Flexible Load Scheduling Methods for Load Aggregators

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Abstract. Four typical flexible load resources in the customer side, i.e., industrial users, central air-conditioning load, electric vehicles, and energy storage stations, are first considered and modelled in this paper. Then, we present the combined dispatching model for load aggregators involving four flexible load resources mentioned above. Our results of numerical experiments demonstrate that on one hand, four typical flexible load resources on the user side can be dispatched to decrease peak-load as well as increase valley-load. On the other hand, scheduling the load resources with energy storage properties operates in accordance with pre-instructions. Compared with independent scheduling, the combined scheduling of various flexible loads can achieve significant advantages of various load characteristics and strengthen the dispatching ability of load aggregators. The methodology proposed in this paper can effectively promote renewable energy integrations, improve grid stability, and then reduce operating costs of load aggregators.

1. Introduction

With the development of science and technology, in order to cope with the increasingly severe traditional energy crisis and environmental problems, the grid-connected capacity of renewable energy such as wind power and photovoltaics has been increasing. However, renewable generation has the characteristics of strong randomness and high volatility. In 2020, the cumulative installed capacity of wind and photovoltaic power in China has reached 281 million kW and 253 million kW respectively. As the increasing of the proportion of renewable energy in the energy structure, it will be difficult to achieve the balance of power system supply and demand by solely relying on the regulation of the power generation side. Currently, how to tap the potential of load dispatching from the user side to increase the stability of the power system has become a popular research topic in the world.

On the other hand, with the vigorous advancement of smart grids, user-side equipment tends to be diversified. Increasing applications of flexible loads such as distributed energy storage stations and electric vehicles can promote the interaction between the grid side and the user side. At the same time, the promotion of smart data acquisition equipment has greatly enhanced the observability on the user side. Fully mobilizing the enthusiasm of load users to participate in load regulation can make the whole power system more efficient, low-carbon and intelligent. Due to the large number of flexible and adjustable resources on the user side, the load aggregator can guide the load users to actively participate in dispatching, which can promote the ability of renewable consumption, improve the safety and stability of the power grid, and realize the reasonable allocation of resources.
With the continuous developing of power market reform, load aggregators are one of the essential market entities for user-side flexible and adjustable resources participating in the power dispatch. Although there are lots of distributed resources on the demand side, which have considerable scheduling potential, the enthusiasm for load users to participate in the demand side response is not enough. Load aggregators can aggregate a large number of distributed adjustable resources to form load groups with considerable capacity, which can participate in the demand responses to make full use of user-side flexible resources\(^5\).

At present, the existing research mostly studies from the perspective of power grid dispatching agencies or power companies, optimizing dispatching with the total operating cost of the system on the grid-side as the main optimization goal. Load aggregators only participate as the executor of the above dispatching results. Literature [1] demonstrates the feasibility and peak-shaving effect of air-conditioning load control technology by establishing a central air-conditioning cluster model and reasonably dispatching the air-conditioning load for incentive demand response. Literature [2] and [3] optimize electric vehicle load group scheduling from the perspective of load aggregators. Literature [4] discusses the potential of using energy storage stations to increase wind power benefits in the day-ahead and balanced markets. The above research mostly focuses on the independent control of certain adjustable load resource by the load aggregator. Compared with independent scheduling, the combined dispatch of various flexible loads can achieve complementary advantages of various load characteristics and strengthen the dispatch ability of load aggregators\(^7\).

In this paper, we aim to reduce the operating costs of load aggregators by dispatching various flexible load resources together\(^6\). We first established four typical flexible load models to evaluate their dispatching potential. Specifically, based on the power supply structure and the load distribution characteristics in Shaanxi Province, we propose a combined scheduling model for load aggregators to control industrial loads, air-conditioning loads, electric vehicle loads and energy storage power stations together. Then, we conducted the calculation example analysis for the combined scheduling model in GAMS environment. Our numerical results show that through the optimal dispatch of load aggregators, the industrial load is significantly reduced during the peak period, and the electricity consumption is obviously increased at night to achieve the purpose of peak-shaving and valley-filling. At the same time, the peak-to-valley difference of industrial load is decreased and the load factor is increased. Central air-conditioning load, electric vehicles and energy storage stations are user-side adjustable load resources, which combine the characteristics of load and energy storage. Through planned dispatch, these three types of loads are operated in accordance with instructions. Energy storage and electric vehicles are charged at night when electricity price is low, and discharge to the grid at peak electricity consumption period, thereby promoting renewable consumption, improving grid stability, and reducing operating costs of load aggregators.

2. Modelling multi-type adjustable flexible loads on the customer side
In this section, to solve the uncertainty problems brought by large-scale renewable integration in Shaanxi Province, we present models to analyse the feasibility of multi-type adjustable loads participating in power grid regulation. Based on the power supply structure and the load distribution characteristics in Shaanxi Province, we select four types of typical flexible loads: industrial users, air-conditioning loads, electric vehicle loads and energy storage power stations, which show a considerable schedulable potential among all city loads. Load aggregators can improve the economic operation level of the power grid and the ability to consume renewable generation by dispatching these four types of flexible loads.

2.1. Industrial load model
Shaanxi power grid has a wide coverage of industrial users, involving metallurgy, steelmaking, chemical and other industries. Aim to realize various industrial users participating in power grid dispatch in collaboration, we divide industrial loads into rigid load and flexible load. Rigid load is the part must be guaranteed in industrial production, which has low controllability. For industrial loads,
we divide flexible loads into transferable load and the cuttable load. The following industrial loads scheduling model is to minimize the total cost of load aggregators through adjusting transferable load and the cuttable load.

The objective function (1) aims to minimize the total cost of load aggregators. It consists of electricity purchase cost, transferable load dispatch cost and interruptible load dispatch cost over the entire dispatching periods. \( p_{it} \) is the power load of the \( i \)-th factory in period \( t \). \( c_{cost} \) is the unit purchase price for load aggregators. The transferable load dispatch cost \( C^{TF} \) consists of the load transferred in different periods multiplied by the corresponding transfer prices. Divide the load level of one day into peak period, flat period, and valley period \([11]\), we have different load cut off dispatch price \([10]\). The load cut off dispatch cost \( C^{CT} \) consists of the load cut off costs in each period. The complete formulation of industrial loads modelling is described as follows.

1) Objective function

\[
\min \left( \sum_{t=1}^{T} \sum_{i=1}^{n} p_{it} \Delta t \right) \cdot c_{cost} + C^{TF} + C^{CT}
\]  

2) Constraints

\[
p_{it}^{tr}_{(t_k-t_j)} \leq \alpha \cdot p_{it_k}
\]

\[
p_{it}^{cut} \leq \beta \cdot p_{it}
\]

\[
\sum_{j=1}^{n} p_{it}^{tr}_{(t_k-t_j)} \leq \alpha \cdot P_{max}
\]

\[
\sum_{t=1}^{T} p_{it}^{cut} \leq \beta \cdot P_{max}
\]

\[
\sum_{i=1}^{n} p_{it}^{tr} \leq \alpha \cdot P_{max}, t = 1,2, \ldots, T
\]

\[
\sum_{i=1}^{n} p_{it}^{cut} \leq \beta \cdot P_{max}, t = 1,2, \ldots, T
\]

\[
\sum_{t=1}^{T} \sum_{i=1}^{n} p_{it}^{tr} = 0
\]

In the above formulation, \( p_{it}^{tr}_{(t_k-t_j)} \) represents the load transferred by one industrial user at a certain time, which can be transferred to several industrial users at the same time. Similarly, one industrial user can also accept the load transferred by several users at a certain time. \( p_{it}^{cut} \) represents the load cut off by industrial users. Constraints (2) and (3) guarantee that the load transferred or cut off by each industrial user at each moment does not exceed a certain limit. The limitation depends on the actual load of industrial users at that moment, \( \alpha \) and \( \beta \) are the coefficients limit the value of the load transferred or cut off respectively, normally \( \alpha \) takes the value of 0.3 and \( \beta \) takes the value of 0.1. Constraints (4) and (5) are limitations for each industrial user over the entire scheduling periods. The limitation depends on the maximum load limit for each industrial user \( P_{max} \), multiplied by the coefficients \( \alpha \) and \( \beta \) in the same way. Constraints (6) and (7) are limitations for each moment with all industrial users. For load aggregators, the load can be scheduled at each moment cannot exceed the maximum value, which depend on the product of the coefficients \( \alpha \) and \( \beta \) with the maximum load at that moment \( P_{max} \). Constraint (8) states the transfer characteristics of transferable loads.

2.2. Air-conditioning load model

The air-conditioning load aggregator signs a contract with the central air-conditioning users in advance to implement direct load control of the central air-conditioning load by formulating start-stop scheduling planning \([11]\). In order to study the electricity consumption law of central air-conditioning, it is necessary to study the indoor temperature change law under the direct control of central air-conditioning. In this paper, the equivalent thermal parameters (ETP) model is used for simulation, and the temperature expression can be simplified as follows.
\[ T^{\text{off}}(m) = T_{\text{out}} - \left( T_{\text{out}} - T^{\text{off}}(0) \right) e^{-\frac{m}{\mu C}} \]  
(9)

\[ T^{\text{on}}(m) = T_{\text{out}} - \mu P_{\text{t}} \psi_{\text{COP}} - \left( T_{\text{out}} - \mu P_{\text{t}} \psi_{\text{COP}} - T^{\text{on}}(0) \right) e^{-\frac{m}{\mu C}} \]  
(10)

In the equation (9), \( T^{\text{off}}(m) \) is the indoor temperature when the air-conditioning is shut down at the \( m \)-th moment. \( T^{\text{on}}(m) \) is the indoor temperature when the air-conditioning starts cooling at the \( m \)-th time in the equation (10). \( T_{\text{out}} \) is the outdoor temperature, \( \mu \) and \( C \) are the thermal resistance and thermal capacity parameters of the room respectively. \( \psi_{\text{COP}} \) is the cooling energy efficiency ratio of air-conditioning.

From the above equations (9) and (10), we can derive the expressions for the length of downtime and the length of cooling time as following.

\[ \tau_{\text{off}} = \mu C \ln \left( \frac{T_{\text{out}} - T_{\text{min}}}{T_{\text{out}} - T_{\text{max}}} \right) \]  
(11)

\[ \tau_{\text{on}} = \mu C \ln \left( \frac{\mu P_{\text{t}} \psi_{\text{COP}} + T_{\text{max}} - T_{\text{out}}}{\mu P_{\text{t}} \psi_{\text{COP}} + T_{\text{min}} - T_{\text{out}}} \right) \]  
(12)

\[ T_{\text{max}} = T_{\text{set}} + \delta \]  
(13)

\[ T_{\text{min}} = T_{\text{set}} - \delta \]  
(14)

In the equation (11) above, \( \tau_{\text{off}} \) is the length of downtime of air-conditioning. In the equation (12), \( \tau_{\text{on}} \) is the length of cooling time of air-conditioning. \( T_{\text{set}} \) is the air-conditioning set temperature and \( \delta \) is the allowable temperature deviation in equations (13) and (14). The complete formulation of industrial loads modelling is described as follows.

The objective function (16) aims to minimize the operating costs for load aggregators, which consists of three parts. The first item is the cost of electricity purchase of load aggregators, \( \gamma_{\text{buy}} \) is the price for purchasing electricity. \( P_{\text{t}} \) is the air-conditioning power gathered by the \( w \)-th aggregator in period \( t \), determined by the equation (15). \( P_{\text{t},w} \) is the equivalent power of air-conditioning. \( \lambda_{\text{t},w} \) is a binary variable, which equals to 1 means that the user participates in scheduling. The second item in equation (16) represents the cost of fines caused by insufficient power provided by the aggregator. \( \gamma_{\text{punish}} \) is the punishment fine. The last item represents the compensation costs for air-conditioning users participating in scheduling. \( \gamma_{\text{comp}} \) is the compensation costs for dispatching air-conditioning users.

\[ p_{\text{t},w}^{\text{pro}} = \sum_{t=1}^{n_w} \lambda_{\text{t},w} P_{\text{t},w} \]  
(15)

1) Objective function

\[ \min \left( \sum_{w=1}^{M} \left( \sum_{t=1}^{T} p_{\text{t},w}^{\text{pro}} \cdot \gamma_{\text{t}} \right) + \sum_{t=1}^{T} \left( \max(0, k_{\text{t},w}^{\text{plan}} - P_{\text{t},w}^{\text{pro}}) \cdot \gamma_{\text{punish}} \right) + \sum_{t=1}^{T} \sum_{w=1}^{n_w} \lambda_{\text{t},w} \gamma_{\text{t},w}^{\text{comp}} \right) \]  
(16)

2) Constraints

\[ k_{\text{t},w} \leq \frac{T}{\tau_{\text{on}}^{\text{t},w} + \tau_{\text{off}}^{\text{t},w}} \]  
(17)

\[ \sum_{w=1}^{M} \lambda_{\text{t},w} \leq 1, \quad \lambda_{\text{t},w} \in [0,1] \]  
(18)

\[ P_{\text{min},w} \leq p_{\text{t},w}^{\text{pro}} \leq P_{\text{max},w} \]  
(19)

In the above formulation, constraint (17) restricts the number of air-conditioning starts and stops times. \( T \) is the duration of each period. \( k_{\text{t},w} \) is the number of start and stop cycles in \( t \) period. Constraint (18) restricts the scope of decision variables \( \lambda_{\text{t},w} \), which means one air-conditioning user can only participate in one plan at the same time. Constraint (19) restricts the minimum and maximum power participating in scheduling.

2.3. Electrical vehicle load model

For load aggregators, as a typical flexible load resource, electric vehicles are numerous and widely distributed on the user side, and combine the characteristics of load and energy storage. It can promote
the stable operation of the power grid in terms of peak-shaving and valley-filling for renewable consumption, etc. Large-scale electric vehicles connected to the grid and charged disorderly will greatly increase the load on the power system, by effectively aggregating electric vehicle loads, load aggregators can participate in the user side demand response in an orderly manner through reasonable optimization scheduling methods.

The objective function (20) aims to minimize the costs of load aggregator according to pre-instruction scheduling, which consists of two parts. The first item is the penalty cost of plan execution deviation, \( t \) is the number of control period, \( i \) is the number of vehicle and \( w \) is the number of aggregators. \( P_{\text{plan}}^{i,t,w} \) is the planned power of the grid, \( P_{\text{sum}}^{i,t,w} \) is the total equivalent load of electric vehicle group and \( \gamma_t^{\text{punish}} \) is the penalty coefficient. The second item is the electricity purchase cost when charging electric vehicles. \( P_{\text{cha}}^{i,t,w} \) is the charging power and \( \gamma_t^{\text{buy}} \) is the purchase price.

1) Objective function

\[
\min \left( \sum_{w=1}^{M} \sum_{t=1}^{T} \left( (P_{\text{plan}}^{i,t,w} - P_{\text{sum}}^{i,t,w}) \cdot \gamma_t^{\text{punish}} \right) + \sum_{t=1}^{T} \sum_{i=1}^{n} P_{\text{cha}}^{i,t,w} a_{i,t,w} \gamma_t^{\text{buy}} \right) \tag{20}
\]

2) Constraints

\[
P_{\text{sum}}^{i,t,w} = \sum_{i=1}^{n} (P_{\text{cha}}^{i,t,w} a_{i,t,w} - p_{\text{dis}}^{i,t,w} b_{i,t,w}) \tag{21}
\]

\[
\begin{align*}
0 \leq P_{\text{cha}}^{i,t,w} a_{i,t,w} & \leq p_{\text{cha,max}}^{i,t,w}, & a_{i,t,w}, b_{i,t,w} & \in \{0,1\} \\
0 \leq p_{\text{dis}}^{i,t,w} b_{i,t,w} & \leq p_{\text{dis,max}}^{i,t,w}, & a_{i,t,w}, b_{i,t,w} & \in \{0,1\}
\end{align*}
\tag{22}
\]

\[
SOC_{i,t-1,w}^{i,t-1,w} + \frac{P_{\text{cha}}^{i,t,w} a_{i,t,w} \eta_{\text{cha}} - p_{\text{dis}}^{i,t,w} b_{i,t,w} \eta_{\text{dis}}}{E_{i}^{\text{cap}}} \Delta T = \begin{cases} 
SOC_{i,t-1,w}^{i,t-1,w} + \frac{P_{\text{cha}}^{i,t,w} a_{i,t,w} \eta_{\text{cha}} - p_{\text{dis}}^{i,t,w} b_{i,t,w} \eta_{\text{dis}}}{E_{i}^{\text{cap}}} \Delta T & t \geq 2 \\
SOC_{i,\text{initial},w}^{i,\text{initial},w} + \frac{P_{\text{cha}}^{i,t,w} a_{i,t,w} \eta_{\text{cha}} - p_{\text{dis}}^{i,t,w} b_{i,t,w} \eta_{\text{dis}}}{E_{i}^{\text{cap}}} \Delta T & t = 1
\end{cases}
\tag{24}
\]

\[
SOC_{i,t,w}^{\text{min}} \leq SOC_{i,t,w}^{i,t,w} \leq SOC_{i,t,w}^{\text{max}} \tag{25}
\]

\[
SOC_{i,t,w}^{i,t,w} \geq SOC_{i,t,w}^{\text{set}}, \quad t = T_{t,w}^{\text{out}} \tag{26}
\]

\[
P_{\text{min},w} \leq P_{\text{sum}}^{i,t,w} \leq P_{\text{max},w} \tag{27}
\]

In the formulation above, \( a_{i,t,w} \) and \( b_{i,t,w} \) are both binary variables that characterize the charging and discharging states respectively. Constraint (21) represents the total power balance, which means the total load of an electric vehicle is equal to the difference between the charging load and the discharging load. Constraints (22) and (23) restrict the charge and discharge power respectively. \( p_{\text{cha,max}}^{i,t,w} \) and \( p_{\text{dis,max}}^{i,t,w} \) are the maximum charging and discharging power respectively, electric cars can only be charged or discharged at the same time. Constraints (24) and (25) are the SOC constraint of electric cars, \( \eta_{\text{cha}} \) and \( \eta_{\text{dis}} \) represent charging and discharging coefficients of electric cars respectively. Constraint (26) is to meet the travel needs of users, \( SOC_{i,t,w}^{\text{set}} \) indicates the lowest expected SOC value set by the owner of \( i \)-th vehicle. It is required that the SOC of the vehicle at the end of the last controllable period \( T_{t,w}^{\text{out}} \) is not lower than the expected \( SOC_{i,t,w}^{\text{set}} \). Constraint (27) restricts the minimum and maximum power participating in scheduling.

2.4. Energy storage power station model

For load aggregators, the energy storage device distributed on the user side plays the similar role as the electric vehicles. It combines the characteristics of load and energy storage. By rationally dispatching distributed energy storage resources, it can effectively promote the consumption of renewable energy and reduce the operating costs of aggregators. Compared to the model of electric vehicles, the model of energy storage station is described as following.

1) Objective function
\[
\min \left( \sum_{w=1}^{M} \left( \sum_{t=1}^{T} \left( |p_{t,w}^{\text{plan}} - p_{t,w}^{\text{sum}}| \cdot \gamma_{t}^{\text{punish}} \right) + \sum_{i=1}^{n_{w}} \sum_{t=1}^{T} p_{t,a_{i,t,w}}^{\text{cha}} \cdot \gamma_{t}^{\text{buy}} + \sum_{i=1}^{n_{w}} E_{i}^{\text{cap}} \cdot \text{SOC}_{i,\text{initial,w}} \cdot \gamma_{\text{valley}} \right) \right)
\]  

(28)

Compared to the model of electric vehicles, the objective function of ESS adds the third item, which represents the night charging cost of energy storage devices. \(E_{i}^{\text{cap}}\) indicates the energy storage capacity configured by the \(i\)-th user, \(\gamma_{\text{valley}}\) indicates the price of electricity purchased by users at night.

2) Constraints

The constraints of energy storage stations model are same as the constraints of electric vehicles model (21)-(27).

2.5. Combined dispatching model for all flexible loads

For load aggregators, compared with independent scheduling, the combined dispatch of various flexible loads can achieve complementary advantages of various load characteristics and strengthen the dispatch ability of load aggregators. The objective function of the model is to minimize the sum of above objective functions (1) (16) (20) and (28). And the constraints of the model are the combination of constraints (2)-(8), (17)-(19) and (21)-(27).

3. Computational results

In this section, we used typical industrial user day load curve in Shaanxi Province for research, and select the typical parameters of central air-conditioning, electric vehicles, and energy storage stations. Load aggregators dispatch these four types of flexible loads together to improve the power grid economic operation level and the ability to prompt renewable consumption. The corresponding formulation and solution methodology are coded in GAMS environment.

For industrial loads, due to its huge power demand, we expect to reduce operating costs by transferring some load from peak period to valley period and reduce some of cuttable load. As load aggregators, we give certain subsidies to industrial users for participating in user-side scheduling.

| Table 1. The peak-valley difference before and after dispatching. |
|---------------|----------------|----------------|
| Maximum load  | Minimum load  | Peak-valley difference (kW) |
| (kW)          | (kW)          |                            |
| Before scheduling | 661          | 410                        | 251                        |
| After scheduling     | 635.885      | 444                        | 191.885                    |

The numerical results shown in Table 1 are analyzed as following. We calculated the daily load curves before and after the industrial users participating in the aggregator scheduling, then calculating the peak-valley difference. We can see through the table data that the peak-valley difference before scheduling is 251 kW, and the peak-valley difference after scheduling is 191.885 kW, which is approximately 76.4% of the former value. It shows that the optimal scheduling of load aggregators can achieve the purpose of peak-shaving and valley-filling.

| Table 2. The load factor before and after dispatching. |
|---------------|----------------|----------------|
| Maximum load  | Average load  | The load factor (\%) |
| (kW)          | (kW)          |                             |
| Before scheduling | 661            | 547.5                     | 82.83                      |
| After scheduling     | 635.885      | 549.2223                  | 86.37                      |
Table 2 gives the calculation result of load factor before and after the industrial users participating in the aggregator scheduling. We can see through the table data that the load factor before scheduling is 82.83%, and the load factor after scheduling is 86.37%, which shows that the optimal scheduling of load aggregators can achieve the effects of improving equipment utilization and reducing operating cost.

Experimental results for dispatching industrial users are shown in figure 1. It can be seen from figure 1 that we can make better use of load resources and reduce operating costs through the load aggregator scheduling. Curve with triangle point represents the industrial load curve before dispatch and the curve with dots represents industrial load curve after dispatch. 24.00 a.m. to 6.00 a.m. is the lowest load period of the day with the lower electricity price, we can transfer peak load to this period through scheduling to reduce operating costs. Similarly, we can reduce the cuttable load during peak period to achieve the same purpose.

Figure 1. The industrial load curves.

Figure 2. Air-conditioning load curves.
Figure 3. Electric vehicles load curve. Figure 4. Energy storage station load curve.

Figure 2—figure 4 above respectively show the results of air-conditioning load, electric vehicle load and energy storage dispatch results according to pre-instructions. These three types flexible loads combine the characteristics of load and energy storage. Curve with square points represents the planned load curve instructed by load aggregators and the curve with dots represents the actual load curve after dispatch. As can be seen from the above figures, the trends of actual load curves after optimized scheduling is basically in accordance with the planned load curves. And the maximum deviation between planned curve and actual curve is within a certain reasonable range.

Dispatching air-conditioning load according to pre-instructions to meet the requirements of comfort of users and reducing operating cost at the same time. Energy storage and electric vehicles are charged at night when electricity price is low, and discharge to the grid at peak electricity consumption period, thereby promoting new energy consumption ability, improving grid stability, and reducing operating costs of load aggregators.

4. Conclusion
This paper first establishes four types of flexible load models, which include industrial users, air-conditioning loads, electric vehicle loads and energy storage power stations. Then we make analysis of the schedulable potential and the operating characteristics of these four types flexible loads on the user side. Finally, according to the classification and the optimal scheduling model of these four types flexible loads participating in the demand side response, a combined optimal scheduling model for load aggregators is proposed.

Numerical results on the combined optimal dispatching model for several flexible loads show that compared with independent operation, after the combined optimal scheduling by load aggregators, the peak-valley difference is reduced by 23.55% and the load rate is increased obviously, showing that the optimal scheduling of load aggregators can improve renewable energy utilization. For aggregators, the operating costs can be reduced through transferring peak-load to valley-load as well as dispatching the energy storage loads operating on the customer side according to pre-instructions.

Acknowledgments
This work has been supported by Technology Project of State Grid Shaanxi Electric Power Company under Grant SGSN0000TKJS2001799.

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