Research on multi-objective optimal scheduling of virtual power plant based on self-supplied coal-fired power plants

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Abstract. With the development of renewable energy, improving the absorption capacity of power grid has become a difficult problem. It is very important to establish virtual power plants based on self-supplied coal-fired power plant to coordinate renewable energy consumption, especially in Xinjiang Province, China. This paper studied the optimal scheduling of a virtual power plant including wind turbines, photovoltaic units, and energy storage equipment based on the self-supplied power plant. First, a mathematical model of the power and power generation cost of each unit inside the virtual power plant was established, and the demand response mechanism was introduced. Secondly, a multi-objective optimization model is established by considering the maximization of net income of virtual power plants, the minimization of system coal consumption and the maximization of user interruption load benefits, and the use of analytic hierarchy process to determine the weights of three objective functions, of which user interruption load benefits are used to reflect the enthusiasm of users to interrupt the load. Finally, the particle swarm algorithm is used to solve the model. The optimization results show that when the coal price rises, the net income of the system decreases, and even a loss occurs, however, the change in coal price has little effect on the Interrupted load of user. In addition, multi-objective optimization can improve the enthusiasm of users while ensuring the net income of the system, it proves that the model has a good optimization effect.

1. Introduction
Due to severe environmental pollution and energy shortages, renewable energy has received more attention, but the large-scale addition of renewable energy has an impact on the stability of the grid, and improving the grid's ability to absorb renewable energy has become a priority. Virtual power plant (VPP), which was cleverly integrate and independently handle a large number of distributed energy sources, energy storage utilities, and loads, which portrays and controls the energy generation activities and contracts sensibly on the electricity market [1].

Over conventional power plants, VPPs have substantial advantages in terms of efficient transmission facilities, flexible physical characteristics, and highly regulative control architectures [2]. Inherently, they are clusters of Distributed Generation Resources (DER), energy storage utilities, and controllable loads connected to a centralized entity that superintends the energy flow within the aggregation [3]. Each unit of VPP has different operating characteristics and states, which makes it necessary to optimize the scheduling of the VPP system. Liu studied the operation scheduling of VPP system with the goal of maximizing the net income of the system [4]. Huo established a multi-objective optimization scheduling model considering the benefits and environmental costs [5]. Lria proposed scenario-based random
optimization methods and flexible load optimization methods to reduce their net market costs with exploits the flexibility of prosumers’ appliances [6]. Chen presented a two-stage stochastic operation method for a multi-energy micro-grid (MEMG), which can optimally schedule distributed generators, electric boilers, electrical chillers, and storage devices under the system technical constraints [7]. The study of VPP’s optimized scheduling also considers the safety of power grid, the flexibility of power system and the practical significance of self-contained power plant. Naughton proposed a scenario-based, uncertain multi-energy VPP operation optimization method that optimizes participation in multiple energy and ancillary service markets while reducing the limitations of local networks and providing reactive support [8]. Coelho presented a network-secure bidding optimization strategy to assist aggregators of multi-energy systems calculating electricity (energy and reserve), gas and carbon bids, considering multi-energy network constraints [9].

At present, the research of self-supplied power plant mainly focuses on two points including improving response speed and saving energy and reducing consumption. Adding the self-owned power plant into the VPP system can improve the absorption capacity of renewable energy and reduce the coal consumption. However, the optimization goals of existing research only focus on VPP system benefits and environmental costs, do not consider the enthusiasm of users to participate in dispatching. This paper conducts a research on VPP optimal dispatch based on self-supplied power plants, taking full account of system benefits, fossil energy consumption and users' enthusiasm to participate in dispatching.

2. Research object
The VPP established in this paper includes a coal-fired self-supplied power plant, a wind power unit, two photovoltaic power generation units and an energy storage unit, and the parameters of each internal unit including rated power, operating cost and unit power variation range are shown in Table 1. In this system, the self-supplied power plant mainly supplies power to industrial users, and the electricity price is based on the time-of-use electricity price of the local large industrial power. The maximum interrupted load of industrial users, the compensation coefficient of interrupted load, and the electricity price of each period are shown in Table 2.

Table 1. Parameters of VPP internal unit.

| Power source            | Rated power (MW) | Operation and maintenance costs (Yuan/MWh) | Power range (MW) |
|-------------------------|------------------|--------------------------------------------|-----------------|
| Self-supplied power plant| 350              | Annual coal price changes                  | 105-350         |
| Wind power              | 200              | 164                                        | 0-200           |
| Photovoltaic power      | 4.5x2            | 230                                        | 0-9             |
| Energy storage          | 100              | 84                                         | 0-100           |

Table 2. Parameters of electricity price and user interruption load in a certain area of Xinjiang.

| Parameter | $P_{DR, max}$ | $k_1$ | Peak  | Normal period | Valley |
|-----------|---------------|-------|-------|---------------|--------|
| Value     | 10MW          |       | 0.267 | 0.62          | 0.378  | 0.136  |

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Where $P_{DR, max}$ is maximum interrupted load, which refers to the maximum value that the user can reduce the load when receiving instructions, $k_1$ is compensation coefficient of interrupted load, which refers to the compensation standard of VPP for user interrupted load.

The power generation of wind turbines and photovoltaic units is heavily dependent on meteorological conditions. This paper collects typical daily wind speed and solar radiation intensity data in Urumqi, Xinjiang in March, as shown in Figure 1.
3. Optimal scheduling model of VPP

3.1. Internal unit modeling of VPP

3.1.1. Self-supplied coal-fired power plant model. In this study, the operating cost of a self-supplied power plant only comes from the consumption of coal. Coal consumption is closely related to unit power, through the study of coal consumption and power in a self-supplied power plant under design conditions, the mathematical relationship between the two factors is as follows:

$$\frac{r}{r_*} = 592.7 + \frac{10288}{P_f / P_{f_*}}$$

(1)

where $r$ is the Coal consumption rate, kg/(MW·h); $P_f$ is the power generation, MW. $r_* = 1$ kg/(MW·h), $P_{f_*} = 1$ MW.

The power generation cost of a captive power plant is:

$$C_f = \sum_{i=1}^{24} [\lambda_m \times r \times P_f \times \Delta t]$$

(2)

$$P_{fu} = \eta_f \times P_f$$

(3)

where $\lambda_m$ is the coal price, $r$ is the coal consumption and $t$ is the power generation time, $\Delta t = 1$ hour, $P_{fu}$ is the service power of power plant, $\eta_f$ is the service power rate of power plant.

3.1.2. Other unit models. The power and operating cost models of wind power and energy storage equipment can be found in the Literature [10]. The photovoltaic power generation model can be found in the Literature [5]. Demand response is mainly divided into price-type and incentive-type, and the cost and other issues arising from the implementation of these two mechanisms are calculated by the models in the Literatures [10, 11].

The Figure 2 shows the load changes of each unit of the VPP, which includes the predicted value of the user load after taking into account the demand response, the output of the wind power unit and the photovoltaic unit, and assumes that all the renewable energy in the VPP is consumed, and the remaining output is all supplied by the self-supplied power plant and energy storage unit. Since the output of the energy storage unit is uncertain, the combined output of the self-supplied power plant and the energy storage device is given in the form of equivalent power, as shown in Figure 2.
Figure 2. The power of each unit of the VPP system and the load change of the user.

3.2. Multi-objective optimization model of VPP

When optimizing the scheduling of VPP, this paper takes the combination of maximizing net income of VPP, minimizing coal consumption, and maximizing user benefits as the optimization goal.

(1) Net income of VPP

The objective function of maximizing the economic benefits of the system:

\[ F_1 = \max (R_L + R_d - C_w - C_{pv} - C_f - C_s - C_{PB}) \]  

where \( C_w \), \( C_{pv} \), and \( C_s \) are the operating costs of wind power, photovoltaics, and energy storage equipment, respectively. The calculation method of \( C_w \) and \( C_s \) is shown in [10], and the calculation method of \( C_{pv} \) is shown in [5]. \( C_{PB} \) is the cost of implementing price-based demand response, its calculation method shown in [10]; \( R_L \) is the revenue from selling electricity to users; \( R_d \) is the revenue from trading with the power grid, and \( \lambda_t \) is supplying power to users; \( \lambda_{DR} \) is the incentive response price, \( \lambda_{sale} \) and \( \lambda_{buy} \) are the selling price and purchase price of VPP and grid electricity, \( \mu \) is 0 or 1, which means selling or purchasing electricity to the grid, \( P_L \) is the user’s electrical load, \( P_{DR, max} \) is the user’s maximum interrupted load, and \( P_{DR} \) is the load actually interrupted by the user.

(2) Coal consumption

The objective function of minimizing coal consumption in self-supplied power plant:

\[ F_2 = \min (\sum_{t=1}^{24} r \times P_f) \]  

where \( r \) is the Coal consumption rate, kg/(MW·h); \( P_f \) is the power generation, MW.

(3) Participate in demand response and make benefits for users

This paper takes the benefits obtained by users participating in demand response as an objective function. We assume that when the user gains more revenue during the scheduling process, the user’s enthusiasm for interrupting the load is higher, so the objective function is used to reflect the enthusiasm of industrial users to interrupt the load.

\[ F_3 = \max \{ \sum_{t=1}^{24} [\lambda_t P_{DR,max} - \lambda_{DR} (P_{DR,max} - \Delta P_{DR})] + C_{DR} \} \]  

where \( C_{DR} \) is the Compensation for interrupted load, and its calculation method shown in [10]; \( P_{DR, max} \) is the user’s maximum interrupted load; \( \lambda_t \) is supplying power to users; \( \lambda_{DR} \) is the incentive response price.
Since $F_1$ and $F_3$ are benefit-based targets, and $F_2$ is a cost-based target, each target needs to be normalized, and the processing method is as follows:

$$F_1' = \frac{\max F_1 - F_1}{\max F_1 - \min F_1}, F_2' = \frac{F_2 - \min F_2}{\max F_2 - \min F_2}, F_3' = \frac{\max F_3 - F_3}{\max F_3 - \min F_3}$$ (9)

The final optimization objective function:

$$F = \omega_1 F_1' + \omega_2 F_2' + \omega_3 F_3'$$ (10)

In this paper, the analytic hierarchy process is used to determine the above-mentioned weights. The elements of the judgment matrix are given by the Saaty scaling method, and three experts evaluate the importance of the above objective function. After that, the consistency check is performed on the obtained judgment matrix, and the three weights $\omega_1$, $\omega_2$, and $\omega_3$ are 0.6064, 0.2164, and 0.1773 respectively.

3.3. Constraint condition

(1) Power balance constraint

$$P_L + P_d - \Delta P_{DR} = P_w + P_{pv} + P_s - P_f - P_{fu}$$ (11)

where $P_L$ is the user's electrical load, $P_d$ is the power supplied by the grid, and $P_w$, $P_{pv}$, and $P_s$ are the power of wind power, photovoltaic and energy storage equipment respectively.

(2) Power constraints of self-supplied power plant

$$P_{f,max} \leq P_f \leq P_{f,min}$$ (12)

where $P_{f,min}$ is the minimum output of the self-supplied power plant, which is 30% of the rated power.

(3) Constraints on energy storage equipment

The remaining battery power must be maintained within a certain range:

$$SOC_{min} < SOC < SOC_{max}$$ (13)

where $SOC$ is the battery capacity, $SOC_{min}$ is the lower limit of the battery capacity, which is 10MWh, $SOC_{max}$ is the upper limit of the battery capacity, which is 1000MWh,

The power of energy storage devices is also limited:

$$P_{s,min} \leq P_s \leq P_{s,max}$$ (14)

where $P_{s,min}$ and $P_{s,max}$ are the minimum and maximum power of the energy storage equipment respectively, where $P_{s,min}$ is less than 0, indicating that the battery is storing electric energy.

(4) Incentive demand response constraints

$$0 \leq \Delta P_{DR} \leq P_{DR,max}$$ (15)

(5) Grid transaction constraints

The electricity transaction volume between VPP and the grid is within a certain range:

$$-P_{d,max} \leq P_d \leq P_{d,max}$$ (16)

where $P_{d,max}$ is the maximum power that can be transmitted between the VPP and the grid.

4. Results

The VPP optimal scheduling model based on the self-supplied power plant established in this paper. All the process of model building and data processing were completed by MATLAB software, and the particle swarm optimization algorithm was used to solve the model, and discusses the optimization results.

4.1. Impact of coal prices

As shown in Figure 3, when the coal price increases, the net income of the VPP system and the system coal consumption gradually decreases. When the coal price reaches 800 Yuan/ton, the system is operating at a loss. In addition, the changes in coal prices have no significant impact on users’ enthusiasm for interrupting the load.
Figure 3. The impact of coal prices on different indicators.

As shown in Figure 4(a), as the coal price decreases, the power of the self-supplied power plant will increase. As shown in Figure 4(b), as the coal price decreases, the system will purchase electricity from the grid during the valley period of electricity consumption, and the system sells electricity to the grid at the maximum power during the peak electricity consumption period; as the coal price rises, the system shifts from selling electricity to the grid to purchase electricity from the grid during the period of parity.

As shown in Figure 4(c) and 4(d), with the increase in coal prices, the energy storage device stores more electricity during the valley period of electricity consumption, and the discharge capacity increases during the rest of the period. In addition, when coal price changes, the change trend of user interruption load over time is basically unchanged, because this load is mainly affected by electricity prices and is not sensitive to changes in coal prices.

Figure 4. The operation of the system when coal prices change.
4.2. Comparison of multi-objective optimization and other methods

In addition to the multi-objective optimization of the VPP, the system was optimized using the three single-objective models $F_1$, $F_2$, and $F_3$ mentioned in this paper, and the coal price was selected as 600 Yuan/ton. The calculation results are shown in Table 3.

| Optimization goal and R | VPP net income (Yuan) | Coal consumption (kg) | User benefit (Yuan) |
|-------------------------|-----------------------|-----------------------|--------------------|
| $F_1$                   | 475220.10             | 4162107.20            | 60460.40           |
| $F_2$                   | 139132.37             | 3199785.87            | 86094.74           |
| $F_3$                   | 100635.55             | 4231236.74            | 104319.32          |
| $F$                     | 405282.24             | 3862947.36            | 103693.60          |

In this paper, $R$ is used to represent the closeness of the multi-objective optimization result to the optimal value of the objective optimization, when the $R$ value is closer to 1, it indicates that the optimization effect of the model is better. The calculation method is as follows:

$$ R = (1 - \left| \frac{\text{potV}(F_i) - F}{\text{potV}(F_i) - \text{wosV}(F_i)} \right| ) $$

where $\text{potV}$ and $\text{wosV}$ represent the optimal value and the worst value respectively.

| Optimization goal | R of VPP net income | R of coal consumption | R of User benefits | R average |
|-------------------|---------------------|-----------------------|--------------------|-----------|
| $F_1$             | 1.0000              | 0.0670                | 0.0000             | 0.3557    |
| $F_2$             | 0.1028              | 1.0000                | 0.5845             | 0.5624    |
| $F_3$             | 0.0000              | 0.0000                | 1.0000             | 0.3333    |
| $F$               | 0.8133              | 0.3571                | 0.9857             | 0.7187    |

Table 4 shows the comparison of multi-objective and single-objective optimization results. As can be seen from the table, through multi-objective optimization, the R of net VPP income is 0.8133, and the R of net user income is 0.9857, which is very close to the optimal value of corresponding target optimization. After multi-objective optimization, the R of coal consumption is 0.3571, which is better than the results of single-objective $F_1$ and $F_3$, however, there is a large gap between the results of multi-objective optimization and the optimal value, which may be because the coal consumption is more dependent on the influence of coal price. In general, the R average of multi-objective optimization result is 0.7187, which is higher than the other three single-objective optimization models, indicating that the multi-objective optimization model proposed in this paper has a good optimization effect.

5. Conclusions

This paper introduces a VPP system with multiple power sources based on self-supplied power plant, and establishes a multi-objective optimization model considering net income of VPP, coal consumption of system and users’ interrupted load benefits, aiming to explore the influence of coal price on system optimal scheduling and how to ensure users’ enthusiasm for interrupted load. The research results are as follows:

1. Coal prices have greater impact on the VPP system based on coal-fired power plant. As coal prices increase, the net income of the VPP system decreases. However, changes in coal prices have little effect on users’ enthusiasm to interrupt load.
(2) Compared with single-objective optimization, multi-objective optimization has better optimization effect. Through multi-objective optimization, it is possible to increase the enthusiasm of users to participate in the interruption of the load while guaranteeing the benefits of the system.

The current research discusses the economy of the VPP system, and the future work will pay more attention to the security and stability of the operation of VPP.

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