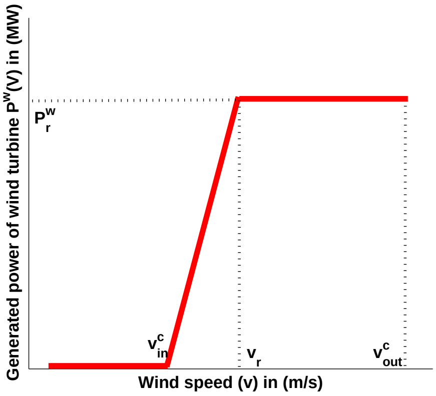

Fig. 3. The power curve of a wind turbine