The Journal of Engineering

The 7th International Conference on Renewable Power Generation (RPG 2018)

Optimal operating control strategy for biogas generation under electricity spot market

eISSN 2051-3305
Received on 29th October 2018
Accepted on 09th January 2019
E-First on 10th July 2019
doi: 10.1049/joe.2018.9311
www.ietdl.org

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Abstract: This study presents an approach of biogas generation coupled with electricity trading under electricity spot market to maximise the biogas power profits. The aim of this study is to achieve a minimal generation cost for the biogas generation system while eliminating the dependence on batteries due to the storage and tunable properties of biogas digester. In terms of the electricity prices at different times in the spot market, the operating control strategy for biogas generation is established to perform the optimal generation scheduling, which give the two model comparison results. The practical case of biogas engineering in the ecological park in Hunan Province in China is carried out to validate the effectiveness and practicability of the proposed strategy.

1 Introduction

The power industry of an increasing number of countries is embarking on an intense process of reforms oriented to the electricity customers and generation companies [1]. Although long and medium-term markets are expected to gain importance [2], the electricity spot markets, in which energy is traded for immediate delivery, have played increasingly more important roles under direct electricity trading [3] by large consumers, given that they can accurately reflect electricity supply and demand in different periods and regions [4]. It is of significance to develop the optimal generation scheduling and maximise the profits for biogas power plants in different real-time forecasting price.

However, a large number of generation companies are arranging the generation and utilisation scheduling under uncertainty about the price fluctuation mechanism of spot markets. In view of the above problems, many researchers have put forward some economic dispatch strategies considering the renewable energy integration in the spot market. The dynamic economic dispatch model of the microgrid consisting of a wind turbine, photovoltaic (PV) cells, a storage battery, a micro turbine, a fuel cell, heating and electric loads was established [5], which coupled with different generation characteristics of distributed resources and realised the internal randomness accommodation of the microgrid, but the model has poor economic benefits. The later study [6] emphasised the whole generation costs of microgrid including PV power generation and biomass generation, and proposed a dynamic economic dispatch model considering both grid-connection and islanding operation modes. The biogas plants with excess power unit and storage capacity in electricity and control reserve markets can adapt the unit commitment to the demand and the market prices [7], but the generation scheduling for the renewable energy integrated spot market has not been reported yet. Although several studies [8] have shown that the energy storage system coupled with electric energy transaction is of value in the spot electricity market, there are still many bottlenecks in non-scaled storage, high construction and maintenance costs.

As an energy resource, biomass is very versatile in terms of the variety of forms and the number of options available for its utilisation [9]. The recycling of the carbon by photosynthesis is one of the many attractive features of biomass utilisation. Biogas generation is, in general, characterised by high coordinative adaptation for intermittent energy, low operation and maintenance costs, and zero fuel costs [10]. In view of price fluctuations under electricity spot market, we optimise generation scheduling while reducing total operating costs using the flexibility of biogas generation. It is an effective means to improve the local consumption of renewable energy and maximise the economic benefits of generation companies by developing the optimal operating control strategy for biogas generation.

In order to eliminate the dependence on batteries and reduce energy storage costs, a method of biogas generation coupled with electricity trading under spot market is performed, which utilises the storage and tunable properties of biogas digester and make it the energy storage device of traditional microgrid. In this work, we show how the integrated control strategy can be used to optimise the generation dispatch of biogas and maximise generation company profits in days-spot-market. Meanwhile, we adopt the electricity price forecasting technique to simulate electricity prices and calculate the minimum total capital costs. The effectiveness of the proposed strategy is verified by the biogas project case in an ecological park of Hunan Province in China.

2 Theoretical analysis

2.1 Operating and control framework of biogas generation

The operating and control system of biogas generation based on price forecasting in spot market is as shown in Fig. 1, whose framework mainly consists of price forecasting unit, control unit, biogas power generation unit and trading unit.

Where, price forecasting unit is used to forecast electricity energy prices and purchase prices by the existing price forecasting techniques in the days-spot-market. According to the previous real-time energy prices and purchase prices tracking of biogas power plant, we can forecast the subsequent moment price on the basis of the monotonic trend of historical data.

Biogas power generation unit mainly includes anaerobic digester, biogas pumps, combined heat and power (CHP) units, gas storage and other equipments, which utilises the anaerobic digestion of biomass (typically animal wastes) to yield biogas (a mixture of methane, CO_2 and other gases). In remote rural areas or farms, biogas is the most economic option for cooking, lighting, and even for electric power generation using CHP or other generators. It can greatly improve energy efficiency and reduce energy consumption [11]. After receiving a command and controlling the valve of biogas pump, the biogas stored in the digester or storage tank can be delivered to CHP, and then CHP start to work. Simultaneously, the output of CHP can be controlled by analysing the data of methane intake and pressure collected via

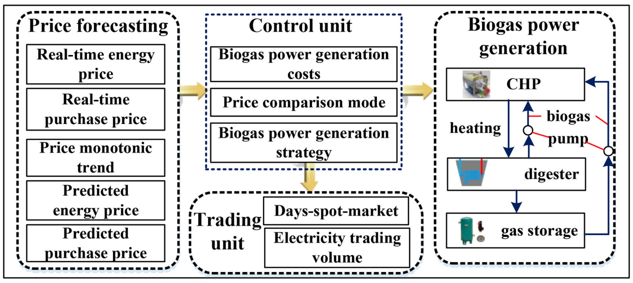

Fig. 1 *Operating and control framework of biogas generation*

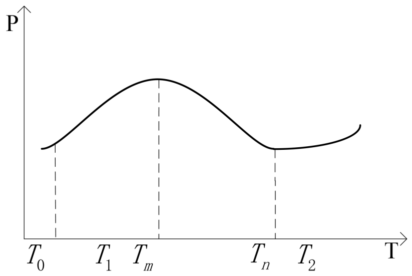

Fig. 2 *Relation between electric energy price and time*

the ultrasonic gas flow metre. According to the instantaneous flow rate and other data, smart sensors analyse whether gas leakage exists or not, to ensure the stability and efficiency of the system. When the control unit issues a command to stop generating electricity, the biogas is stored in the gas storage tank by closing the valve of the biogas pump, thus realising the rational allocation of resources.

The trading unit is used to adjust the trading volume of the electricity market in the day. That is, when the purchase price is the lowest, raising the trading volume of the electricity market in the day, and when the electricity purchase price is the highest, reducing the trading volume of the electricity market in the day.

The control unit is significant for the whole system, whose working mechanisms is to form the price comparison mode, to determine the operating strategy and to control the generation unit and the trading unit acting in the light of price forecasting result and costs of CHP. In this way, the optimal plan of power generation for electricity users can be presented.

2.2 Techniques of price forecasting

We assume that the real-time market is a balanced market one hour ago, take electricity price as an example. The relation between electricity price and the time is shown in Fig. 2. The electricity price at T_0 is the actual price tracked in real time, and the electricity price and purchase price after T_0 are predicted prices. The moment of T_m is any time from T_1 to T_2, and T_n is any time after T_m. Electricity prices tend to be monotonous from T_m to T_n, and then price monotonic trend changes after T_n.

The steps of price forecasting are listed below:

(i) Obtain the electricity energy price P_0^{eng} and purchase price P_0^{ele} at T_0;
(ii) According to the historical trends, forecast the electricity energy price P_1^{eng} and purchase price P_1^{ele} at T_0;
(iii) According to the trend of price, determine the extreme value of the purchase price P_m^{ele} between the time T_1 and T_2 and the corresponding moment T_m;
(iv) Determine the monotonic trend of the electrical energy price from T_m to T_n, and the monotonic trend changes after the moment T_n;
(v) According to the monotonic trend of the energy price, forecast the energy price P_n^{eng} at the moment T_n.

2.3 Objective function of generation costs

The biogas power system performs bidirectional power exchange with the low-voltage distribution network via the tie line, whose important aims is to minimise the operating costs of the CHP units and the exchange costs with the distribution network. In terms of the electricity prices at different times in the spot market, the total capital cost of the biogas power generation system can be expressed as the following model (1). In addition, the generation costs mainly include the biogas fuel costs, the capital recovery costs, operation and maintenance costs, the influence of pollution emissions to the environment cost, and the heating earning of CHP units [12]

$$\min P^{cost} = \sum_{t=1}^{n} \left(C_t^W + C_t^{DP} + C_t^{\text{OM}} + C_t^{\text{e}} + C_t^{EX} - C_t^{\text{QH}} \right) \tag{1}$$

$$C_t^{DP} = \frac{C_{\text{istall}}}{8760\ \text{k}} \times \frac{R(1+R)^Y}{(1+R)^Y - 1} \times W_t^{\text{eng}} \tag{2}$$

$$C_t^{\text{OM}} = K_{\text{OM}} \times W_t^{\text{eng}} \tag{3}$$

$$C_t^{\text{e}} = \sum_{j=1}^{l} \left(V_{\text{e}j} + V_j \right) \times Q_j \times W_t^{\text{eng}} \tag{4}$$

$$C_t^{EX} = P_m^{\text{ele}} \times W_t^{\text{ele}} - P_n^{\text{eng}} \times W_t^{\text{eng}} \tag{5}$$

$$C_t^{\text{QH}} = H_{\text{CHP}} \times P_t^{\text{QH}} \tag{6}$$

where P^{cost} is the microgrid generation cost. $C_t^W, C_t^{DP}, C_t^{\text{OM}}, C_t^{\text{e}}, C_t^{EX}, C_t^{\text{QH}}$ are the biogas fuel costs, the capital recovery costs, operation and maintenance costs, the influence of pollution emissions to the environment cost, and the heating earning of CHP, respectively. W_t^{eng} is the active power of CHP at time t; W_t^{ele} is the exchanged active power between microgrid and power grid at time t. C_{istall} represents the installed cost in per capacity; is the capacity factor of CHP, which is equal to the annual generating capacity of CHP/(8760*the rating output of the unit); is the fixed annual interest rate of per unit; represents amortisation period of CHP, which is usually equal to the lifetime of CHP; K_{OM} is the cost coefficient of CHP operation and maintenance per unit; $V_{\text{e}j}$ represents the environmental value of the j pollutant; V_j is the fine for the j pollutant; Q_j is emission amounts of the j pollutant; l represents the types of pollutant; H_{CHP} is the price of per heat e; P_t^{QH} is the heat quantity of CHP system.

2.4 Details of the constraints

The constraints in this study include the power balance constraints of system (7), the unit output constraints (8), the minimum continuous start and stop time constraints (9) and the consumption constraint of biogas daily yields (10)

$$W_t^{\text{eng}} + W_t^{\text{ele}} = W_t^{\text{Load}} \tag{7}$$

$$W_{t,\min}^{\text{eng}} \le W_t^{\text{eng}} \le W_{t,\max}^{\text{eng}} \tag{8}$$

$$s_t = \begin{cases} 1 & 1 \le \tau_{\max} \\ -1 & -\tau_{\min} < t \le -1 \end{cases} \tag{9}$$

$$F_{\min}^{\text{Bio}} \le F^{\text{Bio}} \le F_{\max}^{\text{Bio}} \tag{10}$$

where W_t^{Load} is the load at time t; $W_{t,\max}^{\text{eng}}$ and $W_{t,\min}^{\text{eng}}$ are the upper and lower bounds of output power, respectively; $\tau_{\max}$ and $\tau_{\min}$ are the minimum running time and outage time, respectively; F^{Bio} is the biogas yields, $F_{t,\max}^{\text{Bio}}$ and $F_{t,\min}^{\text{Bio}}$ are the maximum and minimum of biogas daily yields, respectively.

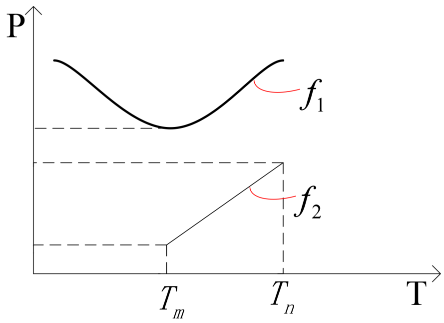

Fig. 3 *Mode 1 of price comparison*

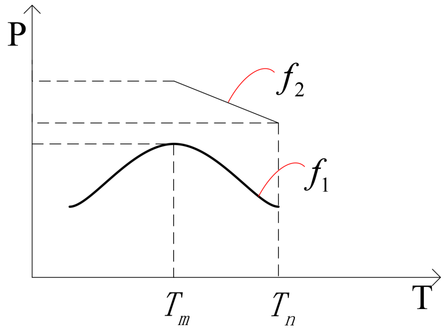

Fig. 4 *Mode 2 of price comparison*

2.5 Operating control strategy

According to the cost objective function of the biogas power generation system, the control strategy model of biogas power generation can be described as follows:

$$J_t^{\text{CHP}} = \left(P_n^{\text{eng}} - \min P^{cost}/W_t^{\text{e}}\right) - P_m^{\text{ele}}) \quad (11)$$

$$J_t^{\text{CHP}} > 0 \;\&\; P_m^{\text{ele}} = \min P_k^{\text{ele}}(k \in \{1, n\}) \quad (12)$$

$$J_t^{\text{CHP}} < 0 \;\&\; P_m^{\text{ele}} = \max P_k^{\text{ele}}(k \in \{1, n\}) \quad (13)$$

where J_t^{CHP} is the comparison result between electricity prices and purchase price at time t in spot market; P_n^{eng} is the electricity price of biogas generation at time T_n; P_m^{ele} is the purchase price from power grid at time T_m; W_t^e is the rated power of the biogas generator.

Mode 1: When the comparison result meets the formula (12), the system emits a command that requires CHP to stop generating electricity at time T_m, while rising electricity trading volume of day-spot-market after time T_m. The curve describing relation between electric energy price and purchase price is shown in Fig. 3, where f_1 depicts relation between purchase price and time, f_2 conveys relation between energy price of biogas generation and time.

Mode 2: When the comparison result meets the formula (13), the system emits a command that requires CHP to generate electricity at time T_m, while reducing electricity trading volume of day-spot-market after time T_m. The relation between electric energy price and purchase price is demonstrated in Fig. 4.

3 Case study

A case study of biogas generation project in Hunan Province is presented to demonstrate the superior performance of the proposed methodology. The parameters and data of biogas renewable microgrid system are taken from the actual project and [13, 14].

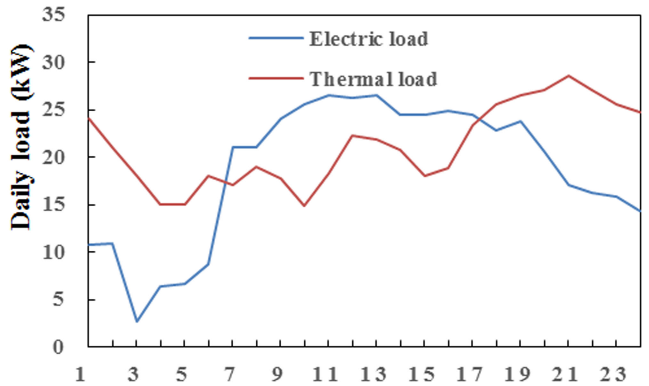

Fig. 5 *Typical daily load change of ecological park in winter*

Table 1 Daily biogas content of farms

Season	Daily waste capacity, kg/m^3	Biogas production rate, m^3·d^{-1}	Daily biogas content, m^3
summer	411.98	0.537	221
winter	411.98	0.322	133

Table 2 Magnitude of penalty for pollutant emission $/kg

SO_2	NO_x	CO_2	CO
0.125	0.250	0.00125	0.020

3.1 Load demand analysis

The power loads of the ecological park mainly include lighting, production and heating, and the electric stability load is about 23 kW. The typical daily load change of ecological park in winter is shown in Fig. 5.

3.2 Biogas resources analysis

Biogas resources are mainly from the farms in the park. The amount of annual storage cattle in the farm is about 200, and the effective capacity of the biogas digester is 320 m^3. Owing to the influence of temperature on the biogas production, the daily biogas content of farms in winter is generally about 60% in summer [13]. The potential daily biogas contents in winter and summer are calculated according to the amount of waste output and the biogas production rate of animal waste, as shown in Table 1.

3.3 Calculation results of generation cost

The ecological park has CHP units with 30 kW capacity, whose working efficiency is about 75%, so the average daily power output is 225 kWh by working ten hours per day. The pollutant emission data, the pollutant value standard and the penalty level are taken from [14].

The fuel cost is zero because the fuel used biogas power generation (primary energy source) in the ecological park is locally sourced and does not need to be purchased. According to the data in Table 2 and the related formula in this paper, R is 8%, Y is 30 years, k is 0.25 calculated by parameter in accordance with [10]. The calculation results of other power generation costs considering the environmental benefits are shown in Table 3.

3.4 Scheduling results analysis

Combined with the calculation results of generation costs, we predict the spot market price for one day in this ecological park via the price forecasting techniques [15]. The price prediction result is shown in Fig. 6.

On the basis of the mode matching results, we can get the optimal output curve of biogas power generation as shown in Fig. 7. It can be obviously seen that when the biogas generation time of the CHP unit is arranged from 8:00 am to 10:00 am and from 14:00 pm to 20:00 pm, the generation efficiency of the

Table 3 Calculation results of generation costs $/kWh

Type	C_t^W	C_t^{DP}	C_t^{OM}	C_t^e	C_t^{QH}
costs	0	0.1622	0.046	−0.168	−0.016

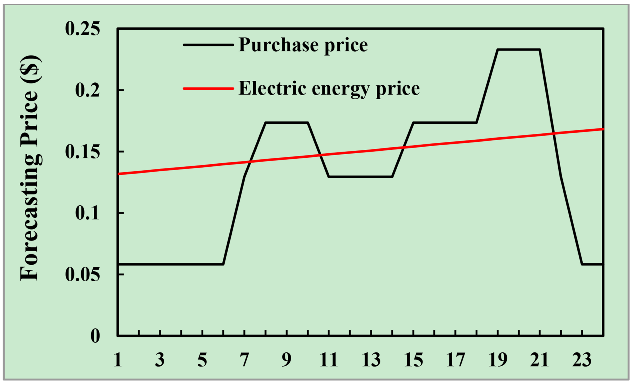

Fig. 6 *Result of price forecasting*

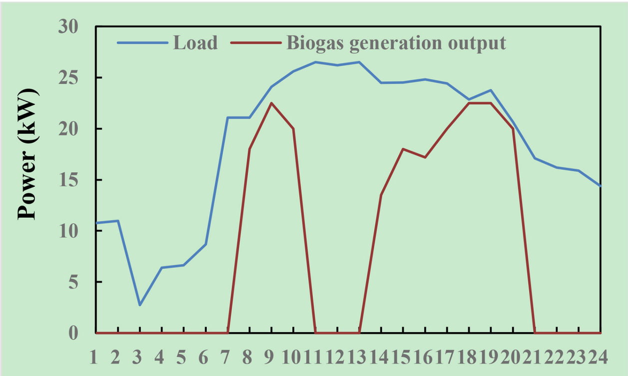

Fig. 7 *Optimal output of ecological park biogas generation*

ecological park is the highest, which can reasonably share the peak cost and guarantee the optimality of overall revenue.

4 Conclusion

An operating control strategy of biogas generation based on price forecasting techniques in spot electricity market is proposed for formulating the optimal power generation scheduling, which helps to guide the electric energy trading of biogas generating units in the intraday market, and to provide important theoretical basis for the consumption of new energy and the reasonable allocation of peak cost. The case study based on realistic data of biogas renewable microgrid demonstration project is carried out. The results show that the proposed methodology is effective.

5 Acknowledgments

The authors gratefully acknowledge the support of the Sino-US International Science and Technology Cooperation Project under grant no. 2016YFE0105300.

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