Optimal dispatching of integrated energy system considering flexible load

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Abstract—Demand response, as an effective dispatching method, has been widely used in the optimization research of integrated energy system (IES). In this article, first, the mathematical model of flexible loads including shiftable electric, heat, and cooling load are established in line with their characteristics. Second, an optimal scheduling model of the IES is built, where the minimum sum of system operation and maintenance and the environmental protection costs comprise the objective function. Furthermore, the alternating direction multiplier method is used to solve the optimal scheduling model in a fully distributed manner. Finally, simulation results show that the proposed model and algorithm can efficiently solve the IES optimal dispatching problem, reduce the peak-valley difference, and improve the stability of the system.

1. Introduction

With the development of power systems in recent years, numerous scholars and experts have achieved rich results in optimization [1-5] and control [6-13]. For integrated energy system (IES) with a high proportion of wind and solar renewable energy power generation output, the strategy of considering the response of flexible load (FL) will play an important role to help achieve peak-shaving and valley-filling, make full use of various energy sources, reduce fossil energy consumption, and maintain the stable operation of the entire system and to maximise energy efficiency.

Extensive research has been carried out by domestic and foreign scholars in optimal scheduling of IES. Li et al.[1] aims at the problems of low wind-solar installed capacity, low utilization rate and hydrogen energy demand, and proposed a multi-energy flow integrated energy system dispatching method that considers wind-solar utilization rate and hydrogen-containing energy flow. Cheng et al.[2] proposes a multi-energy flow and multi-energy hub multi-time-scale coordination optimization method for better dispatching according to the uncertainty of variable energy and changing load demand. Li et al.[3] proposes a two-stage optimization operation method that considers multiple uncertainties and comprehensive demand response in view of the existence of multiple uncertainties and demands in the community integrated energy system.

The above literature shows that the existing optimal scheduling of IES mainly focuses on the scheduling of "source" and "load" and giving full play to demand-side response has become an important trend. FL, as a key response method, can be used to improve the load curve [4]. In summary, this paper establishes an optimal scheduling model of IES considering introducing the shiftable load in FL and solves it using ADMM. The effectiveness of the model is verified by developing a day-ahead scheduling and load shifting scheme for a typical day of IES by simulation analysis.
2. Shiftable loads model

2.1. Objective function

2.1.1. Objective function of shiftable electric load

\[
\begin{aligned}
\min & \left\{ \frac{1}{2} \sum_{i=1}^{24} (P_i^{12} - P_i^{10})^2 \right\} \\
\text{s.t.} & \quad P_i^{10} = \frac{1}{\sum_{i=1}^{24} C_{i}^{prgr}} \sum_{i=1}^{24} \tilde{P}_i^{12}
\end{aligned}
\]  

(1)

where \( P_i^{12} \) is the actual value of the shiftable electrical load after shift at time \( t \), kW; \( P_i^{10} \) is the target value of the system's shiftable electric load at time \( t \), kW; \( C_{i}^{prgr} \) is electricity prices at time \( t \), yuan; \( \tilde{P}_i^{12} \) is the predicted value of electric load can be shifted at time \( t \), kW.

2.1.2. Objective function of shiftable heat load

\[
\begin{aligned}
\min & \left\{ \sum_{i=1}^{24} (H_i^{12} - H_i^{10})^2 \right\} \\
\text{s.t.} & \quad H_i^{10} = P_i^{12} f_{HE}
\end{aligned}
\]  

(2)

where \( H_i^{12} \) is the actual value of the shiftable heat load after shift at time \( t \), kW; \( H_i^{10} \) is the target value of the system's shiftable heat load at time \( t \), kW; \( f_{HE} \) is the rated heat-to-electricity ratio of the equipment in the system[14].

2.1.3. Objective function of shiftable cooling load

\[
\begin{aligned}
\min & \left\{ \sum_{i=1}^{24} (C_i^{12} - C_i^{10})^2 \right\} \\
\text{s.t.} & \quad C_i^{10} = P_i^{12} f_{CE}
\end{aligned}
\]  

(3)

where \( C_i^{12} \) is the actual value of the shiftable cooling load after shift at time \( t \), kW; \( C_i^{10} \) is the target value of the system's shiftable cooling load at time \( t \), kW; \( f_{CE} \) is the rated cooling-to-electricity ratio of the equipment in the system.

\[
\begin{aligned}
M_t^{12} &= \tilde{M}_t^{12} + M_t^{ai} - M_t^{ao} \\
M_t^{ai} &= \sum_{a=t,j}^{24} M_{a-t,j} \\
M_t^{ao} &= \sum_{b=t}^{24} M_{t-b,t} \\
f_{CE} &= \frac{K_{COP} \left(1 - \eta_{GT,e}^{GTE} \right) \left(1 - \eta_{EC}^{GTE} \right)}{\eta_{GT,e}^{GTE} \eta_{EC}^{GTE}}
\end{aligned}
\]  

(4)

where \( \tilde{M}_t^{12} \) is the shiftable load forecast value at time \( t \), kW; \( M_t^{12} \) is the actual value of the shiftable load after shift at time \( t \), kW; \( M_t^{ai} \) is the load value shifted in from other moments at time \( t \), kW; \( M_t^{ao} \) is the
load value that can be shifted to other time periods at time $t$, kW; $M_{s-t}$ is the load value shifted from time $a$ to time $t$ at time $t$, kW; $M_{t-b}$ is the load value at time $t$ shifting from time $t$ to time $b$, kW; $K_x^{COP}$ is the system cooling performance factor; $\eta_{GT,e}^{e}$ is electricity production efficiency of gas turbines; $\eta_{EC}^{e}$ is the cooling production efficiency of the electric chiller.

2.2 Restrictions

\[
\begin{align*}
\sum_{i=1}^{24} M_{t}^{ai} &= \sum_{i=1}^{24} M_{t}^{ao} \\
0 &\leq M_{t}^{ao} \leq \tilde{M}_{t}^{12} \\
0 &\leq M_{t}^{ai} \leq \frac{1}{24} \sum_{i=1}^{24} \tilde{M}_{t}^{12}
\end{align*}
\] (5)

3. IES optimal scheduling model

3.1. Objective function

3.1.1. System operating cost objective function

\[
\min C_{total} = \sum_{i=1}^{N} \left( C_{i}^{eng} + C_{i}^{loss} \right)
\] (6)

where $C_{total}$ is the IES operating cost at time $t$, yuan; $C_{i}^{eng}$ and $C_{i}^{loss}$ are the operating cost and energy purchase cost of equipment $i$ at time $t$ respectively, yuan.

\[
\begin{align*}
C_{i}^{eng} &= C_{i}^{grid} + C_{i}^{gas} \\
C_{i}^{grid} &= C_{i}^{eng} \times P_{t}^{grid} \\
C_{i}^{gas} &= C_{i}^{eng} \times P_{t}^{gas} \\
C_{i}^{loss} &= \lambda_{loss} (\tilde{M}_{t}^{1} - M_{t}^{1})
\end{align*}
\] (7)

where $C_{i}^{eng}$ is the cost of operating and maintaining equipment $i$ per unit of power, yuan[15]; $P_{t}^{i}$ is the power of device $i$ at time $t$, which is one of electricity power P, heat power H and cold power C, kW; $C_{i}^{grid}$ and $C_{i}^{gas}$ represent the cost of purchased/sold electricity and gas at time $t$ respectively, yuan; $P_{t}^{grid}$ is the power purchased/sold at time $t$, greater than 0 means power purchased and less than 0 means power sold, kW; $C_{i}^{eng}$ is the purchase and sale price of gas at time $t$, yuan; $P_{t}^{gas}$ is the purchased gas power at time $t$, kW; $C_{i}^{loss}$ is the cost lost by shifting the load at time $t$, yuan; $\lambda_{loss}$ is the shifting load loss factor; $\tilde{M}_{t}^{i}$ is the load forecast before shifting at time $t$, kW; $M_{t}^{i}$ is the actual value of the load after shifting at time $t$ (M includes P, H, C).

3.1.2. Environmental protection cost objective function

\[
\min C_{en} = P_{t}^{grid} C_{CO_2}^{e} + (P_{t}^{P2G,g} + P_{t}^{P2G,sh}) C_{CO_2}^{e}
\] (8)

where $C_{en}$ is the IES environmental protection cost, yuan; $C_{CO_2}^{e}$ is the CO$_2$ emission penalty price per unit of electric power, yuan; $P_{t}^{P2G,sh}$ is the gas power generated by the power to gas equipment at time $t$, kW;
$C_{CO_2}^g$ is the CO\textsubscript{2} emission penalty price per unit of gas power, yuan.

3.2. Energy conversion equipment model

3.2.1. Gas turbine model

\begin{align}
\begin{cases}
    P_{i}^{GT} = P_{i}^{GT,gas} \eta_{GT,e} \\
    H_{i}^{GT} = P_{i}^{GT,gas} \eta_{GT,h}
\end{cases}
\end{align}

(9)

where $P_{i}^{GT}$ is the electric power output of the gas turbine at time $t$, kW; $P_{i}^{GT,gas}$ represents the gas power input to the gas turbine at time $t$, kW; $\eta_{GT,e}$ and $\eta_{GT,h}$ are the electricity and heat efficiency of the gas turbine; $H_{i}^{GT}$ is the heat power output of the gas turbine at time $t$, kW[16].

3.2.2. Gas boiler model

\begin{align}
    H_{i}^{GB} = P_{i}^{GB,gas} \eta_{GB,h}
\end{align}

(10)

where $H_{i}^{GB}$ is the heat power output of the gas boiler at time $t$, kW; $P_{i}^{GB,gas}$ represents the gas power input to the gas boiler at time $t$, kW; $\eta_{GB,h}$ is the heat production efficiency of the gas boiler.

3.2.3. Electrical chiller model

\begin{align}
    C_{i}^{EC} = P_{i}^{EC} \eta_{EC}^{EC}
\end{align}

(11)

where $C_{i}^{EC}$ is the cold power output by the electric chiller at time $t$, kW; $P_{i}^{EC}$ is input the electric power of the electric chiller at time $t$, kW; $\eta_{EC}^{EC}$ is the cold production efficiency of the electric chiller[17].

3.2.4. Absorption chiller model

\begin{align}
    C_{i}^{AC} = H_{i}^{AC} \eta_{AC}^{AC}
\end{align}

(12)

where $C_{i}^{AC}$ is the cold power output of the absorption chiller at time $t$, kW; $H_{i}^{AC}$ is the heat power input to the absorption chiller at time $t$, kW; $\eta_{AC}^{AC}$ is the cold production efficiency of the absorption chiller[17].

3.2.5. Electric to gas equipment model

\begin{align}
    P_{i}^{P2G,gas} = P_{i}^{P2G,gas} \eta_{P2G}^{P2G}
\end{align}

(13)

where $P_{i}^{P2G,gas}$ is input the electric power of the power to gas equipment at time $t$, kW; $\eta_{P2G}^{P2G}$ is the gas production efficiency of the power to gas equipment.

3.3. Constraints

3.3.1. Energy balance constraint

\begin{align}
\begin{cases}
    P_{i}^{PV} + P_{i}^{EC} + P_{i}^{P2G,gas} + P_{i}^{ESS,ch} = P_{i}^{PV} + P_{i}^{wind} + P_{i}^{GT} + P_{i}^{ESS,dis} + P_{i}^{grid} \\
    H_{i}^{GT,GB} + H_{i}^{AC} = H_{i}^{GT} + H_{i}^{GB} + H_{i}^{ESS,dis} \\
    C_{i}^{EC} + C_{i}^{CSS,ch} = C_{i}^{EC} + C_{i}^{AC} + C_{i}^{CSS,dis} \\
    P_{i}^{gas} + P_{i}^{P2G,gas} = P_{i}^{GT,gas} + P_{i}^{GB,gas}
\end{cases}
\end{align}

(14)

where $P_{i}^{ESS,ch}$ and $P_{i}^{ESS,dis}$ are electric storage charging and discharge power at time $t$ respectively, kW;
\( \bar{P}_t^{\text{PV}} \) is predicted value of photovoltaic output at time \( t \), kW; \( \bar{P}_t^{\text{wind}} \) is predicted value of wind turbine output at time \( t \), kW; \( H_t^{\text{HSS, ch}} \) and \( H_t^{\text{HSS, dis}} \) represent heat energy storage charging and discharging power at time \( t \) respectively, kW; \( C_t^{\text{CSS, ch}} \) and \( C_t^{\text{CSS, dis}} \) represent cold storage charging and discharging power at time \( t \) respectively, kW.

### 3.3.2. Energy conversion equipment output constraints

\[
\begin{align*}
0 & \leq P_t^{\text{GT}} \leq P_{\text{max}}^{\text{GT}} \\
0 & \leq H_t^{\text{GB}} \leq H_{\text{max}}^{\text{GB}} \\
0 & \leq P_t^{\text{P2G, g}} \leq P_{\text{max}}^{\text{P2G, g}} \\
0 & \leq C_t^{\text{EC}} \leq C_{\text{max}}^{\text{EC}} \\
0 & \leq C_t^{\text{AC}} \leq C_{\text{max}}^{\text{AC}}
\end{align*}
\]  

where \( P_{\text{max}}^{\text{GT}} \) represents gas turbine output electric power maximum, kW; \( H_{\text{max}}^{\text{GB}} \) represents gas boiler output heat power maximum, kW; \( P_{\text{max}}^{\text{P2G, g}} \) is power to gas equipment output gas power maximum, kW; \( C_{\text{max}}^{\text{EC}} \) represents electrical chiller output cold power maximum, kW; \( C_{\text{max}}^{\text{AC}} \) represents absorption chiller output cold power maximum, kW[18].

### 3.3.3. Contact line transmission power output constraint

\[
\begin{align*}
P_{\text{grid}}^{\text{min}} & \leq P_t^{\text{grid}} \leq P_{\text{grid}}^{\text{max}} \\
0 & \leq P_{\text{gas}}^{\text{max}} \leq P_{\text{grid}}^{\text{max}}
\end{align*}
\]

where \( P_{\text{grid}}^{\text{min}} \) is a negative number, \( |P_{\text{grid}}^{\text{min}}| \) represents the maximum power sold by the electricity contact line, kW; \( P_{\text{grid}}^{\text{max}} \) represents the maximum power purchased by the electricity contact line, kW; \( P_{\text{max}}^{\text{gas}} \) represents the maximum power purchased by the gas contact line, kW.

### 3.3.4. Energy storage (ESS, HSS, CSS) constraints

\[
\begin{align*}
I_t^{\text{min}} & \leq I_t^{i} \leq I_t^{\text{max}} \\
I_{t=1} & = I_{t=24}^{i}
\end{align*}
\]

where \( I_t^{\text{min}} \) and \( I_t^{\text{max}} \) represent the minimum and maximum values of the storage capacity of the storage device \( i \) respectively, kW; \( I_t^{i} \) is the storage capacity of the device \( i \) at time \( t \), kW; \( I_{t=1}^{i} \) and \( I_{t=24}^{i} \) represent the storage capacity of the device \( i \) at time 1 and 24 respectively, kW.

### 4. IES optimization algorithm flow

In this paper, based on the time-sharing tariff, the total electrical load is required to be constant to derive the target electrical load curve. According to the rated cooling and heat ratio of IES, the cooling and heat target load curve is determined, and then the shiftable load model is solved. There are many optimization variables in the model, so the calculation software MATLAB is used to solve it.

Aiming at the solution of the IES model, this paper uses the ADMM algorithm that combines the decomposability of the dual ascent method and the better convergence of the multiplier method and uses it to decompose a large problem into several small problems and alternate iteratively to solve the problem. The core idea is to realize distributed solution [19-20]. The specific process of ADMM optimization algorithm used in this paper is shown in Fig. 1.
5. Case analysis
To verify the effectiveness of the constructed optimal scheduling model and the proposed method, the paper uses the IES topology as shown in Fig. 2. The power forecast of IES for typical day distributed wind power, photovoltaic, electric, heat, and cooling loads are shown in Fig. 3.
Fig. 3 Wind power, photovoltaic and load forecast power

The shiftable loads model is solved by the calculation software MATLAB, and the load optimization diagram in IES is shown in Fig. 4. The figure shows that the peak of electric load after shifting decreases from 648.14kW to 559.29kW, and the valley of electric load increases from 203.96kW to 238.52kW. The peak of heat load after shifting falls from 335.58kW to 277.98kW, and the valley of heat load increases from 107.47kW to 117.22kW. After shifting, the peak of cooling load drops from 555.35kW to 497.45kW, and the valley of cooling load increases from 76.33kW to 77.96kW. The load shifting in IES reduces the peak-valley difference and improves the load curve. The load shifting plays a role in shaving peaks and filling valleys.

Fig. 4 Optimized shiftable loads results
The IES optimization model is solved using the ADMM algorithm, the optimized day-ahead scheduling results of IES is shown in Fig. 5. The figure shows that gas turbines mainly work during 9:00-18:00, which is because the gas price is lower than the electricity price during this period and the power supply cost of the system can be reduced by burning natural gas. From 24:00-7:00 the next day (the electrovalence is lower than the gas price), IES purchases electricity from the grid to meet the electricity demand, as shown in Fig. 6. The gas boiler and gas turbine realize the optimal complementary operation of the two under the guidance of heat cost. Compared to absorption chillers, electric chillers are more efficient and less costly to operate and maintain, thus taking up most of the cooling load. The optimized results of energy storage equipment are shown in Fig. 7. Electrical storage devices are discharged at peak times and charged at valley times to ensure a good economic benefit while ensuring power balance. The "peak-shaving" effect of heat and cooling energy storage devices further enhances the "flexibility" of IES and contributes to the stable operation of the system.
Fig. 7 Optimized results of energy storage equipment output

Fig. 8 Convergence of ADMM primal residuals and dual residuals

Fig. 8 shows that after 23 iterations, the primal residuals and dual residuals converge rapidly, indicating that the distributed optimization method based on ADMM has better convergence and higher solution efficiency.

6. Conclusion

The scheduling of the IES considering shiftable loads in the FL results in a more coordinated electric, heat and cooling load on the system and optimises the load profile. The economic and environmental benefits of the IES are improved after the regulation of shiftable loads, reducing the peak-to-valley difference in the system, which has the effect of cutting the peaks and filling the valleys and making the system operation more reliable.

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