Study of Flexible Load Dispatch to Improve the Capacity of Wind Power Absorption

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Abstract. The dispatch method which track the trend of load demand by arranging the generation scheme of controllable hydro or thermal units faces great difficulties and challenges. With the increase of renewable energy sources such as wind power and photovoltaic power introduced to grid, system has to arrange much more spinning reserve units to compensate the unbalanced power. How to exploit the peak-shaving potential of flexible load which can be shifted with time or storage energy has become many scholars’ research direction. However, the modelling of different kinds of load and control strategy is considerably difficult, this paper choose the Air Conditioner with compressor which can storage energy in fact to study. The equivalent thermal parameters of Air Conditioner has been established. And with the use of “loop control” strategies, we can predict the regulated power of Air Conditioner. Then we established the Gen-Load optimal scheduling model including flexible load based on traditional optimal scheduling model. At last, an improved IEEE-30 case is used to verify. The result of simulation shows that flexible load can fast-track renewable power changes. More than that, with flexible load and reasonable incentive method to consumers, the operating cost of the system can be greatly cut down.

1. Introduction
With the large-scale wind power integrated to grid, the anti-peaking characteristic of Wind Power’s output power scales up the valley-to-peak differences. Wind abandoning which is common in China’s three north areas has been a big obstacle blocking renewable energy development in China. Power grid of most China’s north areas where combined heat and power plants take up absolute proportion, thus grid lack substantial reserve capacity to absorb renewable energy. With smart grid’s development, it has been achieved that power grid communicates with end users. Demand-side response has huge potential in acting as reserve for power and shifting power from peak to valley. Flexible load with certain energy storage ability can respond to the instructions of power grid dispatch which not only absorbs power in the peak of grid but also release power in the valley[1-2].

The Ancillary services market’s establishment provide transactions of peak-load regulation. With reasonable compensation and incentive schemes, the market can work very well and there is no need to build up more reserve power plants and retail as well as industry electricity price can be reduced[3].

This paper proposes load dispatch scheme which is shown as figure 1. Through the optimization of the output power of the wind farm, the load aggregator receives the instruction and establishes the local optimal decision model to minimize the adjustment amount, and then feeds back the result to the
system dispatching and system scheduling. And then adjust the instructions to the load aggregator, the final load aggregator will control the command through the distribution network communication system to the user terminal smart meters, intelligent terminals to complete the final control of the flexible load control process[4-5]. The multi-level hierarchical load scheduling model proposed in this paper not only realizes partial controllability on the generation side, but also realizes the partial controllability of the electricity measurement through the demand side response technology, increases the system's peak regulation capacity, of the consumption capacity[6].

![Diagram of Load Dispatch Scheme](image)

**Figure 1. Load dispatch scheme**

2. Background

2.1 Heat Pump Air Conditioner Mathematical Model

Compared to single-refrigerator air-condition, heat pump air conditioner can be used for cooling and heating. The heating or cooling load of air condition is associated with multiple parameters, including the equivalent capacitance of building, effective thermal mass, solar effective radiation area, ventilation rate, equipment efficiency, the weather condition, the thermal energy equipment producing, indoor thermal energy human producing and set temperature of building. To simplify the process, solar radiation, ventilation rate and the influence of indoor heat human producing can be ignored.

When the air condition turns off:

\[
T_{in}^{t+1} = T_o^{t+1} - (T_o^{t+1} - T_i^{t}) e^{-\Delta t / RC}
\]  
(2.1)

When the air condition turns on:

\[
T_{in}^{t+1} = T_o^{t+1} + Q \cdot R \cdot (T_o^{t+1} + Q \cdot R \cdot T_i^{t}) e^{-\Delta t / RC}
\]  
(2.2)

Here:

- \( T_{in} \) represents the temperature of room,
- \( C \) represents the equivalent thermal capacity
- \( R \) represents equivalent thermal resistance
- \( Q \) represents equivalent thermal power
- \( \Delta t \) represents time step
- \( T_o \) represents ambient temperature

Formula 2.1 and 2.2 can be unified formula expressed as

\[
T_{in}^{t+1} = eT_{in} + [1 - (1 - e) \cdot \eta \cdot P_{AC} / A] \cdot T_{out}^{t+1} / S
\]  
(2.3)
In order to avoid air condition frequent switching, air-condition is usually set at some temperature within a certain temperature range and the temperature range is known as the dead zone. Using cooling air condition as example, when the temperature reaches the set upper temperature, the air condition began to work until the temperature reaches the lower limit[7-8]. By changing the operating temperature range of air condition, the air condition can be controlled to work, which is shown in Figure 2, the indoor temperature T change between $T_{\text{max}}$ and $T_{\text{min}}$. The electric power $P_t$ of air condition is pulse sequences with different time intervals.

![Figure 2. Controlled capacity forecast of regenerative air condition](image)

Controlled capacity of air condition is the maximum load scheduling at the moment in scheduling period air-condition aggregators can provide. According to local weather information, managing air-condition capacity as well as the appropriate temperature set by users, load aggregators forecast controllable capacity effectively[9].

Since there are many different types of air condition, this paper adopt a method which aggregate air conditions with similar equivalent thermal parameters into a group under one unified "control loop", so you can ensure that each group remains basically same in load scheduling capacity, specific principle is shown as Figure 3:

![Figure 3. alternative control strategy of air conditioners](image)

Suppose there are 10 air conditions in each group, the thermodynamic characteristics of each air-conditioning is basically the same, while the adjusted room set temperature and the ambient temperature is the same, each air-conditioning adjusted so that the same indoor temperature change required for the same power. By calculating the temperature was raised to room temperature to set the maximum time required, for air conditioning and refrigeration by the time from the maximum
temperature to a minimum temperature is required, the entire cycle is divided into 10 intervals from a lowest set temperature, figure 4, in which the first seven intervals air conditioning is shut down, the follow-up interval of 3 is turned on, assuming that each air conditioner through the "loop control" approach to all air-conditioning control, after a pre-conditioned air-conditioned state delay a time interval so by dynamically adjusting air conditioning switch group to ensure that the desired air conditioning load power group remained unchanged. Assume, for example the air conditioning turned on each time, closing time, each air-conditioning if required power, the air conditioning group, the total power is cut.

3. Load Aggregator Optimization Model and Unit Commitment

3.1. Heat pump type load aggregator optimization decision control model

Load Aggregator's operational management optimization objective is to minimize the total electricity purchased at each moment by scheduling flexible loads such as heat pump-type air conditioning loads, regenerative electric boilers, and electric vehicles.

3.1.1. Objective function: Load reduction to meet the power system peak shaving task of auxiliary services, air conditioning load aggregator declared to the power company to cut capacity, the power company after optimization calculation, while meeting the system safety check, the load reduction requirements issued to each load aggregator, The load aggregator obtains the actual load reduction capacity by bidding[10].

Suppose that the load reduction capacity assigned to load aggregator $k$ by the grid is $D_k(t)$. Air conditioning in the state of the moment is $S(t)$, $S(t)=0$ Indicates that the air conditioner is in the stop state, $s(t)=1$, Indicates that the air conditioner is on. The load-shedding capacity provided by the aggregator at all times is:

$$G_t(k) = \sum_{i=1}^{n} s_i(t) \times P_i(t)$$  \hspace{1cm} (3.1)

The time-load aggregator load reduction provides a capacity deviation from the system schedule

$$e_t(k) = G_t(k) - D_t(k)$$  \hspace{1cm} (3.2)

The objective function of the load aggregator optimization control decision model is the revenue of the load aggregator, equal to the gain from the grid minus the user compensation cost. The power grid at each time the market clearing price is equal to the bid of all successful load aggregators the highest offer $\eta_{\max}(t)$ . For each load aggregator, when the load aggregator's actual load reduction is less than the scheduled schedule reduction, it is calculated according to the actual load reduction; if the scheduled load reduction is exceeded, the load reduction required by the safety plan is calculated. If the load reduction is less than the maximum allowable deviation of the scheduled dispatch plan, the grid will impose a fine on the excess capacity reduction, assuming a unit capacity penalty $\gamma_{MW \cdot h}$

$$F_t(k) = \begin{cases} \sum_{i=1}^{M} \eta_{\max} D_t(k) \Delta x, G_t(k) \geq D_t(k) \\ \sum_{i=1}^{M} \left[ \eta_{\max} G_t(k) - \gamma \delta_t(k) \right] \\ G_t(k) < D_t(k) \end{cases}$$  \hspace{1cm} (3.3)
The compensation rate is: The compensation paid by the aggregator to the user is

\[ F_2(k) = \gamma_2 \sum_{t=1}^{M} G_t(k) \Delta x \quad (3.4) \]

The objective function is the payoff of load aggregation:

\[ F(k) = F_1(k) - F_2(k) \quad (3.5) \]

3.1.2. Constraints.

(1) indoor temperature limit set on the upper and lower limits

\[ T_{\text{room}}^{\text{min}} \leq T'_{\text{room}} \leq T_{\text{room}}^{\text{max}} \quad (3.6) \]

(2) upper and lower air conditioning capacity constraints

\[ Q_{\text{min}} \leq Q \leq Q_{\text{max}} \quad (3.7) \]

In this paper, the packet sorting algorithm can be used to adjust the total load power by controlling the reference temperature setting of each group, and then the total load power can be effectively adjusted by superimposing each group. In each group of air conditioning load, the air conditioning load is divided into two groups: the operation group and the shutdown group. The operation group is arranged in descending order. The shutdown group is arranged in ascending order. The upper limit of the temperature setting in the operation group can be closed to reduce the load demand. Of the load can be switched on by way of increased load power to adjust the load size[11-12].

4. Day-ahead scheduling optimization model

In this paper, the load regulation is added to the load in the traditional economic dispatching load load reduction. The load reduction reduction is considered in each load node, and the load reduction time and load reduction are taken into account. The compensation cost of compensation load reduction is considered in the objective function. At the same time increase the number of economic dispatch a few days ago, the economic scheduling model from the previous 24-hour interval of 15min to 96 nodes. Considering the randomness and volatility of wind power in the optimization model, the wind speed prediction model based on SVM is established, and the prediction accuracy can reach ± 20%.

The running cost of the wind turbine is negligible, the objective function is the coal consumption cost, the start-stop cost and the user compensation cost are minimum[13]:

\[ \min \sum_{t=1}^{N} \sum_{i=1}^{M} \left[ f_i(P_t) * I_t + ST_i \alpha_i + SD_i \beta_i \right] + \sum_{m=1}^{M} \gamma_m * P_{L,m} \quad (4.1) \]

Here:
\[ ST_i, SD_i \] Denote start-up costs and downtime costs for unit i, respectively;
\[ \alpha_i, \beta_i \] represent the start and stop status variables of a conventional unit, unit i is started at time t, \[ \alpha_i \] equal to 1, otherwise equal to 0; When unit i stops at time t, \[ \beta_i \] equal to 1, otherwise equal to 0
\[ \gamma_i, \Delta P_i \] Denote the compensation price of load aggregator and load demand adjustment respectively

The user compensation price adopts the time-sharing price TOU, and the compensation price is different in different load periods.

A few days ago the scheduling decision model constraints are as follows:

(1) system power balance constraints (excluding network loss):

\[ \sum_{n=1}^{N} P_n * I_n + \sum_{j=1}^{N} P_{W_j} + \sum_{i=1}^{M} \Delta P_i = P_{D,t} \quad (4.2) \]

(2) system rotation reserve capacity:

Positive rotation reserve constraint:
\[
\sum_{i=1}^{N} R_{u,i} I_{u} \geq \Delta P_{d,i} + \mu \% P_{w,i} \\
R_{u,i} = \min \left( P_{i,max} - P_{u}, U R_{i} \Delta T \right) 
\]

Negative spin reserve constraint:
\[
\sum_{i=1}^{N} R_{d,i} I_{d} \geq d \% P_{w,i} \\
R_{d,i} = \min \left( P_{u} - P_{i,min}, D R_{i} \Delta T \right) 
\]

(3) the upper and lower limits of output unit:
\[
P_{i,min} \leq P_{u} \leq P_{i,max} 
\]

(4) unit climbing rate constraints

By the rate of climbing restrictions, the conventional unit of output per unit time change can not be higher than a certain value, the specific formula is as follows:

Ramp-up Rate Constraint:
\[
P_{u,it} - P_{(t-1)it} \leq U_{R0} \Delta T 
\]

Down-ramp rate constraint:
\[
P_{(t-1)it} - P_{u,it} \leq D_{R0} \Delta T 
\]

(5) conventional unit start-stop time constraints:
\[
T_{u}^{i} \geq T_{u,n}^{i}, \quad T_{d}^{i} > 0 \\
-T_{d}^{i} \geq T_{d,n}^{i}, \quad T_{d}^{i} < 0 
\]

(6) Line current security constraints

\[
-P_{i,max} \leq P_{u} \leq P_{i,max}, \quad l \in L 
\]

(7) load adjustment capacity constraints

Load Adjustment Capacity The maximum aggregate load capacity declared by the aggregator
\[
P_{LA,m} < P_{LA,m} < \bar{P}_{LA,m} 
\]

In [9], an optimal allocation algorithm for building energy-efficient power plants with household temperature control load considering electrical comfort constraints is proposed. The state-queue response control model is used to control the heat pump load switch status. The simulation results show that the energy- The Rationality of the Most Allotted Model. In [10], a multi-objective optimization model of air conditioning start-up is established to ensure that the room temperature is within a certain range, and the temperature constraint is converted into the air-conditioning continuous shut-off time constraint and the shut-down time open time proportion relation.

5. Computational results and analysis

In order to verify the effectiveness of the proposed dispatch strategy of Heat pump air conditioners, several simulations are made with yalmip optimization toolbox in Matlab software. The study case in figure 4 based on IEEE-30 node system is added 5 load aggregators in nodes 2, 4, 7, 12, and 16.

| Load Aggregators | Bidding capacity (MW) | Bidding price ($/MW) |
|------------------|------------------------|----------------------|
| LA1              | 2                      | 8                    |
| LA2              | 10                     | 8                    |
| LA3              | 3                      | 8                    |
| LA4              | 5                      | 8                    |
| LA5              | 7                      | 8                    |

Table 1. Load Aggregators bidding information
Figure 4. IEEE-30 bus system with 5 load aggregators

1. Economic Optimization Scheduling

The following table shows the maximum load reduction capacity and the corresponding compensation price declared on the load aggregation system for 96 time periods (15-minute intervals), as shown in Table 1. Scheduling optimization model, the system scheduling optimization by calculating the next day peak hours 10:00-12:00 and 20:00-22:00 LA1-LA5 load of the five load-sharing program, as shown in Table 2.

Predictive load reduction capacity and reporting capacity of LA1-LA5 air conditioning load aggregators can be obtained through the controllable air conditioning prediction method.

Table 2. The Results of Dispatch Optimization from 10:00-12:00

| Period at 15 minutes intervals | Load Aggregators | Bidding price | Amount scheduling capacity |
|-------------------------------|------------------|---------------|---------------------------|
| 1                             | A 1.5, B 2.5, C 5, D 0, E 2 | 8             | 11                        |
| 2                             | A 1.5, B 2.5, C 5, D 0, E 2 | 8             | 11                        |
| 3                             | A 1.5, B 2.5, C 5, D 0, E 2 | 8             | 11                        |
| 4                             | A 1.5, B 2.5, C 5, D 0, E 2 | 8             | 13                        |
| 5                             | A 1.25, B 2.5, C 5, D 2, E 2 | 8             | 12.75                     |
| 6                             | A 1.25, B 2.5, C 5, D 2, E 2 | 8             | 12.75                     |
| 7                             | A 1.25, B 2.5, C 5, D 3, E 3 | 8             | 13.75                     |
| 8                             | A 1.25, B 2.5, C 5, D 3, E 3 | 8             | 11.75                     |

2. Air Conditioning Load Aggregator Decision-Making Control

The parameters of air conditioner regulated by the five load aggregators refer to [12]. For example, a total of 2,000 users in the region managed by LA1 participate in direct control of air conditioning where the average rated cooling power of is 2.5KW, the average energy efficiency of the compressor is 2.7 and indoor space temperature is set 23°C-27°C. The air-conditioning user's equivalent thermal parameter model is 0.96, the heat transfer coefficient is 0.18/KW·°C⁻¹.

Every 2000 air-conditioners’ can be looked as one ideal air condition with the method followed: the 2000 air conditioners will be divided into 100 groups in uneven distribution in order to improve the efficiency of air-conditioning combinatorial optimization. The first 10 groups has 40, 35, 25, 20, 15, 15, 10, 10, 10 elements and the other 90 groups repeat the first 10 grouping. In order to ensure
the diversity of the air conditioning loads, different types of air conditioning load equivalent thermal parameters model initializes in its parameter range. Air conditioners is controlled by priority list method in each group. Figure 5 shows the average temperature change curve for the air conditioning load group.

![Figure 5. average temperature change curve for the air conditioning load group](image)

The air-conditioning load aggregator's decision model is a predictive decision-making control model, known as the state space expression of the air conditioning load and room temperature range to determine the air conditioning grouping cycle control instructions and the average temperature curve, as shown in Figure 5. As the optimization problem itself is nonconvex, and for mixed integer quadratic programming problem, the solution is difficult.

The objective function of the air conditioning load optimization is to reduce the actual load and to minimize the error of the scheduling command type 2, the calculated result is 37.1484MW.

6. Conclusion
In this chapter, we study the feasibility of the condition of load dispatch. At present, two-way communication between the network side system and the user in the smart grid provides the possibility of load scheduling. At the same time, according to whether the load can be adjusted and have a certain energy storage characteristics of the load into rigid demand load and flexible load. Then, three kinds of flexible load heat pump air conditioners, regenerative electric boilers and electric vehicles are discussed respectively, and the factors that they need to consider in order to meet the load dispatch are analyzed. Heat pump type air-conditioning thermodynamic constant is short but fast, can be used for hours of emergency power adjustment, and regenerative electric boilers and electric vehicle energy storage characteristics are relatively good, but the regulation speed is slow, can be used to migrate the load, smooth load Curve, to achieve load shaping, improve system operation efficiency and economy.

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