# Unit Commitment and Multi-Objective Optimal Dispatch Model for Wind-hydro-thermal Power System with Pumped Storage

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***Abstract*—the establishment of more close to the actual model is helpful to quickly implement energy saving and emission-reduction. The day-ahead multi-objective optimal dispatching model containing thermal power, hydro power, wind-power and pumped storage units is given to minimize the total costs and $CO_2$ emission under multiple constraints. Considered the longer startup-shutdown period of thermal power units, the unit commitment of thermal units is predetermined according to the minimal operation costs. the improved hybrid particle swarm optimization algorithm are used to solved the model for the minimal total costs and carbon emission, the unit commitment of pumped storage and the power generation of thermal power, hydro power, wind-power and pumped storage units are obtained. The verification is performed through modified IEEE 118 node test system, and the optimized results that whether or not containing pumped storage units are compared and analyzed, the applicability of the proposed model and algorithm to solving large-scale multi-objective unit commitment is verified. It could effectively improve economic benefit and environmental protection of power system.**

***Keywords*—pumped storage; wind power; unit commitment; particle swarm; day-ahead optimal dispatch**

## I. INTRODUCTION

In recent years, the wind power application in the grid is becoming more widespread, wind energy has certain intermittent and uncertainty, therefore, the multi-objective optimal dispatching model of power system with wind power has become research hotspot[1]. To suppress the intermittent of wind, compensating the fluctuation of wind energy by other generators is an efficient method to ensure the system stability and economy. Thermal power plants are mostly used to compensate wind randomness. If wind power, load peak or load off-peak difference exceeds a certain extent, the compensated thermal power units will be operating in frequent startup-shutdown or peak regulation, which would seriously weaken network security and economy [2]. Further, the frequent startup-shutdown and running of coal-fired unit, the capacity of which is the 75% of the thermal power installed capacity in the power structure of china[3], will further increase greenhouse gas emission, and result in deterioration of environment. Pumped storage power unit not only has the functions of peak-load regulation and frequency modulation, but also has the capability of fast response and excellent load tracking, which can effectively reduce the installed capacity of thermal power, decrease peak-load regulation depth, improve operational efficiency of the power system[4].

Reasonable optimizing and dispatching the power system containing pumped storage units can promote the efficient utilization of resources and reduce costs. To realize the economic operation of grid-connected wind farm, many scholars, combined with pumped storage units, have done a lot of useful work for grid containing wind farm[5-14]. Based on the day-ahead prediction of load and wind power, an optimal dispatching method of joint daily operation for grid containing wind and pumped storage is given in [5] and [6] to maximize the benefit. But it only considers joint planning for wind power and pumped hydro unit, without any other units. As described in [7], [8] and [9], decomposition and coordination of large-scale of system, mixed integer programming and binary particle swarm optimization algorithm are used to calculate the unit commitment of systems, respectively, but in which merely taken the economic cost as targets without considering environmental protection. In [10], only the power balance of grid with high permeability of wind power is focused on, which resulting of the object function is relatively simple. Fitness function and genetic optimization algorithm are adopted in [11] and [12] to analyze joint optimization dispatching model, respectively. But in which power system are containing wind-power, pumped storage and nuclear power unit without considering hydropower unit. Fuel consumption, carbon emission and power purchasing cost as the objectives, a multi-objective dynamic optimal dispatching model for real provincial power system considering wind power is studied in [13], and the entropy-weighted double base points method is used to get a comprehensive optimal solutions. However it does not detailed descript how to determine the unit commitment reasonably. Considered some practical engineering constraints, an optimization model for daily peak-load regulation is developed to minimize the carbon and sulfur oxides and power purchasing cost of multi-unit power system in [14]. But it did not take unit ramp rate and minimum startup-shutdown times into account which led to too simple. For the complexity of power system and the variety of units, the models given in mentioned literatures exist some disadvantages of over-simple or incomprehensive.

As aforementioned, a day-ahead optimal dispatching model for complex power system containing thermal power, hydro power, wind power and pumped storage units is proposed, in which most of practical engineering constraints, such as power balance, reserve capacity, maximum and minimum capacity of thermal power units, unit ramp rate, the special constraints of hydro power and pumped storage are taken into account. Reasonably arranging unit commitment of pumped storage and determining generation dispatching of thermal power, hydro power, wind-power and pumped storage systems units, taken the objects of the minimize the carbon emission and operating costs, the improved hybrid particle swarm algorithm is adopted to solute the multi-objective model, and validity of the model is verified by improved IEEE 118 node test system and a comparative analysis of the power system whether or not containing pumped storage units is carried out, the results show that the proposed model could effectively solve the problem of large-scale units commitment and improve the requirement of economic and environmental protection of grid. It is provided modeling and solving reference for day-ahead multi-object optimization of power system.

## II. UNIT COMBINATION AND OPTIMIZATION MODELS

### A. Determination of objective function

Hydropower and wind power, whose energy consumption is far smaller than fossil energy, is cleaner energy. To simplify the calculation process, this paper does not consider the startup-shutdown cost of hydropower, nor do $CO_2$ emission of hydropower and wind power.

The two states of pumped storage are simulated with virtual generator and virtual motor[15]. Taken total cost and $CO_2$ emission minimum as object, considered the states switching costs of pumped storage, the objective function is defined by

$$\begin{aligned}\min F1=&\sum_{t=1}^{T}\sum_{i=1}^{Ng}(u_{i,t}C_i(p_{i,t})+u_{i,t}(1-u_{i,t\text{-}1})S_{i,t})\\&+\sum_{t=1}^{T}(\sum_{j=1}^{Np}(S_{pj,t}(I^{g}{}_{j,t},I^{p}_{j,t}))\end{aligned}\qquad(1)$$

$$\min F2=\sum_{t=1}^{T}\sum_{i=1}^{Ng}(u_{i,t}C_{coi}(P_{i,t})+u_{i,t}(1-u_{i,t\text{-}1})S_{coi})\qquad(2)$$

Where $N_g$ is the number of thermal units, $N_p$ is the number of pumped storage units, $C_i(P_{i,t})$ is operation cost function of thermal units, $S_{i,t}$ is start up cost of thermal unit $i$ in period $t$, $u_{it}$ is the state variables of thermal units, $u_{it}=0$ or $u_{it}=1$, and $u_{it}=1$ represents thermal unit $i$ is in operation at time $t$, otherwise $i$ is in outage. $S_{pj,t}(I^{g}_{j,t}, I^{p}_{j,t})$ is the cost function for states transition at $t$ period of pumped storage units, $I^{g}_{j,t}$, $I^{p}_{j,t}$ are the state variable of pumped storage units in different running conditions, respectively.

The operation cost function of thermal units[16]:

$$C_i(p_{i,t})=a_i+b_iP_{i,t}+c_i(P_{i,t})^2\qquad(3)$$

The start-up cost of thermal units[16][17]:

$$S_{i,t}=\delta_i+\sigma_i(1-\exp(T^{off}_{i,t}/\tau_i))\qquad(4)$$

Where $\delta_i$, $\sigma_i$, $\tau_i$ are the coefficients of thermal power unit $i$, $T^{off}_{i,t}$ is the continuous operating or shutdown period of thermal unit $i$ at time $t$.

$CO_2$ emission of thermal power units using different fossil to running is defined by[18]:

$$C_{coi,l}(P_i)=c_{coi,l}(K_{i0}+K_{i1}P_i+K_{i2}P_i^2)\qquad(5)$$

Where $c_{coi,l}(P_i)$ is $CO_2$ emission per hour of thermal power units $i$ using fossil $l$, $K_{i0}$, $K_{i1}$, $K_{i2}$ gained by curve fitting, are calorific coefficients of units, $c_{coi,l}$ is $CO_2$ emission of per million British Thermal unit when the unit uses fossil $l$, (in lb/MBtu), this paper assumes all of the thermal power units are coal-fired unit, the $CO_2$ emission $c_{coi,l}$ equals to 215lb/MBtu[18]. All units satisfy the following constraints..

### B. System power balanced and reserve constraints

$$\sum_{i=1}^{N_g}P_{i,t}u_{i,t}+\sum_{j=1}^{N_p}P_{j,t}+\sum_{k=1}^{N_h}P_{k,t}+\sum_{w=1}^{N_w}P_{w,t}=P_{L,t}\qquad(6)$$

Where $P_{i,t}$ is generation power of thermal power unit $i$ in period $t$, $P_{j,t}$ is generation power of power storage unit $j$ in period $t$, $P_{j,t}$ is positive as the unit is in state of generating electricity, and $P_{j,t}$ is negative as the unit be in state of pumped storage. $P_{k,t}$ is generation power of hydropower unit $k$ in period $t$. In this paper, wind power could be flexible dispatching, and $P_{w,t}$ is grid-connected power of wind power $w$ in period $t$, $P_{L,t}$ is the total of electrical demand of power system in period $t$.

$$\begin{aligned}&\sum_{i=1}^{N_g}u_{i,t}(P_{g\max,t}-P_{i,t})+\sum_{j=1}^{N_p}(P_j^{\max-g}-P_{j,t})+\\&\sum_{k=1}^{N_k}(P_{k\max,k}-P_{k,t})\geq K_LP_{L.t}+K_W\sum_{W=1}^{N_W}P_{W,t}\end{aligned}\qquad(7)$$

Where $P_j^{\text{max-}g}$ is the maximum power generation of power storage $j$, $P_{\text{gmax},i}$ is output upper limit of thermal power unit $i$, $P_{h\text{max},k}$ is output upper limit of hydropower unit $k$ in period $t$, $k_L$、$k_w$ are fluctuation coefficients of load and fluctuation coefficient of wind power respectively, $k_L=k_w=5\%$. It is required that reserve constraints meet the random fluctuation load and wind power.

### C. Thermal power unit and pumped storage unit constraints

The upper/lower limit and ramp rate of thermal power unit

$$P_{g\min,i}u_{i,t} \le P_{i,t} \le P_{g\max,i}u_{i,t} \tag{9}$$

$$-R_{di}u_{i,t} \le P_{i,(t+1)} - P_{i,t} \le R_{ui}u_{i,t} \tag{10}$$

Where $R_{ui}$, $R_{di}$ are the ramp rates of thermal power unit $i$ loading and unloading in period $t$ respectively, $P_{\mathrm{gmin},i}$ is output lower limit of thermal power unit $i$.

The minimum startup-shutdown time constraints of thermal power unit

$$\begin{cases}(X_{i,t-1}^{on} - T_i^{on}) \times (u_{i,t-1} - u_{i,t}) \ge 0 \\ (X_{i,t-1}^{off} - T_i^{off}) \times (u_{i,t-1} - u_{i,t}) \ge 0\end{cases} \tag{11}$$

Where $T_i^{on}$, $T_i^{off}$ are the minimum startup-shutdown time of thermal power unit $i$, respectively, $X^{\mathrm{on}}_{\mathrm{i},t\text{-}1}$, $X^{\mathrm{off}}_{\mathrm{i},t\text{-}1}$ are the continuous power and shutdown time duration of thermal power unit $i$ in period $t$-1, respectively.

### D. Pumped storage unit constraints

There were two different states of pumped storage unit, whose running conditions are simulated by virtual generator and virtual motor, are generation and pumped storage.

Then within each period, the pumped storage unit can only be in one of three states: generation, idle and pumped storage, and power generation $P_{j,t}$ (generation is positive and pumped storage is negative) and water flow $Q_{j,t}$ (generation is positive and pumped storage is negative) in period $t$ are given by[19]

$$P_{j,t} = P_{j,t}^{g} - P_{j,t}^{p} \tag{12}$$

$$Q_{j,t} = Q_{j,t}^{g} - Q_{j,t}^{p} \tag{13}$$

Where $P^g_{j,t}$, $Q^g_{j,t}$ are power generation and water quantity of the $j$th pumped storage unit, which is working in generating state, in period $t$ respectively, $P^p_{j,t}$, $Q^p_{j,t}$ are power consumption and water consumption of the $j$th pumped storage unit , which is working in pumping storage state, in period $t$ respectively, $P_{j,t}$, $Q_{j,t}$ are nonnegative variables.

At different operations, the unit state variables $I^g_{j,t}$ and $I^p_{j,t}$ satisfy

$$I_{j,t}^{g} + I_{j,t}^{p} \le 1 \tag{14}$$

Where $I^g_{j,t}$、 $I^p_{j,t} \in \{0,1\}$ are discrete variables, if the unit $j$ is working in generating state, $I^g_{j,t}=1$, vice versa, $I^p_{j,t}=0$.

If the unit $j$ is working in pumping state, $I^p_{j,t}=1$, vice versa, $I^p_{j,t}=0$.

The operation pumped storage units satisfy constraints as follows

$$P_j^{p\min} \le P_{j,t}^{p} \le P_j^{p\max} \tag{15}$$

$$P_j^{g\min} \le P_{j,t}^{g} \le P_j^{\mathrm{gmax}} \tag{16}$$

Where $P_j^{p\max}$, $P_j^{p\min}$ are the maximum and minimum pumping power of pumped storage unit $j$, $P_j^{g\min}$, $P_j^{g\max}$ are the maximum and minimum generating power of pumped storage unit $j$.

$$Q_j^{p\min} \le Q_{j,t}^{p} \le Q_j^{p\max} \tag{17}$$

$$Q_j^{g\min} \le Q_{j,t}^{g} \le Q_j^{g\max} \tag{18}$$

Where $Q^p_{j,t}$ is the displacement of pumped storage unit $j$ in pumping states at time $t$, $Q^g_{j,t}$ is the displacement of pumped storage unit $j$ in generating power states at time $t$, $Q_j^{p\max}$, $Q_j^{p\min}$ are the maximum and minimum displacement of pumped storage unit $j$ in pumping states, $Q_j^{g\max}$, $Q_j^{g\min}$ are the maximum and minimum displacement of pumped storage unit $j$ in generating power state.

The upper/lower reservoir content constraint of unit

$$V_j^{\mathrm{U}\min} \le V_{j,t}^{\mathrm{U}} \le V_j^{\mathrm{U}\max} \tag{19}$$

$$V_j^{\mathrm{L}\min} \le V_{j,t}^{\mathrm{L}} \le V_j^{\mathrm{L}\max} \tag{20}$$

Where $V_{j,t}^{\mathrm{U}}$, $V_{j,t}^{\mathrm{L}}$ are reservoir content of the upper and lower pumped storage unit respectively, $V_j^{\mathrm{U}\ \max}$, $V_j^{\mathrm{U}\ \min}$ are the maximum and minimum reservoir content of the upper pumped storage unit respectively, $V_j^{\mathrm{L}\ \max}$, $V_j^{\mathrm{U}\ \min}$ are the maximum and minimum reservoir content of the lower pumped storage unit respectively.

The reservoir contents of the upper and lower pumped storage unit ars satisfied constraints as follow:

$$V_{j,t}^{\mathrm{U}} = V_{j,t-1}^{\mathrm{U}} - Q_{j,t}^{g} I_{j,t}^{g} + Q_{j,t}^{p} I_{j,t}^{p} \tag{21}$$

$$V_{j,t}^{\mathrm{L}} = V_{j,t-1}^{\mathrm{L}} + Q_{j,t}^{g} I_{j,t}^{g} - Q_{j,t}^{p} I_{j,t}^{p} \tag{22}$$

### E. The hydro power unit constraints

Hydropower output was quadratic function of hydropower exchange rate and reservoir storage, the time is very short in day-ahead dispatching model, so it is assumed there is no change for reservoir storage. Then the relationship of water-electrical conversion of operation hydropower unit[20],

$$P_{hjt} = A_k H^2{}_{hkt} + B_k H_{hkt} + C_k \tag{23}$$

Where $A_k$, $B_k$, $C_k$ are the coefficients of water-electrical conversion, and the hydropower unit meets

$$P_{h\min,k} \le P_{k,t} \le P_{h\max,k} \tag{24}$$

Where $P_{h\max,k}$, $P_{h\min,k}$ are the maximum and minimum output of hydropower unit $k$, and $P_{k,t}$ is generating power of hydropower unit $k$ in period $t$.

$$H_{h\min,k} \le H_{k,t} \le H_{h\max,k} \tag{25}$$

Where $H_{h\min,k}$, $H_{h\max,k}$ are the maximum and minimum water-transform quantity of hydropower unit $k$, $H_{k,t}$ is the water-transform quantity of hydropower unit $k$ in period $t$.

## III. DETERMINATION OF UNIT COMMITMENT OF THERMAL UNIT

Taken the minimum operation cost as object, considered the starts and stop time and all constraints, The improved IEEE118 nodes system is used to analyze the unit commitment of thermal power on the premise. The IEEE 118 nodes system includes 54 thermal power units, 7 hydropower units, 3 pumped storage units and 3 wind power farms. The maximum output power of the wind farms are 562MW, 500MW, 538MW, respectively[21]. The thermal power unit with longer startup-shutdown time would increase calculation difficulty. To simplify the calculation, the operation states of thermal power unit are determined in advance. CPLEX is adopted to solve the unit commitment involved mixed-integer linear programming. The more units resulted of the solutions of unit commitment more. In this paper, the only one of the solutions is given by Table.I.

TABLE I. THERMAL POWER UNIT COMMITMENTS

| Period($t$/h) | 1-5 | 6 | 7 | 8 | 9-23 | 24 |
|---|---|---|---|---|---|---|
| TG1 | 1 | 1 | 1 | 1 | 1 | 1 |
| TG2-3 | 0 | 0 | 1 | 1 | 1 | 0 |
| TG4-5 | 1 | 1 | 1 | 1 | 1 | 1 |
| TG6 | 0 | 0 | 1 | 1 | 1 | 0 |
| TG7 | 1 | 1 | 1 | 1 | 1 | 1 |
| TG8-9 | 0 | 0 | 0 | 1 | 1 | 0 |
| TG10-11 | 1 | 1 | 1 | 1 | 1 | 1 |
| TG12-13 | 0 | 0 | 0 | 1 | 1 | 0 |
| TG14 | 1 | 1 | 1 | 1 | 1 | 1 |
| TG15 | 0 | 0 | 0 | 1 | 1 | 0 |
| TG16 | 1 | 1 | 1 | 1 | 1 | 1 |
| TG17-18 | 0 | 0 | 0 | 1 | 1 | .0 |
| TG19-31 | 1 | 1 | 1 | 1 | 1 | 1 |
| TG32 | 0 | 1 | 1 | 1 | 1 | 0 |
| TG33-37 | 1 | 1 | 1 | 1 | 1 | 1 |
| TG38 | 0 | 0 | 0 | 1 | 1 | 0 |
| TG39 | 1 | 1 | 1 | 1 | 1 | 1 |
| TG40 | 1 | 1 | 1 | 1 | 1 | 1 |
| TG41 | 0 | 0 | 0 | 1 | 1 | 0 |
| TG42-43 | 1 | 1 | 1 | 1 | 1 | 1 |
| TG44-45 | 0 | 0 | 0 | 0 | 0 | 0 |
| TG 46 | 0 | 0 | 0 | 0 | 1 | 0 |
| TG47-48 | 1 | 1 | 1 | 1 | 1 | 1 |
| TG49 | 0 | 0 | 0 | 0 | 1 | 0 |
| TG50 | 0 | 1 | 1 | 1 | 1 | 0 |
| TG51-52 | 1 | 1 | 1 | 1 | 1 | 1 |
| TG53 | 0 | 0 | 0 | 0 | 0 | 0 |
| TG54 | 0 | 1 | 1 | 1 | 1 | 0 |

Based the results of unit commitment in Table.I, the improved hybrid particle swarm algorithm is used to solve unit output power in power system.

## IV. IMPROVED HYBRID PARTICLE SWARM ALGORITHM

Based the unit commitment and all of constraints, in order to realize the minimum operation cost and CO2 emission, the output power of system units is need to determine, in which includes pumped storage unit, hydropower unit and thermal unit. The parameters of pumped storage units come from [22], and revised as Table.II.

TABLE II. BASIC PARAMETERS OF PUMPED-STORAGE UNIT

| units | PS1 | PS2 | PS3 |
|---|---|---|---|
| $P_j^{g\min}/P_j^{g\max}$（MW） | 100/24 | 100/24 | 204/34 |
| $P_j^{p\max}/P_j^{p\min}$（MW） | 91/91 | 91/91 | 203/203 |
| $V_j^{\mathrm{U}\max}/V_j^{\mathrm{U}\min}$（hm$^3$） | 150/50 | 150/50 | 200/60 |
| $V_j^{\mathrm{L}\max}/V_j^{\mathrm{U}\min}$（hm$^3$） | 450/350 | 450/350 | 450/400 |
| $Q_j^{g\max}/Q_j^{g\min}$（hm$^3$/h） | 15/5 | 15/5 | 20/7 |
| $Q_j^{p\max}/Q_j^{p\min}$（hm$^3$/h） | 5/10 | 5/10 | 5/15 |
| Convert cost at states（$） | 100 | 100 | 100 |

As the improved hybrid particle swarm algorithm is used to solve the operation states of pumped storage unit and the output power of pumped storage unit, hydropower unit and thermal unit. The main steps of algorithm are given as follows:

(1)Input the system of data, initialize the number of particles and that of particle swarm, and random initialized the position and velocity of particles. The state variable of pumped storage units, which are discrete values, is needed to continuous treat.

(2)Based the $CO_2$ emission and operation cost of units, built the objective function $F_{11}$, $F_{12}$ respectively, and the relative relationship is adopted to transform the double objective function into single objective function. Assuming reference quantity was $f_0$, $f_0$=($f_{01}$, $f_{02}$), then $F_2= f_0/f_{01}$, $F_3=F_1/F_{11}$, and the relative relationship $\varepsilon$[23] for $F_2$、$F_3$ is obtained. Gray difference degree is introduced as $F$, and $F$=1-$\varepsilon$, and the larger $\varepsilon$ represents the smaller $F$, which means optimal results are closer to ideal values. In optimization process, the minimum objective function, as reference sequences, is required to update continuously.

(3)Take the minimum total cost and $CO_2$ emission as objects, gray difference degree of objective function is determined, build the unit functions to meet all constraint, and transform the constraint function into the form $C(x)\leq 0$ and $C_{\mathrm{eq}}(x)=0$. Penalty function method is used to build penalty function of the objective function and constraint function, and constraint problem is turned into unconstrained one.

$$G(x)=F(x)+\sum_{i=1}^{m}(r_{1i}\cdot\varphi_i(x))+\sum_{j=1}^{n}[r_{2j}\cdot C_{eqj}(x)]^2 \qquad (25)$$

Where $\varphi_i(x)$=max{0,$C_i(x)$}, $C_i(x)$ is the constraint functions of all inequalities, $C_{eqj}(x)$ is the constraint functions of all equalities，$r_{1i}$、$r_{2j}$ are penalty factors varying with $\varphi_i$ and $C_{eqj}$.

(4)The minimum $G(x)$ as object, all positions of the particles are substituted into objective function and obtained the results. The minimum value, as global extremism, is obtained by compared objective functions with positions of all particles.

(5)Produce the newer population particles, and update the position and velocity of particles by

$$\begin{aligned} v_{mD}(N+1) &= \omega v_{mD}(N_k) + c_1 r_1 [p_{mD}(N) - x_{mD}(N)] \\ &+ c_2 r_2 (p_{gD}(N) - x_{mD}(N)) \end{aligned} \quad (26)$$

$$x_{mD}(N+1) = x_{mD}(N) + v_{mD}(N+1) \quad (27)$$

Where m is particle population size, D is dimensions of particles, N was iterative times, w is the weight, $c_1$, $c_2$ are learning factors, $r_1$, $r_2$ are random numbers even distributing in the range [0,1], $v_{i,j}$ is assigned by users, $v_{i,j} \in$ [-vmax，vmax]. $v_{mD}(N)$ is the velocity of particle m in $D$th dimension at the $N$th iterative, $x_{mD}(N)$ is the position of particle m in the $D$th dimension at the Nth iterative, $v_{mD}(N)$ is the minimum particle m in the $D$th dimension, $v_{mD}(N)$ is the optimum position of particle population in the Dth dimension.

(6)In order to increase the late convergence rate, seek the neighborhood space of global extremism using chaos optimization algorithm. The global extremism is not stopped updating until the given precision or the maximum seeking number are fulfilled. The updated particle swarm is as current swarm and return step (5).

(7)In order to accelerate calculation speed, use synchronous learning factor to improve the learning factors $c_1$, $c_2$ at interval of 20 iterations.

(8)As iterative number is less than the maximum value or fitness value is less than set value, the seeking is stopped and output the objective function and particle, vice verse, return step (5).

## V. ANALYSIS OF EXAMPLES

Using minimum operating costs and carbon emission as a target, the unit commitment and power generations of all units of the improved IEEE118 nodes system are determined.

The main steps of calculation are as follows: firstly, considered all of the constraints, the minimum operation cost and carbon emission are obtained separately, and the two of minimum values are served as the reference. Second, it is calculated by the improved particle swarm algorithm to further identify the unit commitment and power generations of all units, and the operation cost and carbon emission that whether or not containing pumped storage units are compared and analyzed.

Wind power output was predicted to weaken the fluctuation of wind speed, and prediction results of wind power output are given as shown in Fig.1.

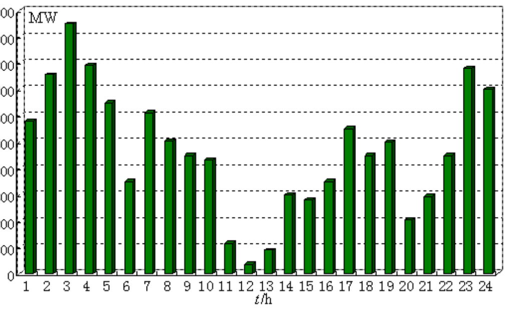

Fig. 1. Predicted wind power data.

The load in day-ahead dispatching model is predicted by the method given in [24], the results as shown in Fig.2.

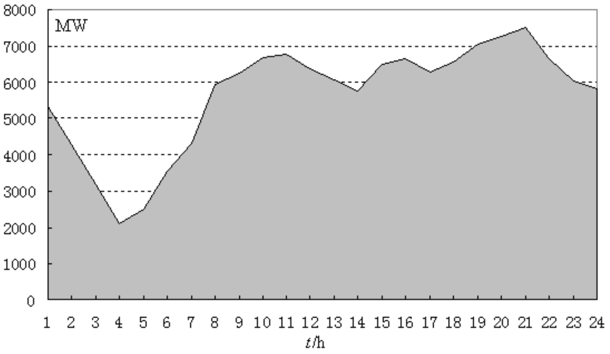

Fig. 2. Predicted load data

The unit commitment of pumped storage is solved with mentioned model and algorithm as shown in Table.III.

TABLE III. UNIT COMMITMENTS OF PUMPED STORAGE

| period（t/h） | PS1 | PS2 | PS3 |
|---|---|---|---|
| 1 | -1 | 0 | 0 |
| 2-6 | -1 | -1 | -1 |
| 8-9 | 0 | 0 | 0 |
| 10 | 0 | 0 | 1 |
| 11-12 | 1 | 1 | 1 |
| 13-14 | 0 | 0 | 1 |
| 15-16 | 0 | 0 | 1 |
| 17-18 | 0 | 0 | 0 |
| 19-21 | 1 | 1 | 1 |
| 23-24 | 0 | 0 | 0 |

Table.III gives the unit states of pumped storage at various times. Where 1 represents the unit in generating state, 0 represents in idle state and -1 represents in pumped state.

In day-ahead dispatching model, the outputs of thermal power units, hydroelectric power units and wind power units without pumped storage are given in Fig.3.

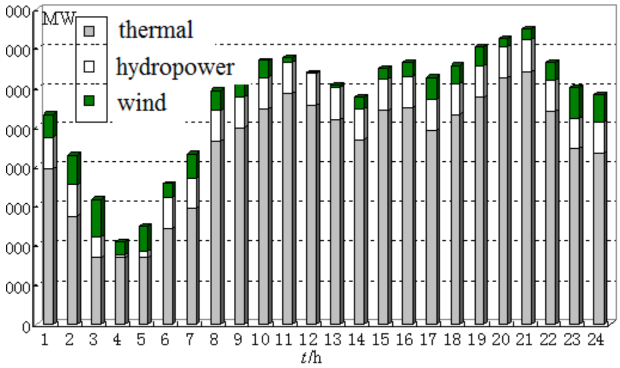

Fig. 3. Output of hydro, thermal, wind power without pumped storage

If there are pumped storage units, the outputs of pumped storage units, thermal power units, hydropower units and wind power farms are given in Fig.4.

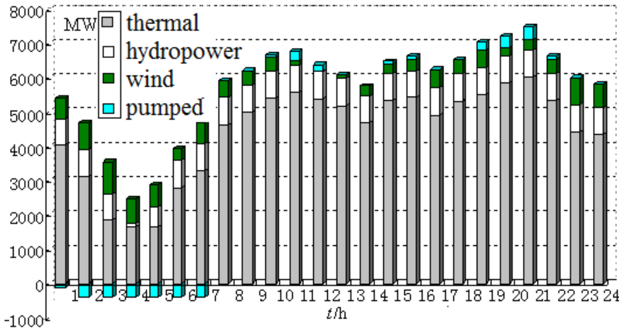

Fig. 4. Output of hydro, thermal, wind, pumped storage power

The $CO_2$ emission and generating costs are obtained by calculation and shown in Table.IV.

TABLE IV. COMPARISON BETWEEN $CO_2$ EMISSION AND TOTAL GENERATING COSTS

| type | cost（M$） | $CO_2$ emission(10 kt) |
|---|---|---|
| System with pumped | 2.31 | 23.3 |
| System without pumped | 2.37 | 23.9 |

It could be seen that the $CO_2$ emission and total generating cost of power system with pumped storage are less than that of the one without pumped storage units, and decreased 2.51% and 2.53%. The results verify that the pumped storage can decrease generating costs and $CO_2$ emission of power system, and prove the effectiveness of the proposed model and algorithm.

To further discuss the applicability of the proposed model and algorithm, grid-connected utilization of wind power(the ratio of actual grid-connection power and prediction generating power) at different times is compared with whether or not containing pumped storage units, as shown in Table.V.

It could be seen from Table.V that grid-connected utilization of wind power considering pumped storage units is doubled that of non-considering pumped storage units at 4 o'clock. The pumped storage units can increase the grid-connected utilization of wind power and reduce abandoned wind. It is further verify that rational planning the wind-hydro-thermal power system with pumped storage can decrease the generating cost and carbon emission effectively.

TABLE V. WIND POWER UTILIZATION

| period（*t*/h） | 1-3 | 4 | 5-24 |
|---|---|---|---|
| utilization of wind power with pumped storage | 100% | 89.9% | 100% |
| utilization of wind power without pumped storage | 100% | 41.3% | 100% |

Considering several of units and constraint conditions in day-ahead dispatching model, this paper proposed the optimization model and algorithm that closer to the actual. It is help to grid dispatching effectively and improving environmental protection and economy of power system.

## VI. CONCLUSIONS

(1)Based on several of real constraint conditions, the day-ahead optimal dispatching model of power system with wind-hydro-thermal-pumped storage units was built. Considering different startup-shutdown periods of units, taking the minimum cost as object, the unit commitment was determined. Then the unit states of pumped storage were identified in day-ahead dispatching model taken the minimum cost and carbon emission as objects. The effectiveness for model solving large-scale multi-objective unit commitment was verified by IEEE 118 nodes system.

(2)Considered the wind power schedulable, Taken the minimum cost and carbon emission as objects, the improved particle swarm algorithm was used to calculate the output power of each unit. IEEE 118 nodes system was adopted to test the model with pumped storage units and the results was compared with that without pumped storage units, it was shown that the operation cost decreased by 2.53%, the $CO_2$ emission decreased by 2.48%. At the same time, the grid-connected utilization of wind power was improved effectively. It was proved feasibility and practicability of the proposed algorithm.

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