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A comparative study of virtual power plant operation optimization strategy[1]

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Abstract. A strategy of a virtual power plant is proposed, consisting of a cogeneration system and a solar power system. First, an optimization model is built based on day-ahead market and real-time optimization. Then, different optimal operation strategies of real-time optimization and reference situation are compared, which is illustrated with an examples.

Key words. Virtual power plant, operation optimization strategy, total operation cost, imbalance error reduction.

1. Introduction

In recent years, the rapid development of world's economy results in an increasing demands on energy [1-2]. However, with increasingly serious energy shortage and environmental issues, people started to realize that the economy development relied on fossil fuels is unsustainable [3]. How to improve energy utilization efficiency and develop renewable energy has becoming a problem urgently waiting to be solved in the process of energy development [4]. Renewable energy power generation technology mainly includes wind power, photovoltaic power generation, biomass power, tidal power, etc. In the existing renewable power generation technology, wind power and photovoltaic power generation are the most mature and most widely used technologies. However, the output of renewable energy is uncontrollable, which exhibits a great deal of volatility and uncertainty. And it will influence the safe and stable operation of power grid in the process of grid connection, and this also becomes the

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obstacle in the way of large-scale renewable energy development [5-7].

In order to solve the above problem and increase the renewable energy generation, now we can use virtual power plant (VPP) combined by different distributed generation technology to compensate the output volatility of renewable energy. The output instability of renewable energy can be covered by other distributed generation system, thus the energy efficiency of the whole system will be improved, and we can achieve the purpose of energy saving and emission reduction. Nowadays, there exists no clear definition of VPP, and one of the typical concept follows: VPP is an organic combination of traditional power plant, distributed power, controllable load and energy storage system in a certain area, participated in the power grid as a whole system through a control center management. The typical structure of a VPP is shown in Fig. 1.

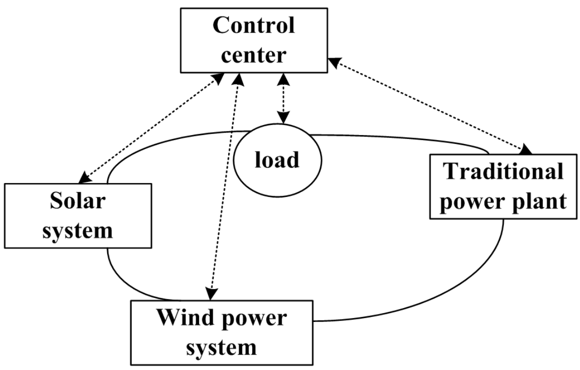

Fig. 1. Typical structure of VPP

The figure above typically contains tow networks, which are energy network and information network. The solid line represents energy network, that consists of the electricity transmission network, connected with the solar system, wind power plant and traditional power plant. The dotted line represents the two-way communication between the control center and other cells in VPP.

At present there is no large-scale application of virtual power plant, and the relevant research is still in its infancy. There are many researches related to virtual power plant, ranging from concept to the joint optimal operation. Ruiz et al. [8] provide an optimization algorithm to manage a VPP composed of a large number of customers with thermostatically controlled appliances. Masuta et al. [9] evaluate the frequency and trend of outages and surpluses of power due to the forecast error of PV power generation by numerical simulations conducted using the power system model of Kanto area in Japan. Eto et al. [10] propose a method deciding a schedule of node movement to cover the target agricultural field from plant to harvest by the minimal number of nodes in order to reduce the node deployment cost. Pandžić et al. [11] studied the operation optimization of a virtual power plant including wind power generation, energy storage system and conventional power plants. El-Sayed and Obara [12] propose a prediction algorithm based on a neural network (NN) to predict the electricity production from a solar cell. Also, Pandžić et al. [13] consider a weekly self-scheduling of a virtual power plant composed of intermittent renewable sources, storage system and a conventional power plant. Ajabshifizadeh et al. [14] consider the predictions of both the amplitude and timing of the next solar cycle will assist in estimating the various consequences of Space Weather.

The structure of this paper is as follows: in section I we introduce the background of virtual power plant, while in section II the optimization models are built up. In section III, we use a case to verify the validity of the model. In section IV, the article is summarized.

2. Material and methods

2.1. Formulation of the problem

Considering the uncertainty of renewable energy output, in order to simplify the model. In this paper, we study the optimal operation of a virtual power plant consisting of a cogeneration system and distributed solar power system. The cogeneration system includes a generator, a waste heat utilization device and an auxiliary boiler, which is used to meet the electricity and heat demands of the users and smooth the solar output.

In order to study the optimal operation strategy of virtual power plant, we will build models based on day-ahead and real-time scenarios, respectively.

2.2. Day-ahead optimization algorithm

The objective function of day-ahead optimization aims at the minimum of the operation cost of the whole system, and may be written in the form

$$\mathrm{Min}\sum_{t=1}^{T}(C-S)=\mathrm{Min}\sum_{t=1}^{T}\left[(fc_{\mathrm{CHP}}+fc_{\mathrm{boiler}})-(r_{\mathrm{sold}}+r_{\mathrm{con}})\right], \tag{1}$$

where fc_{CHP} and fc_{boiler} represent the fuel costs of the CHP system and boiler, respectively, r_{sold} represents the revenue from selling electricity to the grid, and r_{con} represents the saving electricity expense.

The relationship between the fuel consumption and electricity output of the CHP system is given by the equation

$$Q_{\mathrm{CHP}}=\alpha\cdot\sum_{t=1}^{T}\beta(t)\cdot E_{\mathrm{CHP}}(t), \tag{2}$$

in which α is the fuel consumption rate related to the type of equipment and operation environment, β is the running state variable of the CHP system: $\beta=0$ represents its shut down and $\beta=1$ represents on.

In this paper, we assume that the thermal efficiency of boiler γ is constant, thus, the fuel consumed by boiler can be calculated as

$$Q_{\text{boiler}} = \frac{\sum_{t=1}^{T} H_{\text{boiler}}(t)}{\gamma \cdot Q}\,, \tag{3}$$

where Q is the calorific value of natural gas.

Therefore, the total fuel cost of whole system can be obtained by the total fuel cost multiplied with the fuel cost p_{fuel}, i.e.

$$fc_{\text{CHP}} + fc_{\text{boiler}} = (Q_{CHP} + Q_{\text{boiler}}) \cdot p_{\text{fuel}}\,. \tag{4}$$

The total production of electricity E_{CHP} consists of the part generated by CHP system used to satisfy the users' demand E_{con}, and the excess part E_{sold} that can be sold to the grid,

$$E_{\text{CHP}} = E_{\text{con}} + E_{\text{sold}}\,. \tag{5}$$

Therefore, the revenues can be obtained by adding the power usage multiplied with corresponding price

$$r_{sold} + r_{con} = p_{\text{sold}} \cdot E_{\text{sold}} + p_{\text{con}} \cdot E_{\text{con}}\,. \tag{6}$$

In the process of optimization, the system mainly has two aspects of constraints, that is, operation constraints and technical constraints.

The operation constraints ensuring the heat demands of the users can always be satisfied,

$$D_{\text{heat}}(t) = H_{\text{CHP}}(t) + H_{\text{boiler}}(t) + H_{\text{storage}}(t)\,, \tag{7}$$

where H_{CHP} and H_{boiler} represent the heat generated by the CHP system and the boiler, respectively. Symbol H_{storage} is the heat obtained from the heat storage device.

The status of the heat storage device is calculated on the condition that the efficiency η is constant, and its value is 90% in this paper.

$$H_{\text{storage}}(t) = \eta H_{\text{storage}}(t-1) - H_{\text{storage}}(t) \cdot \triangle t\,, \tag{8}$$

where $\triangle t$ is the time interval.

The following technical constraints are used to ensure the safe and stable operation of devices,

$$0 \le H_{\text{storage}} \le H_{\text{s\_max}}\,, \tag{9}$$

$$0 \le H_{\text{boiler}} \le H_{b\text{\_max}}\,, \tag{10}$$

$$H_{\text{CHP\_min}} \le H_{\text{CHP}}(t) \le H_{\text{CHP\_max}}\,, \tag{11}$$

$$E_{\text{CHP\_min}} \le E_{\text{CHP}}(t) \le E_{\text{CHP\_max}}\,. \tag{12}$$

2.3. Real-time optimization algorithm (Strategy 1)

The imbalance of the system mainly comes from the gap between the electric forecast and actual outputs. In this paper, the imbalance of the VPP system is composed from two parts. One of them is the solar output prediction error and the other is the output error of CHP system due to the demand changes.

The optimization objective of Strategy 1 is to minimize the total imbalance error. The economic problems are not considered here and the objective function is given as

$$\mathrm{Min}\sum_{t=1}^{T}[E_{\mathrm{real}}(t) - E_{\mathrm{forecast}}(t)]^2 = \mathrm{Min}\sum_{t=1}^{T}[E_{\mathrm{error}}(t)]^2\,, \tag{13}$$

where R_{real} and E_{forecast} represent the actual and forecast power outputs of the VPP.

Although the objective functions are different, the operation and technology constraints are the same, so here we do not discuss the same constraints again. While there still is a unique constraint, the predict power output of VPP has to be satisfied by the actual power output and electricity E from auxiliary market

$$E_{\mathrm{forecast}}(t) = E_{\mathrm{real}}(t) + E(t)\,. \tag{14}$$

2.4. Real-time optimization algorithm (Strategy 2)

The optimization objective of Strategy 2 is to minimize the total operation cost of the whole system, including the fuel cost of CHP system, boiler, and expense for covering the imbalance error

$$E_{\mathrm{error}} = \mathrm{Min}\sum_{t=1}^{T}(fc_{\mathrm{CHP}} + fc_{\mathrm{boiler}} + c_{\mathrm{error}})\,. \tag{15}$$

As we can see from the equation above, when $E_{\mathrm{error}} > 0$, the VPP system can sell extra electricity and get revenues. In order to avoid opportunistic phenomenon, we set a constraint that the total imbalance error cannot excess the imbalance error caused by the solar instability, that is,

$$\sum_{t=1}^{T}E_{\mathrm{error}}(t) \le \sum_{t=1}^{T}E_{\mathrm{error\_PV}}(t)\,. \tag{16}$$

2.5. Prediction of solar output

The output of the solar system depends largely on the real-time light intensity. Figure 2 shows the solar system output curve under different weather conditions in summer in China, and we can see that the output of solar system has a great deal of uncertainty and unpredictability. But with the permanent development of prediction technology, it will be more and more accurate and reliable.

According to the difference of the methods, the existing prediction methods

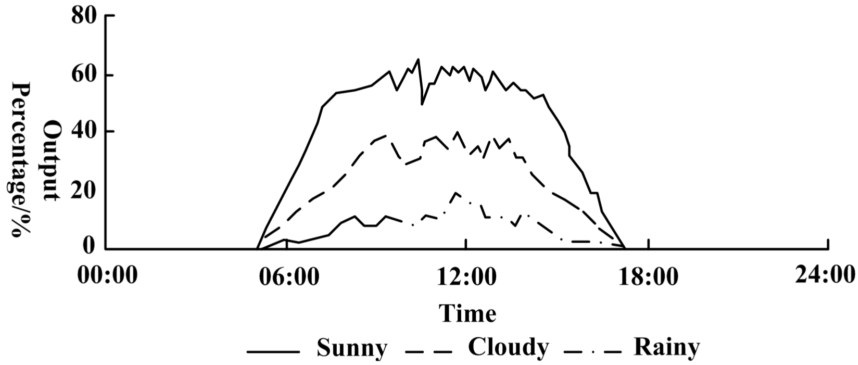

Fig. 2. Output percentage of PV under different weather conditions in summer

mainly can be divided into two groups: statistical methods and physical methods. The former one using the existing physical model obtains the prediction value by input the meteorological forecast data directly. The latter one is based on some statistical methods, analysis of historical data in order to find the internal rule by establishing the relationship between numerical weather prediction and historical output data to predict, mainly including support vector machine (SVM), grey prediction, regression model and so on.

With the continuous development of prediction technology, the accuracy of photovoltaic output prediction in the future will continue to improve, and this will lead to the improvement of the utilization of solar system.

3. Results

In this section, we use the actual output of VPP system without reschedule strategy as reference, compared the two real-time strategies by different indexes. The first index is the capacity for reducing the imbalance error, namely the difference with the day-ahead optimization. The second index is the total operation cost.

3.1. Capacity to reduce imbalance error

Figures 3 and 4 show the output of different scenarios under typical winter and summer days.

In the figures above, the black solid line represents the electric output in day-ahead optimization, and the shadow part represents the output in three different scenarios. As we can see from the preamble, Strategy 1 provides the maximum reduction of imbalance error in theory. We can also draw the conclusion that no matter what the optimization objective is, using optimization strategy can reduce the imbalance error efficiently. However, in Fig. 4 we can find that when using Strategy 2, there still remains larger imbalance error compared to the reference,

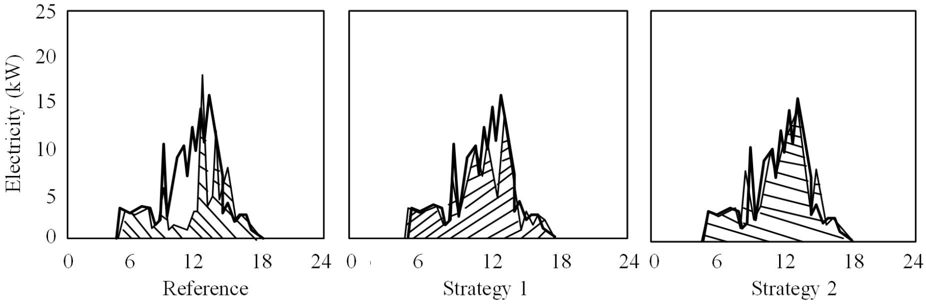

Fig. 3. Electricity outputs of different scenarios in typical winter day

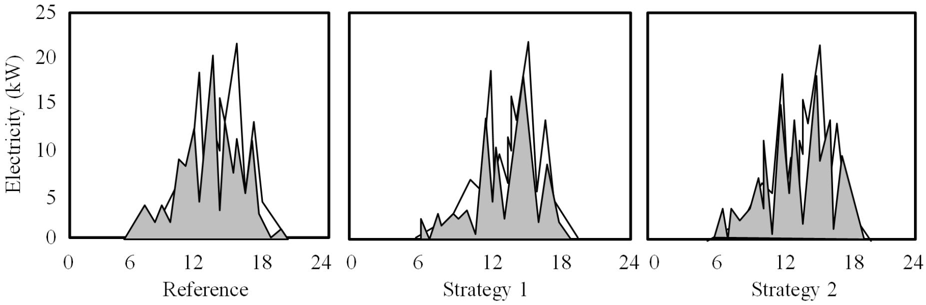

Fig. 4. Electricity outputs of different scenarios in typical summer day

which means that reducing imbalance error in this situation is uneconomical, and the latter analysis will also show the same conclusion.

Figures 5 and 6 reveal the remaining imbalance error in typical winter, summer and general situations. We can easily find that the imbalance error in summer is larger than that in winter, and the positive imbalance error is particularly significant.

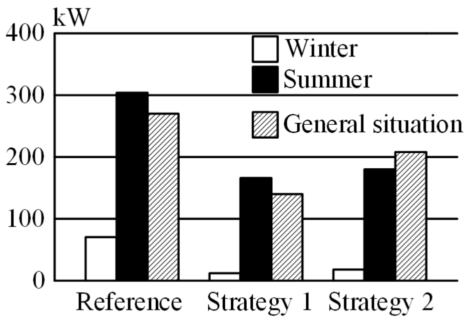

Fig. 5. Positive imbalances in winter, summer and in general situation

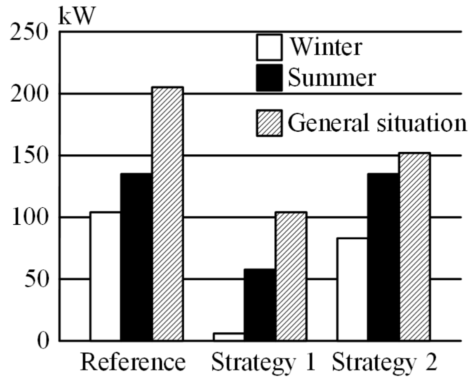

Fig. 6. Negative imbalances in winter, summer and in general situation

3.2. Total operation cost

The total operation cost of VPP system mainly consist of the fuel cost of CHP system, solar power system and the cost for reducing imbalance error (see Fig. 7).

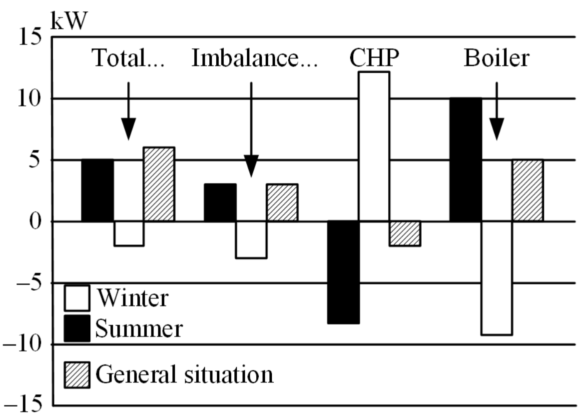

Fig. 7. Cost comparison between "Strategy 1" and "Reference" (yuan/week)

Compared with the reference, the fuel cost of CHP system in winter increases remarkable. This is because the illumination intensity in winter decreases, thus the CHP system has to compensate the shortage of solar generation. Meanwhile, the fuel cost of boiler is reduced, also because of the excessive output of the CHP system (see Fig. 8).

Combined with the above figure we can see that there is a larger positive imbalance error in summer and in general situation, so that the CHP system reduces the output and the fuel cost is lower as well. But this also leads to a great increase of the cost of reducing imbalance error, which proves to be non-economical, as also

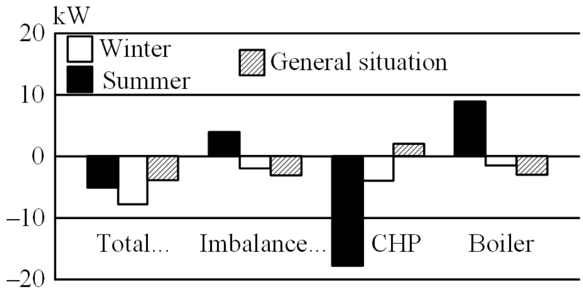

Fig. 8. Cost comparison between "Strategy 2" and "Reference" (yuan/week)

shown above.

4. Conclusion

In this paper, we designed optimized operation models of VPP system under different scenarios, and then compared the different strategies by factual data. As the results showed, no matter whether we want to maximize the imbalance error reduction or minimize the total operation cost, compared to the reference, the imbalance errors are largely reduced by reschedule. However, the results also tell us that the strategy used for reducing the imbalance errors is not always economical, especially in summer.

The application of virtual power plant can effectively improve the utilization efficiency of renewable energy under the condition of ensuring the safe and stable operation of power system. In the meantime, as one of the ways of demand side management, the use of virtual power plants has a great significance in strengthening the demand side management, and realizing the energy saving. While the development and application of virtual power plant still exhibit certain problems, it needs cooperation among technology, management and policy.

Limited by space and the depth of research, the research in this paper about the optimization operation of virtual power plant still has many deficiencies. So, in the further study about VPP, we can carry on the researches on system capacity configuration, price mechanism, the related policy and so on. In order to build a resource-conserving and environment-friendly society, the application of VPP will be surely wider and wider.

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