Joint optimal dispatch of electric vehicles and air conditioning loads in office buildings based on demand response

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Abstract. Centralized use of air conditioning loads and the disordered charging and discharging of large-scale electric vehicles in cities have become the important reason for peak-valley difference increase of grid load in summer, deepening the contradiction between supply and demand during the peak period. Therefore, it is of great significance to improve power grid load characteristic and realize stable and economic operation of power grid by excavating peak shaving potential of large-scale air conditioning loads and electric vehicles. Taking into account the dispatching cost of power grid companies and the benefits of power users, a joint optimal dispatching model of electric vehicle and air-conditioning load is proposed. The power grid provided a low price compensation for loads and a high price compensation for EVs due to its battery loses. The objective function is optimized with the minimum load difference rate of office buildings and the maximum total revenue of users. Analysis of calculation example shows that air conditioning load and electric vehicle have complementary characteristics in energy use, and the joint optimal dispatching has certain effect on office building "peak load reduction", eliminating "secondary peak load" and improving electricity user income.

1. Introduction
As typical refrigeration equipment in summer, Air Conditioning (AC) has an increasing proportion of the load, which often constitutes peak load; Meanwhile, the disordered charging and discharging of large-scale electric vehicle often leads to the phenomenon of "peak on peak", which makes the form of power supply more tense. Therefore, it is an urgent problem to allocate air conditioning load and electric vehicle energy.

Electric vehicles and air-conditioning loads can be used as energy storage units and take part in peak shaving and frequency modulation of power grid as Demand response resources [1], [2]. Based on the analysis of the energy usage habits of electric vehicles, the mathematical model of the peak-valley time-sharing charging and discharging electricity price is proposed [3]. In order to effectively reduce the peak and valley difference of the grid, a layered scheduling framework for orderly charge and discharge of electric vehicles in a long time scale is proposed [4]. A distributed optimal charging algorithm suitable for plug-in electric vehicles is proposed to balance load fluctuations and reduce peak-valley differential by reasonable charging [5].

Air conditioning is also used as a regulatory resource to reduce community operating cost by classifying community power users and establishing time-sharing scheduling model with maximum user income [6]. The phenomenon of load aggregation fluctuation is a serious problem of aggregating AC loads, so a separation control method of upper and lower limits of air conditioning temperature regulation is proposed to solve the problem [7]. Air conditioners and other electric users could participate...
in the real-time operation of the power system in a layered scheduling scheme, which provides auxiliary services for the stable operation of the power system [8],[9].

Most of the above domestic and foreign researches are based on the background of large power grid, and EV or AC load are used as peak load regulation resources for dispatching alone. However, in actual grid dispatching, the adjustable capacity of electric vehicles and air-conditioning load is relatively limited and large-scale dispatching is difficult to implement. In this paper, the dynamic equations of room temperature and air conditioning power are derived based on the equivalent thermal parameter model of small industrial air conditioning. Secondly, the calculation methods of various expenses including charge and discharge subsidy are given. Secondly, a joint optimal scheduling model with the minimum load difference and maximum user benefit is established. Finally, an example of an office building is given to verify the effectiveness of the model.

2. Load characteristics and demand response

Air-conditioning load and electric vehicles account for a large proportion of electricity users in Office buildings. The change of their model of electric consumption is of great significance to the building electricity consumption. The typical daily load distribution in summer is shown in figure 1.

![Figure 1. Load distribution curve of office building](image)

In the case of disordered charging, on the one hand, the centralized charging period of electric vehicles is 12:00 -- 13:00 and 16:00 -- 18:00, which further increases the peak load of office buildings and forms "secondary peak load". On the other hand, most EV charging periods are in peak electricity price periods, and charging costs are high. Therefore, how to reasonably optimize the operation of air conditioning load and electric vehicles is a practical problem that is beneficial to power grid companies and power users.

Demand Response (DR) refers to the power users changing the habit of using electricity under the condition of electricity price incentive, and actively participating in the energy interaction of power grid operation. Users can respond to the change of electricity price autonomously and change the electricity quantity as electricity price elasticity [10]. The elasticity coefficient, elasticity matrix and TOU price model are shown in equations (1), (2) and (3).

\[
\xi = \frac{\partial d}{\partial p} / p
\]

\[
E = \begin{bmatrix}
\xi_{11} & \xi_{12} & \cdots & \xi_{1N} \\
\xi_{21} & \xi_{22} & \cdots & \xi_{2N} \\
\vdots & \vdots & \ddots & \vdots \\
\xi_{N1} & \xi_{N2} & \cdots & \xi_{NN}
\end{bmatrix}
\]
1.2 \ [08:00 \ 12:00] \ [16:00 \ 20:00]
0.9 \ [12:00 \ 16:00] \ [20:00 \ 12:00]
0.4 \ [24:00 \ 08:00]

TOU
t
Pt

\[ t \subseteq [08:00 \ 12:00] \cup [16:00 \ 20:00] \]
\[ t \subseteq [12:00 \ 16:00] \cup [20:00 \ 12:00] \]
\[ t \subseteq [24:00 \ 08:00] \]

Where \( d \) is the quantity demanded and \( P \) is the electricity price; \( \xi_i \) is the self-elastic coefficient, \( \xi_{ij} \) is the mutual elastic coefficient.

3. Model of air-conditioning load
The simplified equivalent thermal parameters \( ETP \) [11] can be used to express the thermodynamic principle of air-conditioning units for home users and small industrial users, and its simplified first order differential equation of ETP model is given.

\[
\begin{align*}
T_i^{t+1} &= T_o^{t+1} - (T_o^{t+1} - T_i^t)\varepsilon, \quad s = 1 \\
T_i^{t+1} &= T_o^{t+1} - P_{cx} / A - (T_o^{t+1} - P_{cx} / A - T_i^t)\varepsilon, \quad s = 0
\end{align*}
\]

Where \( s \) is the state of air conditioning, 1 means off, 0 means on; \( T_i^t \) is the indoor temperature at time \( t \), °C; \( T_o^{t+1} \) is the outdoor temperature at time \( t+1 \), °C; \( \varepsilon \) is the heat dissipation function, and the value is 0.96; \( A \) is the thermal conductivity, 1/(kW·°C⁻¹) and the value is 0.18; \( P_{cx} \) is the rated cooling capacity of the air conditioner at time \( x \).

The average rated power of the air conditioner in a certain period is \( \bar{P} \), and the outdoor temperature is a constant value \( T_{max} \) during the regulation period. Combining expressions (4) with room temperature adjustment margin \( [T_{min}, T_{max}] \), the load control period, as well as the time of opening \( \tau_{on} \) and closing \( \tau_{off} \), and the results are as follows.

\[
T_{max} = T_{on} (1 - e^{\varepsilon \tau_{off}}) + T_{min} e^{\varepsilon \tau_{off}}
\]

\[
T_{min} = (T_{on} - \bar{P} / A)(1 - e^{\varepsilon \tau_{on}}) + T_{max} e^{\varepsilon \tau_{on}}
\]

\[
\tau_c = \tau_{off} + \tau_{on}
\]

There are \( n \) air conditioners in the office building, and the load is divided into \( \tau_c \) different states within a control cycle. The time in the "on" and "off" states is respectively \( \tau_{on} \) and \( \tau_{off} \). The air conditioning load was divided into \( \tau_c \) groups for rotation control on average. Each group of air conditioners is in different states at the same time, and the time interval of each state is 1 minute. In the next minute, there is always a group of air conditioners that are closed and another group of air conditioners that are opened. In this way, the number of air conditioners that are opened at each time can be guaranteed to be the same.

From the above, the controllable capacity \( C_t \) [12] (kW) of air-conditioning load involved in the regulation in time period \( t \) can be obtained as follow

\[
C_t = \frac{\tau_{off}}{\tau_c} \times n\bar{P}
\]

4. Joint optimal scheduling
4.1. The objective function
(1) Air-conditioning load dispatch cost
\[ C_{cl} = \sum_{i=1}^{N} \gamma_i C_r(i) \Delta t \]  

(9)

Where, \( C_r(i) \) is the regulating capacity of air-conditioning load in period \( i \); \( \Delta t \) is the scheduling interval, with the value of 15 minutes; \( N \) is the total number of scheduling time periods.

(2) The charging compensation cost of EV

\[ C_{ch} = \sum_{i=1}^{N} \sum_{j=1}^{n_{EV}} (1 - \gamma) P_r u_{EV}(i, j) \eta_r P_{EV}(i, j) \Delta t \]  

(10)

Where, \( n_{EV} \) is the number of electric vehicles; \( \gamma \) is the discount rate of electricity price; \( P_r \) is real-time electricity price; \( P_{EV}(i, j) \) represents the charging power (kW) of EV \( i \) at moment \( j \); \( \eta_r \) represents the charging efficiency of EV.

(3) Electric vehicle discharge compensation costs

\[ C_{dc} = \sum_{i=1}^{N} \sum_{j=1}^{n_{EV}} P_{EVd}(i, j) \frac{1}{\eta_d} P_{EVd}(i, j) \Delta t \]  

(11)

Where, \( P_{EVd}(i, j) \) is the actual discharge power (kW) of EV at moment \( j \), and \( \eta_d \) is the discharge efficiency of EV.

(4) Load difference ratio \( \omega \) (%)

Assume that the original load of the building in period \( i \) is \( L_o(i) \), \( i = 1, 2, \ldots, N \), the load of period \( j \) after scheduling is

\[ L_{si} = L_o(i) + \sum_{j=1}^{n_{EV}} (P_{EV}(i, j) - P_{EVd}(i, j)) - C_r \]  

(12)

\[ \omega = \frac{\max(L_{si}) - \min(L_{si})}{\max(L_o(i))} \]  

(13)

(5) V2B cost of EV

\[ C_{V2B} = \sum_{i=1}^{N} \sum_{j=1}^{n_{EV}} \gamma P_r u_{EV}(i, j) P_{EV}(i, j) \Delta t - C_{dc} + C_{dc} \]  

(14)

(6) Total cost of disordered charging

\[ C_{cs} = \sum_{i=1}^{N} \sum_{j=1}^{n_{EV}} P_r P_{oc}(i, j) \Delta t \]  

(15)

Where, \( P_{oc}(i, j) \) is the charging power (kW) of EV \( j \) at the moment before dispatching.

(7) Total users’ revenue

\[ C_{up} = C_{cs} - C_{cl} - C_{V2B} \]  

(16)

(8) The objective function

\[ \begin{cases} \min & \omega \\ \max & C_{up} \end{cases} \]  

(17)

4.2. The constraint

(1) On and off time constraint of AC
\[ T_i^\text{off}(t) \leq T_{\text{off}} \]  

\[ \sum_{j=0}^{t} T_i^\text{on}(j) \geq \frac{T_m}{T_{\text{off}}}, \sum_{j=0}^{t} T_i^\text{off}(j) \neq 0 \]  

Where, the initial state is \( T_i^\text{off}(0) = 0 \), \( T_i^\text{on}(0) = T_m \), \( i = 1, 2, \ldots, n \).

(2) Battery capacity constraints for EV

\[ \text{SOC}_{\text{min}} \leq \text{SOC}(t) \leq \text{SOC}_{\text{max}} \]  

Where, \( \text{SOC}_{\text{min}} \) and \( \text{SOC}_{\text{max}} \) are respectively the lowest and highest battery capacities of electric vehicles. Taking into account the service life of batteries, the value is 0.2 and 0.9.

(3) Charge and discharge time constraint

\[
\begin{cases}
T_c \subseteq [12:00 \ 16:00] \\
T_d \subseteq [8:00 \ 12:00] \cup [16:00 \ 18:00]
\end{cases}
\]  

(4) Charge and discharge state constraints

\[ P_{\text{EV}}(i, j) \cdot P_{\text{EV}}(i, j) = 0 \]  

4.3. Solution for model

In this paper, the model is a multi-objective mixed positive number programming problem, and the variables are the switching state of air-conditioning load and charging and discharging state of electric vehicles at all times during working hours. The commercial software CPLEX12.6 and Matlab are used to solve the problem.

5 The analysis of example

5.1. Parameter Settings

In the example, 180 air conditioners can be dispatched in an office building. The rated power of a single air conditioner is 2.5kW, and the energy efficiency ratio is 2.7. There are 30 electric cars, all of which are BYD e6. The parameters are shown in Table 1.

| Parameter                  | Value  |
|----------------------------|--------|
| Battery capacity(kW.h)     | 58.5   |
| The battery price(¥)       | 60000  |
| Number of charges          | 4000   |
| Rated charge-discharge power(kW) | 9.6   |
| Charge-discharge efficiency (%) | 90, 85 |

A scheduling period is 15 minutes, and the scheduling time is the normal working time [8:00 18:00]. \( \gamma = 0.2, \gamma_0 = 0.2, C_{\text{sh}} = 0.256, T_{i_{\text{min}}} = 22, T_{i_{\text{max}}} = 26, T_o = 36 \).

5.2. Analysis of simulation results

The joint optimal scheduling results are shown in figure 2. Air conditioning load control period is 12:00 -- 16:00; Electric vehicles are charged from 12:30 to 15:30; Discharge period is from 16:30 to 18:00. At this point, the load difference rate is 22.22%, and the dispatching cost is 722.7 ¥, among which the air-conditioning load compensation cost is 160 ¥, the electric vehicle charge compensation cost is 158.4 ¥.
¥, and the electric vehicle discharge compensation cost is 404.3 ¥. The cost of participating in V2B for electric vehicles is 359.4 ¥, the total cost of disorderly charging is 672.2 ¥, and the total profit of users is 472.8 ¥. For a single electric vehicle with the same battery capacity change, the disorder charge cost is 19.2 ¥. In V2B mode, the cost is 12.0 ¥, which reduces the cost by 7.2 ¥.

![Figure 2. Load curves before and after dispatching](image)

As shown in figure 4, when joint optimal scheduling is adopted, air-conditioning load regulation time will be shortened, reducing the impact on users' energy comfort. Electric vehicles charge in the air conditioning load regulation period, realizing the complementary use of energy, and reduce the load peak; The effective discharge of electric vehicle before off-duty eliminates the "secondary peak" of load.

5.3. Analysis the influence of air-conditioning load control mode
This paper adopts the control strategy of "group rotation start and stop" (GRSS) of air-conditioning load, and the conventional strategy also includes "both on and off" (BOF). The load curve is shown in figure 3.

![Figure 3. Load curves under different control modes](image)

From figure 3, when the air-conditioning load adopts the strategy of "group rotation start and stop", the power consumption of the office building remains constant and lower than the raw load power during the air-conditioning load regulation period. When the strategy of "both on and off" is adopted, the effect of load equivalent reduction can also be achieved. However, when the air conditioning load is turned on at the same time, the office power is close to or even exceeds the original load power in a short time due to the centralized charging of electric vehicles, and the "peak load real-time reduction" is not well realized. The results show that the combined optimal scheduling of air conditioning load and electric vehicle is more suitable to adopt

6. Conclusion
In order to alleviate the problems brought by the shortage of electricity consumption during the peak period in summer and the disordered charging of electric vehicles, this paper takes the air conditioning load and electric vehicles as peak load regulation resources and the office building as a typical scene.
Under the premise of fully considering the interests of power users and power grid companies, the air conditioning load is compensated with low electricity price, and electric vehicles adopt the demand response mode of charging discount electricity price and discharging real-time electricity price compensation. An optimal scheduling model with the objective function of minimum load difference and maximum user revenue is established. Example results show that. a) The joint optimal scheduling model can reduce the peak load, and eliminate the disorderly charging of electric vehicles caused by the "second peak load". b) In the same battery capacity changes, the cost of a single electric vehicle by 7.2 ¥.

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