Real-time pricing strategy of micro-grid energy centre considering price-based demand response

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Abstract. With the development of energy conversion technology such as power to gas (P2G), fuel cell and so on, the coupling between energy sources becomes more and more closely. Centralized dispatch among electricity, natural gas and heat will become a trend. With the goal of maximizing the system revenue, this paper establishes the model of micro-grid energy centre based on energy hub. According to the proposed model, the real-time pricing strategy taking into account price-based demand response of load is developed. And the influence of real-time pricing strategy on the peak load shifting is discussed. In addition, the impact of wind power predicted inaccuracy on real-time pricing strategy is analysed.

1. Introduction

With the development of economy and demand, the energy dilemma and environmental pollution becomes more and more severe. As a new energy consumption pattern, Energy Internet has received more attention which can improve energy efficiency [1,2]. Nowadays, electricity, natural gas and other energy network is independent in plan and operation. As the development of energy converter, such as power to gas (P2G) and fuel cell, the coupling among electricity, natural gas and heat network become closer and closer [3,4]. Based on it, micro-grid energy centre combines the electricity, natural gas and heat and realizes centralized dispatch will become a trend [5,6].

There are several proposals for energy optimal operation based on energy hub. In [7], optimal energy flow model in electricity-gas integrated energy system was proposed. In [8], the impact of P2G in electricity-gas integrated energy system was considered. These proposals do not consider the impact of load price-based demand respond on real-time pricing strategy and system revenue.

In the other hand, access to renewable energy will have an impact on the operation of micro-grid energy centre. In this paper, optimal energy dispatch model of micro-grid energy centre is established. Based on this model, the real-time pricing strategy considering price-based demand response of load is developed. Furthermore, the impact of wind power predicted inaccuracy on real-time pricing strategy is analyzed.

2. Model description

2.1. Static-state model of micro-grid energy centre

The structure of micro-grid energy centre is shown in figure 1. Typical elements composing a micro-grid energy centre are renewable energy, energy converters and energy storages. The $\boldsymbol{P}$, $\boldsymbol{L}$, $\boldsymbol{R}$, $\boldsymbol{Q}$, $\boldsymbol{S}$ and $\boldsymbol{\eta}$ are represent the input energy flow form network side, output energy flow, renewable energy sources, charge and discharge power of energy storages, input energy flow of energy converters and energy convert efficiency respectively. The total number of variables ***P***, ***L***, ***S***, ***R***, ***Q*** are defined as *M*, *N*, *I*, *K* and H respectively. The static-state balanced equations are shown as formula (1).

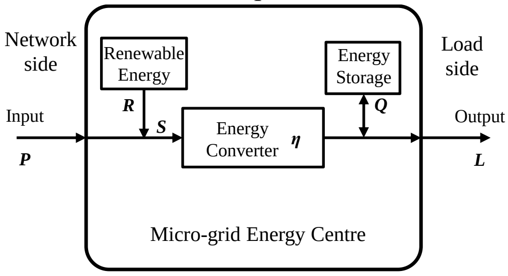

Figure 1. Structure of Micro-grid Energy Centre.

$$\begin{bmatrix} \boldsymbol{Z}_{\mathrm{A}} \\ \boldsymbol{Z}_{\mathrm{B}} \end{bmatrix} \begin{bmatrix} \boldsymbol{P} \\ \boldsymbol{S} \\ \boldsymbol{R} \\ \boldsymbol{Q} \end{bmatrix} = \begin{bmatrix} \mathbf{1} & \boldsymbol{Z}_{\mathrm{AS}} & \boldsymbol{Z}_{\mathrm{AR}} & \mathbf{0} \\ \mathbf{0} & \boldsymbol{Z}_{\mathrm{BS}} & \mathbf{0} & \boldsymbol{Z}_{\mathrm{BQ}} \end{bmatrix} \begin{bmatrix} \boldsymbol{P} \\ \boldsymbol{S} \\ \boldsymbol{R} \\ \boldsymbol{Q} \end{bmatrix} = \begin{bmatrix} \mathbf{0} \\ \boldsymbol{L} \end{bmatrix} \tag{1}$$

In (1), $\boldsymbol{Z}_{\mathrm{A}}$ and $\boldsymbol{Z}_{\mathrm{B}}$ are defined as source incidence matrices and load incidence matrix. **1** is an $M \times M$ unit matrix. Partitioned matrices of $\boldsymbol{Z}_{\mathrm{A}}$ and $\boldsymbol{Z}_{\mathrm{B}}$ include $\boldsymbol{Z}_{\mathrm{AS}}=(z_{mi})_{M\times I}$、$\boldsymbol{Z}_{\mathrm{AR}}=(z_{mk})_{M\times K}$、$\boldsymbol{Z}_{\mathrm{BS}}=(z_{ni})_{N\times I}$ and $\boldsymbol{Z}_{\mathrm{BQ}}=(z_{nh})_{N\times H}$. These partitioned matrices also can be defined as formulas (2).

$$\begin{cases} z_{mi} = \begin{cases} -1 & m \text{ connects with } i \\ 0 & \text{else} \end{cases} \\ z_{mk} = \begin{cases} 1 & m \text{ connects with } k \\ 0 & \text{else} \end{cases} \end{cases} \qquad \begin{cases} z_{ni} = \begin{cases} \eta_{ni} & n \text{ connects with } i \\ 0 & \text{else} \end{cases} \\ z_{nh} = \begin{cases} -1 & n \text{ connects with } h \\ 0 & \text{else} \end{cases} \end{cases} \tag{2}$$

2.2. Model of load considering demand respond

Energy has pricing demand elasticity when it participates in the transaction as a commodity. The pricing demand elasticity is a predetermined parameter which shows energy demand changing with different price. The model of demand can be described as follows.

$$L_t = E_d \rho_t + \beta \tag{3}$$

$$\underline{\rho} \le \rho_t \le \overline{\rho} \tag{4}$$

In formula (4) and (5), E_d is the pricing demand elasticity. The β is a predetermined parameter. Subscript t is the counting variable for time period. The ρ_t represents energy sale price. The $\overline{\rho}$ and $\underline{\rho}$ correspond to upper/lower limits of the ρ_t.

3. Day ahead optimal dispatch of micro-grid energy centre

3.1. Objective function

$$F = \max \sum_{t=1}^{T} \left[\sum_{n=1}^{N} \rho_{n,t} L_{n,t} - \sum_{m=1}^{M} \theta_{m,t} P_{m,t} \right] \tag{5}$$

In equation (6), T is the total number time periods for scheduling. Subscripts, such as m and n are the counting variable for energy input and output. The $\rho_{n,t}$ and $\theta_{m,t}$ represent energy price of output and input respectively.

3.2. Constraints

Operating constraints of micro-grid energy centre include formula (1), (4), constraints of exchange power with networks side and operating constraints of energy converters, renewable energy resources and energy storages. The constraints can be represented as follows.

$$\begin{cases} 0 \le P_m \le P_m^{\max} \\ 0 \le R_{k,t} \le R_{k,t}^{*} \\ S_j^{\min} \le S_{j,t} \le S_j^{\max} \\ -S_j^{\text{down}} \le S_{j,t} - S_{j,t-1} \le S_j^{\text{up}} \\ E_h(t+1) = E_h(t) + Q_h^{\text{ch}}(t) - Q_h^{\text{dis}}(t) \end{cases} \quad \begin{cases} E_h(t)^{\min} \le E_h(t) \le E_h(t)^{\max} \\ E_h(0) = E_h(T) \\ 0 \le Q_h^{\text{ch}}(t) \le \varsigma_h^{\text{ch}}(t) Q_h^{\text{ch,max}}(t) \\ 0 \le Q_h^{\text{dis}}(t) \le \varsigma_h^{\text{dis}}(t) Q_h^{\text{dis,max}}(t) \\ \varsigma_h^{\text{ch}}(t) + \varsigma_h^{\text{dis}}(t) \le 1 \end{cases} \qquad (6)$$

In formula (6), $R_{k,t}^{*}$ is renewable energy power forecast. S_j represents capacity of converters. Subscripts, such as max and min correspond to upper and lower limits of the variable. S^{up} and S^{down} are the upward and downward ramping capacity of converters. $Q_{\text{ch}h}$ and $Q_{\text{dis}h}$ presents charge and discharge power of energy storages respectively. E is energy of energy storage. ς_h^{ch} (t) and ς_h^{dis} (t) are the binary variables.

4. Case study

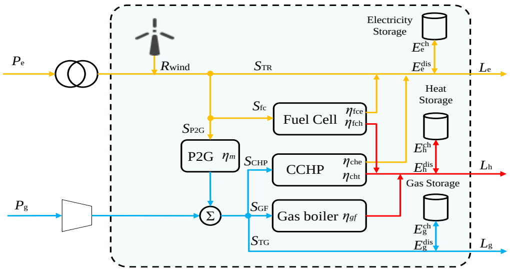

Figure 2. The Model of Micro-grid Energy Centre.

Figure 2 shows the model of micro-grid energy centre. Energy converters include P2G facilities, combined cooling heating and power facilities (CCHP), gas boilers and fuel cells. Parameters of load demand curves are shown as table 1.

Table 1. Parameters of Load Demand Curves.

Type of load	Basic price ($/MWh)	Demand elasticity E_d (MWh2/$)	Lower limits of price ($/MWh)	Upper limits of price ($/MWh)
electric	90	0.11	75	90
		0.06	90	120
heat	50	0.03	40	75
natural gas	80	0.06	70	100

This paper assumes that demand in basic price is called original load. The wind power forecast and original load are shown as figure 3.The prices of purchasing electricity and gas are shown as figure 4.

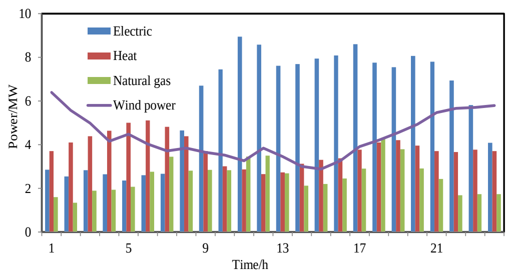

Figure 3. Wind Power Forecast and Original Load.

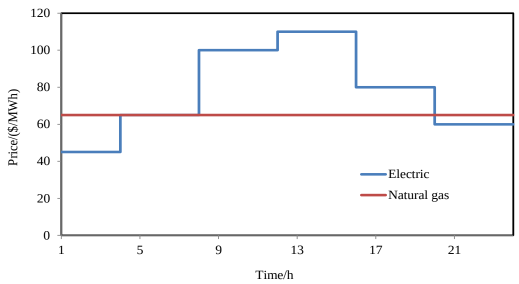

Figure 4. Prices of Purchasing Electricity and Gas.

4.1. Result analysis of optimal dispatch

According to the above data, the real-time pricing strategy, optimized load and energy purchase situation are shown as figure 5 and figure 6.

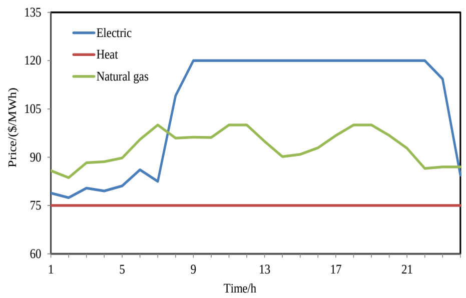

Figure 5. Real-time Pricing StrategyFigure.

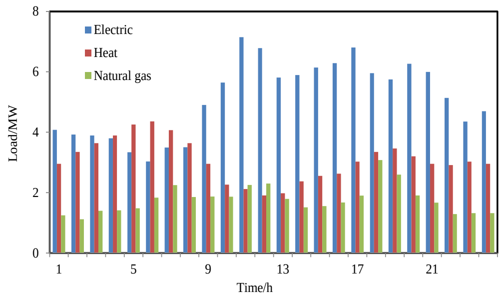

Figure 6. Energy load in Optimal Dispatch.

The 1 o'clock to 7 o'clock and the 21 o'clock to 24 o'clock are the electric trough. At the same time, the wind power is at its peak. In order to achieve the objective of the maximal profit, the electric sale price remains at around 80 $/MWh which has declined compared to the basic price. The 8 o'clock to 20 o'clock are the trough of wind power and peak of electricity. At this time, the purchase price of electricity is at its peak. Thus, the electric sale price almost is set in the upper limits of price to reduce the electric load. The purchase price of natural gas is stable. So the natural gas sale price is positively related to gas demand. The cost of heat is high because heat load can only be provided by electricity and natural gas after conversion. So the heat sale price always is set in the upper limits of price.

Comparison of the variances between the optimized load and the original load is shown as table 2.

Table 2. Comparison of Variances between the Optimized load and the Original load.

Type of load	Variances of original load	Variances of optimized load
electric	2.39	1.22
heat	0.67	0.67
natural gas	0.75	0.46

The variances of the optimized electric and gas load have declined compared to the original. The variance of heat load has not changed because the heat sale price is set in the upper limits of price. Therefore, implementation of real-time price has a significant effect on peak load shifting.

4.2. The impact of predicted inaccuracy on pricing strategy

This paper assumes the wind power in 4.1 is the real wind power and the corresponding pricing strategy is the standard strategy. The impact of ±15% and ±30% wind power predicted inaccuracy on system revenue and pricing strategy are as follows.

Table 3. System Revenue in Different Predicted Inaccuracy.

Predicted Inaccuracy	0	+15%	-15%	+30%	-30%
Revenue /$	12268.85	13208.50	11268.85	14066.04	10215.74
Revenue Inaccuracy	0	7.66%	-8.15%	14.6%	-16.7%

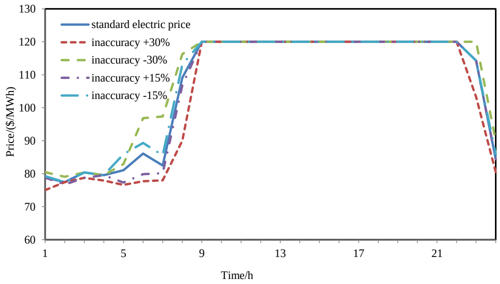

Figure 7. Electric Pricing Strategy in Different Predicted Inaccuracy.

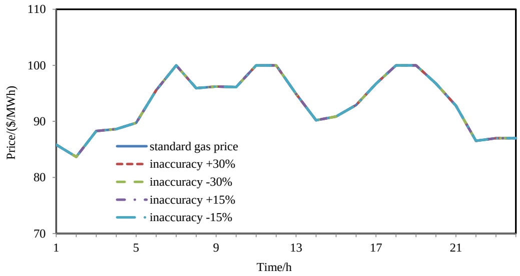

Figure 8. Natural gas Pricing Strategy in Different Predicted Inaccuracy.

Table 3, figure 7 and figure 8 show the revenues and the pricing strategies of electricity and gas under different inaccuracies. Gas load is mainly provided by gas sources because of low capacity of P2G facility. So predicted inaccuracy of wind power has no effect on gas price. In electric trough, electric load is mainly provided by wind power. Thus, predicted inaccuracy of wind power has a significant effect on the electric price in electric trough. Furthermore, the result also shows that the higher the inaccuracy, the greater the price fluctuation.

5. Conclusion

Based on model of micro-grid energy centre, this paper establishes optimal scheduling model considering price-based demand response, which aims at the maximum revenue. In addition, the proposed model has been tested to make the optimal real-time pricing strategy. And extensive simulation studies have indicated the following:

(1) Implementation of real-time price based on micro-grid energy centre is beneficial to peak load shifting.

(2) It is necessary to improve the wind power forecasting method and prediction accuracy of wind power in order to make real-time electric pricing strategy exactly.

(3) Uncertainties of wind power and energy load have a significant effect on real-time pricing strategy. Thus, the real-time price strategy considering these uncertainties needs further study.

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Acknowledgments

This work is supported by National Natural Science Foundation of Chian (No. 51377060).