A Coordinated Peak Shaving Strategy Using Neural Network for Discretely Adjustable Energy-Intensive Load and Battery Energy Storage

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ABSTRACT The large-scale wind power introduces the challenge of the power demand and generation balancing. Energy-intensive load (EIL) is a promising option for peak shaving since it can change its production time and power demand without affecting its overall production. However, EIL which is discretely adjustable is unable to track the net load in real time. A two-stage complementary peak shaving strategy of EILs with the aid of battery energy storage systems (BESSs) is proposed to address this issue. This paper establishes an optimization model with the minimum system operation costs and wind curtailment costs as the objective function, in which EIL operation constraints and BESS power and energy balance constraints are added to the unit commitment model. And the neural network algorithm is used to solve this optimization problem. Finally, a system with a high proportion of wind power is adopted to analyze the functions of EIL and BESS in the method. It is verified that the proposed strategy can effectively reduce the amount of wind curtailment and the operation costs of the system.

INDEX TERMS Energy-intensive load, battery storage, wind power integration, demand response.

I. INTRODUCTION

The demand for reducing fossil fuel consumption has led to rapid development of renewable energy, especially wind power. However, wind curtailment remains unsolved due to high uncertainty, high variability and potential over-generation of wind power. According to the statistics of the National Energy Administration, in the first three quarters of 2018, the national loss of wind curtailment was as high as 11.1 billion yuan in China [1]. Improving the flexibility and the regulation capacity of the power grid by dispatching the demand-side resources and the large-scale BESSs is the effective means to solve the above problem.

Residential load, commercial load and electric vehicles are decentralized demand response (DR) resources assisting wind power integration [2]–[4]. EIE is the industrial load with relatively high proportion of energy value. Since the capacity of EIL is tens or hundreds megawatt class, enough regulating capacity can be provided for balancing even if only small proportion of them are regulated. Thus, it enjoys a comparatively clear advantage in dealing with the large peak-to-valley difference [5]. EIL can be divided into discretely adjustable load, continuously adjustable load and nonadjustable load according to the manufacturing processes [6]–[8]. Several references have researched the operation feature and detailed physical model of EILs with different production processes [7]–[9]. An optimization formulation based on physical load model has been developed for minimizing the electricity cost and reducing the peak demand in reference [9], which can be extended to any type of continuous process industries with controllable loads. Reference [10] proposed an integrated optimization model for generation and batch production load...
scheduling in EIE to get the minimum electricity cost. Most of these models are aimed at reducing the peak demand and electricity costs of the energy-intensive enterprise without considering to optimize the total benefit of the grid.

The discretely adjustable EIL participating in peak shaving provides a fixed amount of adjustable capacity that cannot change the power within a small range. In order to improve the integrated capacity of wind power as much as possible, the peak shaving resources in the power grid should have a certain ability to track the net load change. It makes the discretely adjustable EIL as a demand response resource that provides a large amount of power change cannot be fully utilized. In addition, it is necessary to obtain a day-ahead EIL switching plan considering the actual industrial production. However, the longer the forecast period, the larger the forecast error of load curve and wind power output [11], so it is necessary to set up an operation framework combining the day-ahead plan with the intraday correction.

The energy storage can enable flexible bidirectional adjustment with a wide time scale from millisecond to several days [12]. Due to the flexibility in capacity, siting, and rapid response, battery storage system seems to have more opportunity to mitigate the issues caused by wind generation [13], [14]. However, since the investment and maintenance costs of battery energy storage are related to the installed capacity, the capacity to be configured would be large and not cost-effective if only the battery storage is used for peak shaving. Considering the investment and operation costs of energy storage systems, reference [15] proposed an operation strategy of a hybrid system including pumped storage and battery energy storage. They respectively participate in the day-ahead dispatch and real-time control to realize the balance between generation and load and obtain maximum financial benefits. The above researches show that BESS can effectively compensate for the lack of precision of discretely adjustable EIL in both adjustable time scale and adjustable size.

In this paper, a two-stage optimization dispatch strategy is proposed. Considering the over-generation of wind power, it includes the day-ahead plan and the intraday correction to respectively schedule the discretely adjustable EILs and BESSs during each dispatch interval. And the optimization model for day-ahead plan and the intraday correction is established and applied to a system with a high proportion of wind power. The proposed method can effectively improve the integration of wind power and reduce system operation costs.

II. FUNCTION OF BESS IN PEAK SHAVING

Considering the impact of wind power output on peak shaving, the wind power is taken as a negative load, then the net load is

\[
P_{\text{Leq}} = P_{L} - P_{W}
\]

where \(P_{\text{Leq}}\) is the net load value of the power system, \(P_{L}\) is the load power, and \(P_{W}\) is the wind generation output.

When wind power accounts for a large proportion in the system, the peak-to-valley difference and volatility of net load increase. Adopting the mode of dispatching discretely adjustable EIL with the aid of BESS, the peak-shaving effect diagram is shown in Figure 1, where \(P_{G,\text{max}}, P_{G,\text{min}}\) respectively represent the maximum and minimum available output of the conventional unit. When the net load value at a certain moment exceeds the adjustment range of the conventional unit, it indicates that the peak shaving strategy is not enough to track the net load, and the wind curtailment is needed to balance the generation and demand. The wind curtailment amount in the figure is the area surrounded by the net load curve of the conventional mode, which is below the lower limit of conventional unit. The formula is expressed as follow.

\[
E_{\text{abW}} = \int_{t_1}^{t_5} (P_{G,\text{min}} - P_{\text{Leq},t}) \, dt
\]

\[
= \int_{t_1}^{t_5} (P_{G,\text{min}} + P_{W,t} - P_{L,t}) \, dt
\]

where \(E_{\text{abW}}\) is the quantity of wind curtailment in the dispatch period \(T\). \(P_{\text{Leq},t}, P_{W,t}\) and \(P_{L,t}\) are the values of the net load, wind power output and load in a certain dispatch mode at time \(t\), respectively.

As shown in Fig. 1, the BESS is installed on the load side as an assistance in the intraday correction stage of peak shaving. Based on the day-ahead dispatch plan, real-time charging-discharging control system of energy storage is established. It considers the influence of the day-ahead forecast error. If the adjustment of discretely adjustable EIL (hereinafter referred to as “EIL”) has small vacancy (e.g. \(t_3 - t_4\)) during peak shaving, the excess wind power would be charged into the battery. Otherwise, if the available capacity of EIL is slightly insufficient (e.g. \(t_2 - t_3\)) or the load is at the peak period (e.g. \(t_6 - t_7\)), the stored energy would be released. Hence, BESS can aid to shift the wind power output and smooth the net load curve. It makes the wind curtailment and the peak-to-valley difference of the net load both be reduced.

![FIGURE 1. Energy storage assisted peak shaving diagram (Area 1 is the charging-discharging quantity of BESS).](image-url)
Therefore, in the two-stage operation mode of load-storage complementary peak shaving, the EIL provides large and discrete power variations while the continuously adjustable small-capacity BESS provides fine continuous power variation. When the thermal power units have insufficient peak shaving capability, BESS provides flexible adjustment capability to supplement the peak shaving demand with faster change speed and smaller change range.

III. TWO-STAGE COORDINATED PEAK SHAVING STRATEGY

A. DAY-AHEAD PLAN

In the stage of day-ahead plan, the start-stop situation of the thermal power plants is decided. When it is judged that there will be wind curtailment on the next day, the switching time and capacity of the EILs are determined, which facilitates the energy-intensive enterprises to plan production in advance. At the same time, it also makes certain estimates for the dispatch plan of thermal power plants and wind farms. The steps are as follows:

Step1: The dispatch center obtains the next-day predicted time series of load and wind power output. The initial state of each unit is uploaded by the thermal power plants as the boundary condition. The energy-intensive enterprises report the information about EILs that can participate in the dispatch the next day;

Step2: According to the information mentioned in step 1, the dispatch center generates a day-ahead dispatch plan in the conventional peak shaving mode in which only the thermal power units participate, and determines whether there is wind curtailment;

Step3: If there is no wind curtailment, it is unnecessary to apply the EILs. Hence, the plan can be reported as the day-ahead plan. Otherwise, a new plan should be generated with the joint participation of source-load considering the EILs as part of the demand response;

Step4: The unit operation plan is sent to the thermal power plants. The next-day switching information of the EILs is sent back to the energy-intensive enterprise. The related information of wind power output and wind curtailment is sent to the wind farms.

The resulting EIL switching plan and the thermal power unit start-stop plan are official for the next-day peak shaving, while the specific output plans for thermal power plants and wind farms need to go through intraday correction.

B. INTRADAY CORRECTION

For each period \( t \), there is a difference between the day-ahead planned and the intraday predicted net load

\[
\Delta P_{\text{eq},t} = P_{\text{in},\text{eq},t} - P_{\text{bf},\text{eq},t} \quad (3)
\]

\[
P_{\text{bf},\text{eq},t} = P_{\text{bf},\text{L},t} + P_{\text{h},t} - P_{\text{bf},\text{W},t} \quad (4)
\]

\[
P_{\text{in},\text{eq},t} = P_{\text{in},\text{L},t} + P_{\text{h},t} - P_{\text{in},\text{W},t} \quad (5)
\]

where \( P_{\text{bf},\text{eq},t} \) and \( P_{\text{in},\text{eq},t} \) are the net load obtained after optimization in the stage of day-ahead plan and the intraday predicted net load respectively. \( P_{\text{bf},\text{L},t} \) is the day-ahead predicted load, \( P_{\text{bf},\text{W},t} \) is the dispatched output of wind power in day-ahead plan, \( P_{\text{in},\text{L},t} \) and \( P_{\text{in},\text{W},t} \) are respectively the intraday predicted load and the possible maximum output of wind power. \( P_{\text{h},t} \) is the power of EIL obtained after optimization in the day-ahead plan stage.

On the basis of the day-ahead plan, the start-stop of thermal power units and the switching of EILs are determined. However, in order to reduce the deviation between the day-ahead plan and the actual operation caused by the wind power prediction, power regulation of thermal power units and charging-discharging of BESS are applied to compensate for the peak shaving demand. Additionally, there is wind curtailment when compensation is insufficient. Hence,

\[
\Delta P_{\text{G},t} = \sum_{i=1}^{N_1} \Delta P_{\text{G},i,t} + P_{\text{E},t} + P_{\text{in},\text{Wab},t} \quad (6)
\]

\[
\Delta P_{\text{G},i,t} = P_{\text{bf},\text{G},i,t} - P_{\text{in},\text{G},i,t} \quad (7)
\]

where \( \Delta P_{\text{G},i,t} \) is the difference between the day-ahead planned output and the intraday corrected output of thermal power unit \( i \); \( P_{\text{bf},\text{G},i,t} \) and \( P_{\text{in},\text{G},i,t} \) are the day-ahead planned output and the intraday corrected output of thermal power unit \( i \) respectively; \( N_1 \) is the number of thermal power units; \( P_{\text{E},t} \) is the charging/discharging power of the BESS; \( P_{\text{in},\text{Wab},t} \) is the required wind curtailment power in the intraday correction.

Therefore, the specific steps for the intraday correction are as follows:

Step1: \( K \) is a dispatch cycle and within each \( K \) (e.g. 4h) the dispatch schedule of BESS, thermal power unit, and wind farms are calculated;

Step2: The dispatch schedule of the first period in the cycle is sent as a formal dispatch schedule to the thermal power plants, the energy storage power stations, and the wind farms to participate in real-time operation;

Step3: The next correction is made.

IV. COORDINATED PEAK SHAVING OPTIMIZATION MODEL OF EIL AND BESS

The key to the proposed operation strategy is to consider EIL transfer and BESS charging and discharging in the unit commitment model. Therefore, in chapter 4, a discretely adjustable EIL response model and a BESS model used for assisting peak shaving are firstly established. Then a complete two-stage complementary peak shaving optimization model is established.

A. DISCRETELY ADJUSTABLE EIL RESPONSE MODEL

The discretely adjustable EIL mostly uses furnace (groove) as the unit. The power of a single equipment is not adjustable and only the number of starting equipment can be adjusted by switching to increase or decrease the quantitative load power. However, the change of working hours of energy-intensive enterprises brought by load transfer will also incur certain additional costs. Thus, the response costs of EIL participating in demand response should include equipment starting costs
and load transfer cost. Hence,
\[
f_h = \sum_{t=1}^{T} \sum_{j=1}^{N_h} \sum_{m=1}^{M_j} (C_{j,m,t} \Delta t_{h,j,m,t} + D_{j,m} \Delta v_{h,j,m,t}) \tag{8}
\]
where \(C_{j,m,t}\) is the load transfer cost of the production equipment unit \(m\) in the EIL \(j\) during period \(t\) and \(D_{j,m}\) is the starting cost; \(\Delta t_{h,j,m,t}\) and \(\Delta v_{h,j,m,t}\) are the start-stop state variable and the start variable of the equipment unit \(m\) respectively, \(\Delta t_{h,j,m,t} = 1\) indicates that the equipment unit \(m\) is in the operation state during period \(t\), \(\Delta v_{h,j,m,t} = 0\) indicates the shutdown state; \(v_{h,j,m,t}\) is the start-stop auxiliary variable constraints of the EIL \(j\).

The production equipment \(m\) of the EIL \(j\) can not be started and stopped at the same time. Thus, the equipment unit’s start-stop state should be consistent with the actions of starting and stopping. The start-stop auxiliary variable constraints are shown as (9), (10).

\[
v_{h,j,m,t} + w_{h,j,m,t} \leq 1 \tag{9}
\]
\[
v_{h,j,m,t} - w_{h,j,m,t} = u_{h,j,m,t} - u_{h,j,m,t-1} \tag{10}
\]
where \(w_{h,j,m,t}\) is the shutdown variable of production equipment unit \(m\) in EIL \(j\) at period \(t\). When the value equals 1, it indicates that the operation state of production equipment changes from the operation to shutdown. When the value is 0, there is no shutdown.

In order to ensure the performance and lifetime of the production equipment are affected as less as possible, the switching of EILs needs a certain interval for the equipment stability, that is, continuous and multiple switching is not allowed. Besides, the production demand of energy-intensive enterprises should be considered rather than be cut at will in order to meet the total working hours. So the start-stop time constraints are as follows.

\[
\sum_{k=1}^{M_j} \Delta t_{h,j,m,k} = 0 \tag{11}
\]
\[
\sum_{k=1}^{M_j} \Delta v_{h,j,m,k} = 0 \tag{12}
\]
\[
\Delta t_{h,j,m,t} \times \sum_{k=1}^{M_j} (1 - \Delta v_{h,j,m,k}) = 0 \tag{13}
\]
\[
\sum_{k=1}^{M_j} \Delta v_{h,j,m,k} = 0 \tag{14}
\]
\[
\Delta v_{h,j,m,t} \times \sum_{k=1}^{M_j} (1 - \Delta t_{h,j,m,k}) = 0 \tag{15}
\]
\[
\sum_{k=1}^{M_j} \Delta t_{h,j,m,k} = 0 \tag{16}
\]
\[
(T - T_{h,off,j,m} + 2, \cdots , T) \]
\[
\sum_{k=1}^{M_j} \Delta v_{h,j,m,k} = 0 \tag{17}
\]
Formulas (11)-(13) are the minimum operation time constraints, and \(I_{on,j,m}\) is the minimum time required for the initial continuous operation of the production equipment \(m\) of the EIL \(j\). If it is at the shutdown state at the end of the previous day, \(I_{on,j,m} = 0\). \(T_{h,off,j,m}\) is the minimum continuous operation time that the production equipment allows. Formula (12) considers the influence of the equipment operation state at the end of the previous day on the current day, and Formula (13) indicates that if the remaining time on the current day is less than \(T_{h,off,j,m}\), the operation state must last until the end of the day.

Formulas (14)-(16) are the minimum shutdown time constraints. \(I_{off,j,m}\) is the minimum time required for the initial stop state of the production equipment. If the equipment is at the operation state at the end of the previous day, \(I_{off,j,m} = 0\). \(T_{h,off,j,m}\) is the minimum continuous operation time. The specific constraints are similar to (11)-(13).

In addition, due to the fixed capacity of each EIL, this paper considers that the output is proportional to the total operation time of all EILs. In order to ensure that the daily output of energy-intensive enterprises is not affected, the total operation time constraint should be as follows:

\[
I_{on,j} \leq \sum_{m=1}^{M_j} \sum_{t=1}^{T} \Delta t_{h,j,m,t} \leq \sum_{t=1}^{T} \Delta v_{h,j,m,t} \tag{18}
\]
where \(I_{on,j}\) is the total production time of the EIL \(j\) required for the ordered production, and \(I_{off,j}\) is the total production time of the EIL \(j\) required for the maximum production of the day.

B. BATTERY ENERGY STORAGE ASSISTED SYSTEM MODEL
The operation cost of BESS is

\[
f_{ess} = \sum_{t=1}^{T} C_{ess} P_{E,t} \tag{19}
\]
where \(C_{ess}\) is the unit costs of energy storage; \(P_{E,t}\) is the charging or discharging power of the BESS at time \(t\). It if is positive, it means discharging, and if negative, it indicates charging.

The constraints of the BESS are as follows: maximum and minimum power constraints, remaining capacity constraints, and operation constraints.

\[
\sum_{j=1}^{N_e} P_{E,\text{min}} < P_{E,t} < \sum_{j=1}^{N_e} P_{E,\text{max}} \tag{20}
\]
\[
\sum_{j=1}^{N_e} E_{\text{min}} \leq E_t \leq \sum_{j=1}^{N_e} E_{\text{max}} \tag{21}
\]
\[
E_t = E_{t-1} - P_{E,t} \Delta T \tag{22}
\]
where \(N_e\) is the number of energy storage units; \(P_{E,\text{min}}\) and \(P_{E,\text{max}}\) are the minimum and maximum charging/discharging power of the energy storage unit, respectively; \(E_t\) represents the remaining capacity of the BESS during period \(t\); \(E_{\text{min}}\) and
$E_{\text{max}}$ refer to the minimum and maximum capacity that the energy storage unit allows; $\eta$ is the charging and discharging efficiency of the system.

### C. COORDINATED PEAK SHAVING OPTIMIZATION MODEL

In the conventional unit commitment model with only thermal power units and wind turbines, in order to minimize the wind curtailment, it is often necessary to take the start-stop and economic operation of the thermal power units as the costs. So minimizing coal consumption costs and start-stop costs are often the goal. During the coordinated peak shaving process, the EIL changes the switching time according to the system demand, which brings additional costs, and energy storage assisted peak shaving generates a certain BESS operation cost. Therefore, the operation costs of the thermal power units, the wind curtailment costs, the response costs of EILs should be considered in the objective functions. Hence,

$$\min F = f_{\text{fuel}} + f_{\text{start}} + f_{\text{wind}} + f_{\text{h}} + f_{\text{ess}}$$  \hspace{1cm} (22)

$$f_{\text{fuel}} = \sum_{i=1}^{N_G} \sum_{t=1}^{T} u_{G,i,t}(a_{i}P_{G,i,t}^2 + b_{i}P_{G,i,t} + c_{i})$$  \hspace{1cm} (23)

$$f_{\text{start}} = \sum_{i=1}^{N_G} \sum_{t=1}^{T} C_{st,i}(1 - u_{G,i,t})$$  \hspace{1cm} (24)

$$f_{\text{wind}} = C_{w} \sum_{t=1}^{T} (P_{w,t}^{\text{pr}} - P_{w,t})$$  \hspace{1cm} (25)

where $f_{\text{fuel}}$ represents the coal consumption cost of the thermal power units, $a_{i}$, $b_{i}$ and $c_{i}$ are the parameters of the coal consumption cost. $f_{\text{start}}$ represents the start-up cost. $C_{st,i}$ is the start-up cost of the thermal power unit $i$ and usually the function about shutdown time. A fixed value is used in this paper to simplify the model. $P_{G,i,t}$ is the output of thermal power unit $i$ during period $t$. $u_{G,i,t}$ is the variable of start-stop state of thermal power unit $i$ during period $t$. When the value equals 1, it means that it is in the start state. When the value equals 0, it indicates that it is in the shutdown state. $f_{\text{wind}}$ is the cost of wind curtailment, which is represented by a linear function of wind power output. $C_{w}$ is the on-grid price of wind power; $P_{w,t}^\text{pr}$ is the maximum possible output of wind power during period $t$, i.e. the predicted wind power output; $P_{w,t}$ is the planned output of wind power. $T$ is the duration of time. $N_G$ is the number of thermal power units.

For the day-ahead plan stage, the response of the EILs is taken into account in the conventional peak shaving model, and the objective function is

$$\min F_1 = f_{\text{fuel}} + f_{\text{start}} + f_{\text{wind}} + f_{\text{h}}$$  \hspace{1cm} (26)

The power balance constraint is as shown in (27) and (28).

$$\sum_{i=1}^{N_G} u_{G,i,t}P_{G,i,t} = P_{\text{Eq},t}$$  \hspace{1cm} (27)

$$P_{\text{Eq},t} = P_{L0,t} + \sum_{j=1}^{N_h} \sum_{m=1}^{M_j} u_{h,j,m}P_{h,j,m} - P_{w,t}$$  \hspace{1cm} (28)

where $P_{\text{Eq},t}$ is the net load considering the EILs; $P_{L0,t}$ is the day-ahead predicted fixed load of the system during period $t$; $P_{h,j,m}$ is the fixed regulation power of the production equipment unit $m$ of the EIL $j$.

The constraint conditions are formulas (9)-(17), (27) and (28). In addition, there are thermal power unit output constraints, minimum start-stop time constraints, slope-climbing constraints and wind power output constraints, which are not illustrated here.

For the intraday correction stage, the start-stop state variable of EIL $u_{h,j,m}$ and the start-stop state variable of thermal power unit $u_{G,i,t}$ are determined by (26), so the main considerations are the coal consumption costs of the thermal power units, energy storage operation costs and wind curtailment costs. The objective function is as follow:

$$\min F_2 = f_{\text{fuel}} + f_{\text{wind}} + f_{\text{ess}}$$  \hspace{1cm} (29)

The power balance constraint is as shown in (30).

$$\sum_{i=1}^{N_G} u_{G,i,t}P_{G,i,t} + P_{E,t} = \sum_{j=1}^{N_h} \sum_{m=1}^{M_j} u_{h,j,m}P_{h,j,m} + P_{L0,t} - P_{w,t}$$  \hspace{1cm} (30)

where $P_{L0,t}$ is the intraday predicted fixed load during period $t$.

Constraints also include thermal power unit output constraints, wind power output constraints, and energy storage operation constraints (19)-(21).

Through (29), the thermal power unit output $P_{\text{real}}^{G,i,t}$ and the actual on-grid wind power $P_{\text{real}}^{W,t}$ and the BESS charging-discharging power $P_{\text{ess}}^{W,t}$ which meet the real-time generation and demand balance are obtained.

### V. CASE STUDY

Due to the characteristics of the optimization model, the neural network algorithm is utilized to solve this problem.

#### A. BASIC DATA

The proposed peak shaving strategy and optimization model is tested using the realistic predicted load of one place and the predicted wind power data based on reference [11]. The installed capacity of wind turbines is 1208MW, accounting for nearly 50%. As shown in Fig. 2, the daily wind power output is stochastic, and it is lack of coincidence between wind generation and system peak demand.

The operation and cost parameters of thermal power units and EILs refer to reference [8]. The wind curtailment costs are based on wind power price on-grid, i.e. 0.5 yuan/kWh. In the case, there are 7 thermal power units, and the relevant parameters are shown in Table 1. Assume that there is an EIL that can be discretely adjusted in the system whose total power is 105MW and evenly distributed by three units of...
production equipment. And there is a battery with a capacity of 20MW/60MWh assisting the peak shaving.

In the case, the general working time of the EIL is assumed to be between 8:00 and 18:00, so the load transfer costs curve is shown as Fig. 3. When the demand response is not considered, according to the order requirement of the typical day, the discretely adjustable EIL works from 10:00 to 18:00, i.e. the minimum working time is 8h.

### B. SIMULATION RESULTS

The proposed coordinated peak shaving strategy with EIL and BESS is tested to verify the effect on promoting wind power integration by using the neural network to solve the established optimal model. The simulation results are compared with that of conventional peak shaving mode and the peak shaving mode with EIL alone.

As shown in Fig. 2, load valley is occurred from 1:00 to 6:00. During this period, the load even lower than 900 MW but the predicted wind power reaches more than 1000 MW. The peak-to-valley difference of net load reaches 1055 MW. Therefore, the peak shaving pressure on the day is large considering the wind power integration. The required wind curtailment in the three modes is shown in Fig. 4. In order to maintain the balance between generation and demand of the system, significant wind curtailment occurs in all modes during the peak hours of the wind generation. Combined with Table 2, when the EIL participates in the demand response, the wind curtailment rate is reduced from 10.7% to 6.85%, which means that the EIL transfer has a significant effect on promoting wind power integration. In addition, although the involvement of BESS only reduces the wind curtailment by 0.62% (compared with the mode with EIL alone), but the limited periods of wind power output are greatly reduced, which shows that the BESS mainly serves to provide a continuously varying small-amplitude power demand to reduce the wind curtailment rate.

Fig. 5 is the comparison of the load curves. The initial operation period of EIL is between 8:00 and 18:00, and most of them are adjusted to between 0:00 and 7:00 after the demand response. In addition, a small number of EILs operate between 11:00 and 17:00. In the coordinated peak shaving mode, considering the distribution of typical daily load and wind power in each period comprehensively, the EIL at the period of peak load and insufficient wind power output can be properly removed and transferred to the period of valley load and high wind power at which it is difficult for wind power integration. The daily peak-to-valley difference is reduced from 340.58 MW to 248.27 MW, down by about 27%, while the total load only changes by less than 0.1%. The strategy achieves the purpose of shifting peaks and filling valleys.
TABLE 2. Wind power integration in different peak shaving modes.

| Wind Power Output Indicators | Wind Power Integration (MW-h) | Wind Curtailment Rate | Limited Periods of Wind Power |
|-----------------------------|-------------------------------|-----------------------|------------------------------|
| Conventional Peak Shaving Mode | 16 994.98                     | 10.7%                 | 16                           |
| Peak Shaving Mode with EIL Only | 17 727.78                     | 6.85%                 | 15                           |
| Coordinated Peak Shaving Mode | 17 844.83                     | 6.23%                 | 5                            |

FIGURE 5. Typical daily load curve in different peak shaving modes.

TABLE 3. System operation costs comparison in different peak shaving modes.

| Economic Indicators of Operation | Total Costs($) | Thermal Power Unit Operation Costs($) | Wind Curtailment Costs($) | EIL Transfer Costs($) |
|----------------------------------|----------------|---------------------------------------|---------------------------|----------------------|
| Conventional Peak Shaving Mode   | 324 210        | 180 478                               | 142 521                   | /                    |
| Peak Shaving Mode with EIL Only  | 263 155        | 169 879                               | 91 225                    | 2 500                |
| Coordinated Peak Shaving Mode    | 245 482        | 160 879                               | 83 032                    | 2 350                |

The operation costs of the system in different peak shaving modes are shown in Table 3. Compared with the conventional peak shaving mode, the total operation costs of the peak shaving mode with EIL and the coordinated peak shaving mode decrease by 18.83% and 24.28% respectively, in which the thermal power generation costs of the two modes are reduced by 5.9% and 10.9% respectively and the costs of wind curtailment are reduced by 36% and 41.7%. Therefore, in the coordinated peak shaving mode, although the added energy storage capacity only accounts for about 1% of the installed capacity of the generation devices in the system, the continuous and rapid adjustment of power provided by it greatly reduces the system operation costs. Meanwhile, the EIL switching pressure brought by peak shaving is also relieved to some extent.

VI. CONCLUSION

In this paper, a day-ahead and intraday coordinated peak shaving strategy based on discretely adjustable EIL and small-capacity BESS is proposed. Considering the costs rise caused by the product output limitation of energy-intensive enterprises and changes in load operation period, an optimization model with the minimum operation costs is established. The simulation results show that using the two-stage coordinated peak shaving strategy, the EIL can be effectively transferred from the period of peak load and insufficient wind generation to that of valley load and excessive wind generation. Hence, the large and discretely power can effectively respond to the over-generation of wind power and greatly reduce the peak-to-valley difference and the wind curtailment rate. Moreover, the BESS compensates for the large-grain variation of the discretely adjustable EIL, which further improves the peak shaving flexibility, increases the integration of wind power and reduces system operation costs. Notably, the proposed solution method for peak shaving can greatly promote energy conservation and emission reduction.

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