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Energy Management and Economic Operation Optimization of Microgrid under Uncertainty

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Abstract

Microgrid provides an effective means to promote renewable energy utilization via deploying multiple distributed generations (DGs) with energy storage systems (ESSs), loads, control devices and protect devices, which can operate in either islanded mode or grid-connected mode. In order to coordinate the output of different DGs and realize the potential of renewable energy, energy management and economic dispatch of microgrid is needed. Both distributed energy resources (DERs) and user loads in microgrid have uncertainty characteristics; so the randomness of the wind speed and solar radiation intensity are modeled by interval mathematics and the interval output of the wind turbine and photovoltaic (PV) generation system are obtained. Then, a microgrid economic optimization model based on interval optimization method is proposed. Next, combined with the time-of-use characteristic, issue of the power exchange with the external grid has been considered. Finally, Considering the effect of ESS, this chapter discusses the impacts of uncertainty of renewable energy power and load power on optimization results, as well as the effects of the degree of load uncertainty or load fluctuation on scheduling results. The results verify the robustness and effectiveness of the proposed method in dealing with uncertainty optimization problem of microgrid.

Keywords: economic operation optimization, energy management, microgrid, uncertainty, distributed generation

1. Introduction

With the increasing depletion of fossil fuels, the deterioration of global environment and the dependence of human society on energy, the utilization of renewable energy sources (RESs),

such as wind energy, solar energy, and so on, has been paid more and more attention. Distributed generation (DG) is raising high interests in distribution systems due to the deregulation and environmental concerns, the unique features such as the flexible utilization of dispersed RESs, and the flexible generating strategy. However, single DG cannot provide high-quality and sustainable power. The implementation of dispersed DGs, however, may bring additional challenges while providing various benefits [1]. To make full use of renewable energy, the concept of microgrid came into existence.

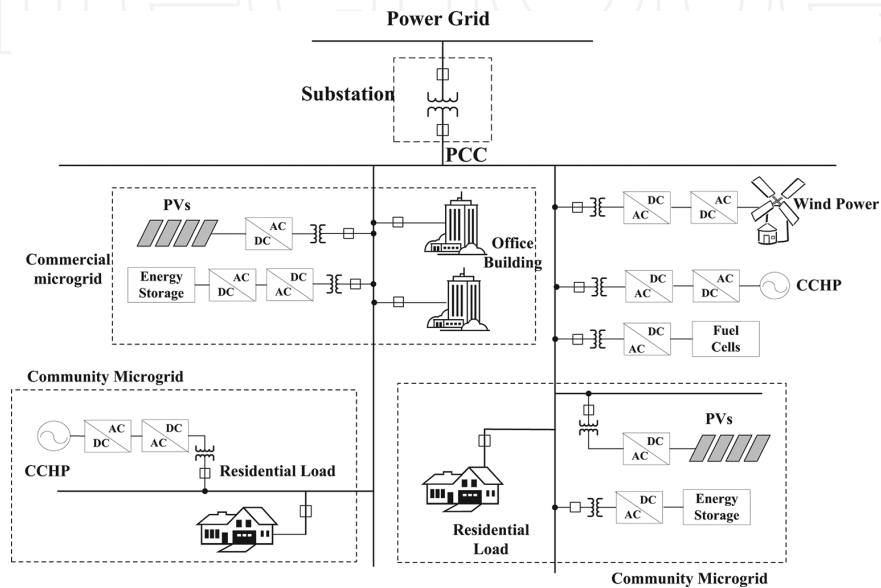


Figure 1. Typical structure of microgrid.

Microgrid is a section of distribution system that contains distributed energy resources (DERs) and can be isolated from the rest of the network when contingency occurs in upstream grid. The ability to operate in islanded mode could potentially enhance the local reliability. Furthermore, microgrid can adopt multiple DGs and the optimal deployment of different types of DGs may complement the intermittent nature of DERs so as to promote the renewable energy utilization [2]. Microgrid usually consists of DGs, ESSs, loads, control devices, and protect devices, etc. It is an autonomous, self-manage, and self-control system, which can operate in either islanded mode or grid-connected mode. In order to coordinate the output of different DGs and realize the potential of renewable energy, the economic dispatch of microgrid is needed [3]. **Figure 1** depicts a typical structure of microgrid.

From **Figure 1**, it can be seen that DGs in microgrid mainly contain wind power generation system [4], photovoltaic (PV) system, combined cooling heating and power (CCHP) and fuel cell (FC). The loads in microgrid consist of the power load and the cold and hot load of residential users and office buildings. The energy storage devices in microgrid consist of DC and AC energy storage, and battery storage is mainly applied [5]. Meanwhile, microgrid includes a number of energy conversion devices, which are mainly AC/DC conversion devices. In general, microgrid operates in grid-connected mode, connecting with the external distri-

bution system through a static switch as the point of common coupling (PCC). When the PCC disconnects, microgrid turns into islanded operation mode and the internal loads are totally supplied by DGs in microgrid. A large microgrid may consist of several smaller ones, which can also operate independently and supply the corresponding loads, respectively. For instance, some small commercial microgrids consist of PV and AC energy storage devices are located around the modern high buildings. Moreover, many small community microgrids consist of gas turbine, and PV and DC energy storage devices are located around residential loads.

Besides the satisfying of electricity demand, microgrid can also meet the cold and hot load demand. The generation units within microgrid can be installed near users, thus the costs of transmission and distribution are reduced, and the utilization efficiency of energy is improved. DGs are easy to identify installing locations, and the installation periods are usually short. In addition, microgrid has advantages of clean energy utilization, low noise, and so on. Therefore, it is significant to do research on the economic operation of microgrid.

As energy conservation and loss reduction are realized through energy dispatch of generators in a conventional power system, the economic and efficient operation of microgrid is realized through energy management and economic operation of microgrid. Compared with a conventional power system, controlled variables in microgrid are much more abundant such as the active power of DGs, the voltage of voltage-type inverter, the current of current-type inverter, the active power of energy storage devices, the reactive power compensation of adjustable capacitors, and the proportion of thermal loads and electricity loads in CCHPs. Considering the normal operation constraints of power system, certain benefits can be realized by adjusting controlled variables such as the properly dispatch of energy and the maximum utilization of renewable energy in microgrid so as to guarantee the economic operation of microgrid. Meanwhile, when microgrid operates especially with high penetration, the energy loss of transformers and feeders in distribution system can be reduced through the effective control of microgrid output.

This chapter mainly studies the characteristics of various DGs, establishes mathematical models, analyzes different operational control strategies, and proposes an economic operation optimization method considering uncertainties of DGs in microgrid [6–7]. The DERs and user loads in microgrid both have the uncertainty characteristics, so it is worth to conduct an in-depth study on how to consider the effect brought by these uncertainty factors in economic optimization of microgrid [8–9]. In order to characterize these uncertainties in microgrid, the randomness of the wind speed and solar radiation intensity are described by interval and then the output prediction interval value of the wind turbine and PVs are obtained. Combined with interval description of load uncertainty, a microgrid economic optimization model based on interval optimization method is proposed [10]. Then combined with the time-of-use characteristic, issue of the power exchange with the external grid has been considered. Finally, take the effects analysis of storage on the economic operation of the system as an example, this chapter has discussed the impacts of uncertainty of renewable energy power and load power on optimization results, as well as the effects of the degree of load uncertainty or load fluctuation on scheduling results. The results verify the robustness of the proposed method and model, and show the effectiveness in dealing with uncertainty optimization problem.

2. Modeling of DGs in microgrid under uncertainty

2.1. Uncertainty model for PV output

PV arrays can convert solar radiation into DC power and then access into AC power via PV inverters. For a PV array, its maximum DC power output can be calculated via Eq. (1). In Eq. (1), the area of the PV array A_{PV} is fixed for a specific PV power generation system. In addition, PV inverters are usually operated in the maximum power point tracking (MPPT) mode with relatively constant power conversion efficiency η . On the other hand, the operation temperature of solar panels T_c and the solar radiation on panels G_T are varied. Several factors, such as the ambient air temperature, the atmospheric pressure, and the wind speed, may impact the operation temperature of solar panels. The operation temperature of solar panels can be calculated via the ambient temperature in Eq. (2). Substituting Eq. (2) into Eq. (1), the output power of a PV array can be calculated in Eq. (3). Eq. (3) shows that the power output of a PV cell is mainly determined by the solar radiation and the ambient temperature. The ambient temperatures may not change dramatically in a very short time period. Thus, the cloud cover is considered as the dominant uncertainty factor that affects the PV output;

$$P = \eta A_{PV} G_T [1 - 0.005(T_c - 25)] \quad (1)$$

$$T_c = T_a + CG_T \quad (2)$$

$$P = \eta A_{PV} G_T [1 - 0.005(T_a + CG_T - 25)] \quad (3)$$

An interval cloud model is introduced to describe uncertainties of the cloud cover. The solar radiation effect on the panels can be calculated by the solar radiation outside the atmosphere and the corresponding cloud cover index as shown in Eq. (4) and **Table 1**:

$$[G_T] = [I] \cdot G_a \quad (4)$$

Weather	Cloud cover index
Rainy, snowy	[0.1, 0.2]
Overcast	[0.2, 0.3]
Overcast to cloudy	[0.3, 0.5]
Cloudy	[0.5, 0.7]
Cloudy to clear	[0.7, 0.9]
Clear	[0.9, 1.0]

Table 1. Cloud cover index.

Given the interval cloud cover model in Eq. (4), the interval PV output model can be formulated via the following two steps:

- a. Predict the next-day solar radiation outside the atmosphere at the PV location. Based on the weather forecast and the solar radiation forecast, the solar radiation interval is calculated as $[\underline{G}_T, \bar{G}_T]$ via Eq. (4).
- b. Obtain the interval of the PV output $[P(\underline{G}_T), P(\bar{G}_T)]$ using the PV power output function via Eq. (3).

2.2. Uncertainty model for WTG output

Wind turbine generators (WTGs) can convert kinetic energy from wind into electricity. The mechanical power generated by the wind turbine P_m can be calculated via Eq. (5);

$$P_m = 0.5\rho AV^3C_p \quad (5)$$

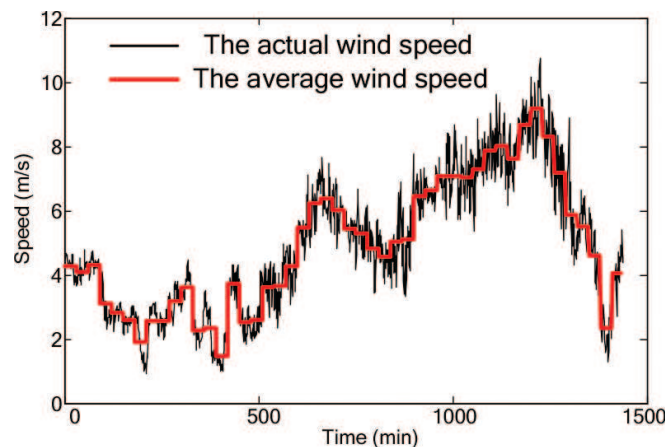


Figure 2. Wind speed variety during one day.

where ρ is the air density, A is the air cross-section, V is the wind speed, and C_p is a function of the speed ratio and the blade pitch angle.

The real power injected into electric power systems by a WTG is mostly affected by wind speed. Figure 2 shows a one-day wind speed profile of a wind farm located in Qindao, China. It illustrates that wind speed varies drastically in a single day as shown in the black line. Because accurate forecast on instantaneous wind speed is difficult, average wind speeds for each 30 minutes are usually used to approximate wind power outputs as shown in the red curve.

As the wind power is proportional to the cubic of wind speed, the wind speed forecast error would lead to considerable errors. To accurately quantify uncertainties of wind speed, an interval WTG output model is formulated as follows:

- a. Predict the wind speed interval $[V_T]=[\underline{V}_T, \bar{V}_T]$ for the next day.

- b. The wind power output interval is calculated as $[P(\underline{V}_T), P(\bar{V}_T)]$ via Eq. (5).

3. Energy management and economic operation strategy of microgrid

Microgrid has the merits of environmental friendliness and economical efficiency. Its environmental friendliness is guaranteed by the utilization of DERs. Its economical efficiency will be guaranteed by energy management and economic operation of microgrid. Economic operation optimization of microgrid is a nonlinear combination optimization problem with multiple variables and multiple constraints, which determines the optimal dispatch scheme of microgrid to achieve the best economic benefit according to the operating costs, parameters, and types of DGs and other components under the precondition of satisfying the load demand of users and operation constraints.

The operational economy of the microgrid is directly related to the interests of the users and the main power grid, and the proper economic operation control strategy is particularly important. The operation control strategy of microgrid has its own features compared with conventional power grid. In a conventional grid, the key to economic operation control is the optimal dispatching of combined fire and hydraulic power plants. And environmental factors are seldom considered. However, a microgrid may comprise many types of DGs, such as the wind turbine and PV, the output power of which varies with the changing of environment. Hence, economic operation of microgrid must consider environmental impact.

The operation mode of microgrid is divided into grid-connected mode and isolated island mode, and the operational control strategies faced by different operation modes should also be different. In grid-connected operation, there is a power exchange between microgrid and distributed power network. External power grid provides a backup to supplement the shortage of electricity or absorb the excess electricity generated by microgrid. Not all loads in microgrid will be supplied power by internal DGs, but only critical loads will be served by microgrid during isolated island operation mode. Faced with the shortage of supply or excess supply, there are significant differences in control strategies between the two operation modes of microgrid.

The control strategy of economic operation of microgrid is to ensure the safe and stable operation of the system under either operation mode of microgrid. When disconnected from the external power grid, the microgrid is capable of local voltage and frequency control and generates or consumes the temporary power to balance the generating power and the load power.

3.1. Grid-connected operation characteristics of microgrid

Microgrid exchanges the power with the external power grid through a static switch as PCC in grid-connected operation mode under normal circumstances. External power grid provides electrical auxiliary support when generating capacity of internal generating unit of microgrid cannot meet the demand of internal loads. On the contrary, external power grid need to absorb

some of the excess power when generating capacity of generating unit is much more than load demand. Under grid-connected operation mode, microgrid system can fully utilize the law of electric power market to control the operation of DGs by the power exchange with the external power grid, which can achieve the best economic performance.

In the grid-connected operation mode, the frequency adjustment of microgrid is done by the interaction with external power grid. High penetration of DGs may cause voltage and reactive power offset or shock. Therefore, effective local voltage control is needed no matter in grid-connected mode or isolated island mode. The regulation of voltage level of microgrid is required to ensure the reliability and stability of local power supply. The voltage-reactive droop controller is an effective method to control the local voltage in microgrid.

3.2. Isolated island operation characteristics of microgrid

The isolated island operation mode of microgrid can be divided into intentional and unintentional islanding mode according to planning in advance or not. The so-called intentional islanding scheme will ensure the stable operation after the formation of an island before microgrid is disconnected with external power grid by proper island division according to distributed power supply capacity, load demand, and system operational state. While unintentional island refers to the case that when a serious fault occurs in the external power grid, the power quality will no longer meet the criterion and the protection device will act, which resulting in the isolation with external power grid unintentionally, the microgrid operates unstably with loads.

The transition from grid-connected operation to isolated island operation state is the primary consideration in the operation of microgrid in the island mode. In this process, the energy conversion and control system of microgrid adopts a more flexible method for frequency regulation because microgrid basically has few rotating generating units and with smaller inertia than conventional power system. Therefore once disconnected with an external power connection, microgrid should consider load shedding according to the priority of loads and to ensure the stable operation of the system when the load demand exceeds a distributed power supply capacity.

3.3. Economic operation strategy of microgrid

At present, there are two basic control strategies in microgrid: Master-Slave operation and peer-to-peer control. Master-slave operation is mainly used in microgrid islanded operation mode, it defines a reference DG to unify the coordinated control of other DGs and maintain the balance of power within the system. Peer-to-peer control adopts the same control scheme for all the DGs and with the aid of the curves of P/f or Q/U and realize automatic adjustment of voltage and frequency based on control strategy of dropping of external characteristic. Various other control strategies can be considered as the improvement and integration of the two control strategies.

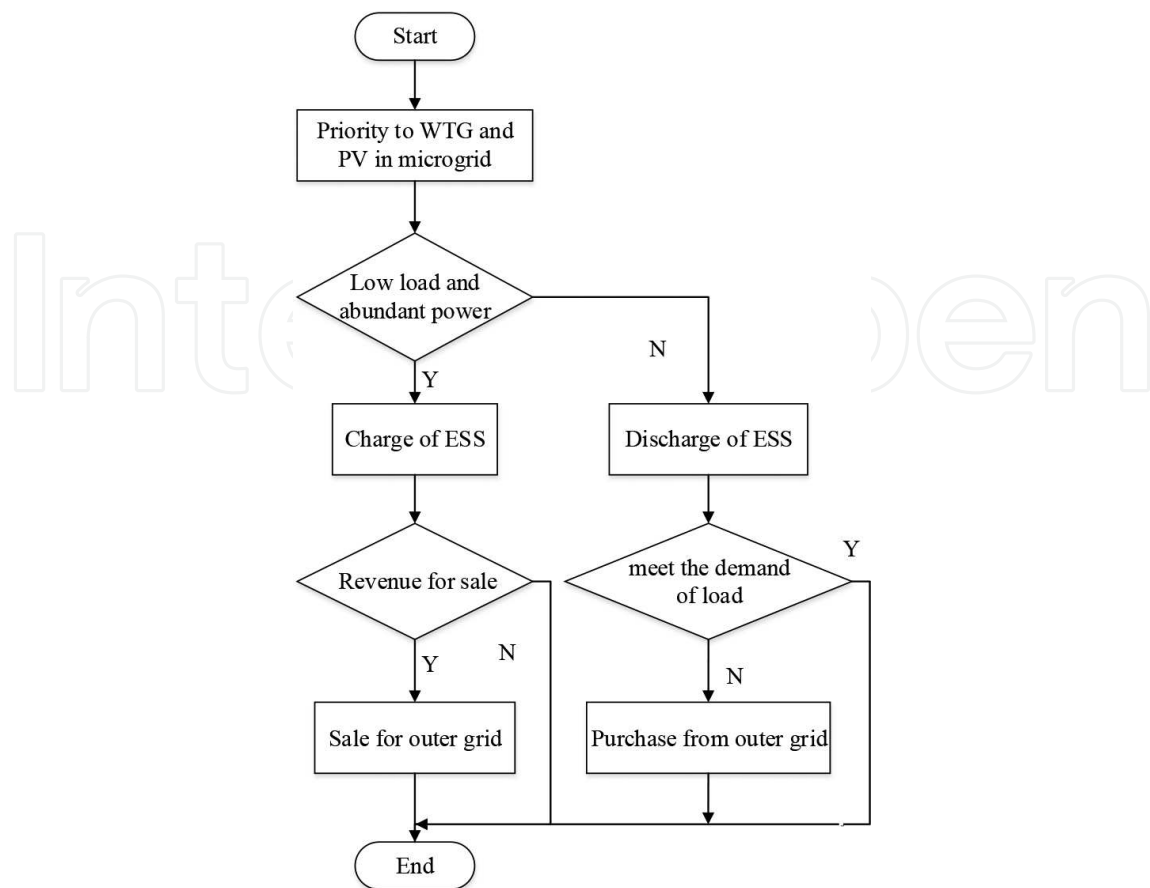


Figure 3. Flowchart of control strategy in grid-connected mode.

In terms of different operation mode, the operation control strategy is also different. In grid-connected mode, the economic operation of microgrid mainly concerns with the benefit of the power exchange with the external power grid. The scale of power exchange mainly follows the following principles: (1) given priority to DG power generations when generation costs of DGs of microgrid are generally lower than the external electricity price; (2) given priority to external power purchase when generation costs of DGs of microgrid are higher than the external electricity price; and (3) if DG power is not enough to take the whole load of microgrid, the energy storage device can be used for power supply first, the shortage will be supplemented from the external power purchase electricity. Taking into account different periods with different electricity price, the energy storage device in microgrid should give priority to charging, and then compare the cost of DG power generation and the revenue from electricity sales to determine whether sell electricity to grid.

The control strategy for each DG in microgrid in grid-connected mode is as follows, which is shown in **Figure 3**.

- Give priority to wind turbine and PV power generation as they are renewable and clean energy in microgrid.

- Considering the effect of real-time electricity price, when the load is low and the power of the wind turbine and PV cells is abundant, the energy storage system (ESSs) will be charged. Only when the electricity price of power grid is higher than the price of the energy storage electricity price, the sale of electricity is considered.
- In the peak period of load, if the wind turbine, PV cells, fuel cell output is insufficient, give priority to the battery discharge, the battery does not meet the discharge limit to meet the load demand, consider the sale of electricity.
- When the battery discharge cannot meet the demand of the peak load, electricity should be purchased from the external power grid.

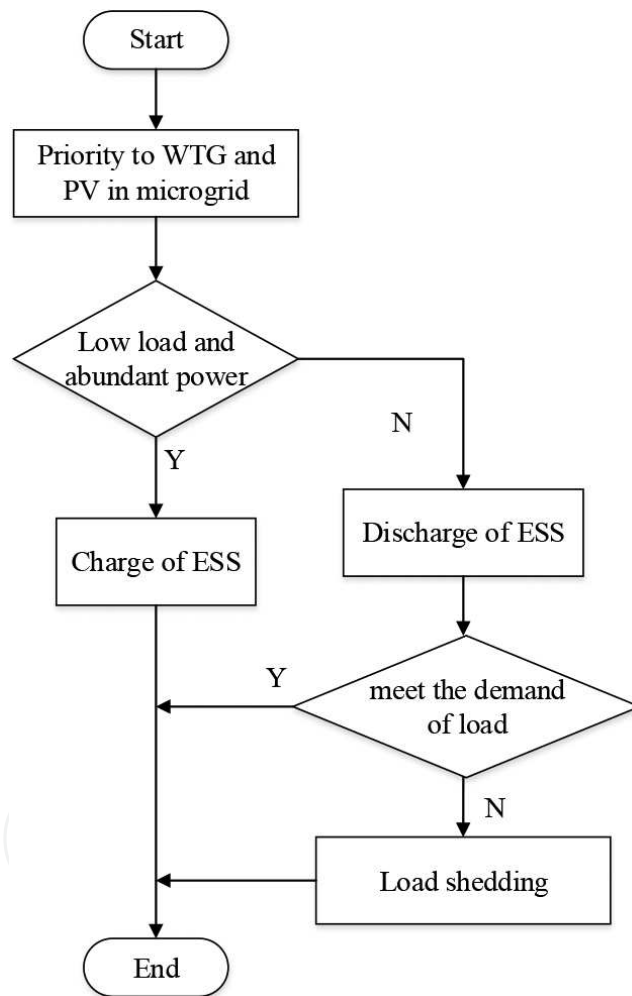


Figure 4. Flowchart of control strategy in island operation mode.

Microgrid in the island operation mode, there is no problem of power exchanging because there is no contact with the external power grid. The control strategy of DGs in microgrid in isolated island mode is as follows, which is shown is **Figure 4**.

- Give priority to wind turbine and PV power generation.

- In the period of valley load, wind turbine and PV output power are abundant, the priority of energy storage system is to charge, while in the peak load period, if lack of wind turbine, PV cells, fuel cell output, priority is given to the discharge of the energy storage system.
- When the discharge of energy storage system cannot meet the demand of peak load, the load shedding should be taken into consideration.

4. Energy management and economic operation optimization of grid-connected microgrid with DGs considering uncertainty

The uncertainty issue of the wind turbine, PV can be modeled by the interval mathematical theory. At the same time, the interval mathematical theory can also satisfy the equation constrains for the forecast value of load and renewable energy. Thus, the interval mathematical theory can achieve better optimization operation of microgrid. This section introduces the proposed interval linear programming model for optimal operation of microgrid considering time of use electricity price. The proposed interval linear programming model can also consider the influence of weather uncertainty on the output of wind turbine and PV system.

Interval linear programming (ILP) is an effective tool for solving the uncertainty problem. ILP is a linear programming method that combines the interval mathematical method and linear programming, and can also solve these problems which object function and constraints have interval number.

The common type of interval linear programming is as follows:

$$\begin{aligned} \text{Min } f^\pm &= C^\pm X^\pm \\ \text{St } A^\pm X^\pm &\leq B^\pm \\ X^\pm &\geq 0 \end{aligned} \quad (6)$$

where $\begin{cases} A^\pm = \{a_{ij}^\pm = [a_{ij}^-, a_{ij}^+] \mid \forall i, j\}, A^\pm \in \{R^\pm\}^{m \times n} \\ B^\pm = \{b_i^\pm = [b_i^-, b_i^+] \mid \forall i\}, B^\pm \in \{R^\pm\}^{m \times 1} \\ C^\pm = \{c_i^\pm = [c_i^-, c_i^+] \mid \forall i\}, C^\pm \in \{R^\pm\}^{1 \times n} \end{cases}$, $X^\pm \in \{R^\pm\}^{n \times 1}$, R^\pm represent a series of interval numbers.

Property I: the function $f^\pm = C^\pm X^\pm$ has best object $f^\pm = C^+ X^\pm$ and worst object $f^\pm = C^- X^\pm$, and there is always $C^- X^\pm \leq f^\pm \leq C^+ X^\pm \quad \forall f^\pm = C^\pm X^\pm (C \in [C^-, C^+])$.

Property II: for the following interval in-equation: $\sum_{j=1}^n a_j^\pm x_j \leq b^\pm$, assume $P_i = P\left(\sum_{j=1}^n a_j^\pm x_j \leq b^\pm\right)$

$$\begin{aligned} \Omega_L &= \left\{ (x_1, x_2, \dots, x_n) \mid \sum_{j=1}^n a_j^+ x_j \leq b^-, \Omega_L' = \left\{ (x_1, x_2, \dots, x_n) \mid \sum_{j=1}^n a_j^+ x_j \leq b^- \right\} \right\} \\ \Omega_U &= \left\{ (x_1, x_2, \dots, x_n) \mid \sum_{j=1}^n a_j^- x_j \leq b^+, \Omega_U' = \left\{ (x_1, x_2, \dots, x_n) \mid \sum_{j=1}^n a_j^- x_j \leq b^+ \right\} \right\} \\ L_t &= \text{len} \left(\sum_{j=1}^n a_j^\pm x_j \right) + \text{len}(b^\pm) - \max \left(0, \sum_{j=1}^n a_j^+ x_j - b^- \right) \end{aligned} \quad (7)$$

The following result can be obtained:

1. if $P_t = 1$, then (x_1, x_2, \dots, x_n) is a solution of the interval in-equation. (x_1, x_2, \dots, x_n) satisfies $(x_1, x_2, \dots, x_n) \in \Omega_L$, in other format $a_j \in [a_j^-, a_j^+]$, $b_j \in [b_j^-, b_j^+]$, (x_1, x_2, \dots, x_n) always be a solution of the interval in-equation.
2. If $0 < P_t < 1$ or $L_t = 0$, (x_1, x_2, \dots, x_n) is a weak solution of the interval in-equation. At this time $(x_1, x_2, \dots, x_n) \in \Omega_S$, $\Omega_S = (\Omega_U \cap \Omega_L')$, there has $a_j^* \in [a_j^-, a_j^+]$, $b_j^* \in [b_j^-, b_j^+]$, (x_1, x_2, \dots, x_n) is a solution of the interval in-equation. However, for the following condition

$$a_j > a_j^* \text{ or } b < b^* \left(a_j \in [a_j^-, a_j^+], b_j \in [b_j^-, b_j^+] \right) \quad (8)$$

The interval in-equation has no result.

3. If $L_t < 0$, then (x_1, x_2, \dots, x_n) is not a solution of the interval in-equation, at this time

$$(x_1, x_2, \dots, x_n) \in \Omega_U' \quad (9)$$

By analyzing the close relationship of the above parameters, control variable, object function and constrains, the proposed problem can be solved by two steps:

1. Obtain the result of the model f^-

$$\begin{aligned} \text{Min} \quad f^- &= \sum_{j=1}^{k_1} c_j^- x_j^- + \sum_{j=k_1+1}^n c_j^- x_j^+ \\ \text{S.t.} \quad & \sum_{j=1}^{k_1} |a_{ij}|^+ \text{Sign}(a_{ij}^+) x_j^- + \sum_{j=k_1+1}^n |a_{ij}|^- \text{Sign}(a_{ij}^-) x_j^+ \leq b_{ij}^\pm \\ & x_j^\pm \geq 0 \quad \forall i, j \end{aligned} \quad (10)$$

where $x_j^\pm, j=1, 2, \dots, k_1$ are the positive interval variables of the object function. $x_j^\pm, j=k_1+1, k_1+2, \dots, n$ are the negative interval variables of the object function. Solving the above Eq. (8), the results can be obtained:

$$x_{j_{opt}}^-(j=1, 2, \dots, k_1), x_{j_{opt}}^+(j=k_1+1, k_1+2, \dots, n). \quad (11)$$

2. Obtain the result of the model f^+

$$\begin{aligned} \text{Min} \quad f^+ &= \sum_{j=1}^{k_1} c_j^+ x_j^+ + \sum_{j=k_1+1}^n c_j^+ x_j^- \\ \text{S.t.} \quad & \sum_{j=1}^{k_1} |a_{ij}|^- \text{Sign}(a_{ij}^-) x_j^+ + \sum_{j=k_1+1}^n |a_{ij}|^+ \text{Sign}(a_{ij}^+) x_j^- \leq b_{ij}^\pm \\ & x_j^\pm \geq 0 \quad \forall i, j \\ & x_j^+ \geq x_{j_{opt}}^-, \quad j=1, 2, \dots, k_1 \\ & x_j^- \leq x_{j_{opt}}^+, \quad j=k_1+1, k_1+2, \dots, n \end{aligned} \quad (12)$$

In a similar way, by solving Eq. (9) we can obtain the following result: $x_{j_{opt}}^+(j=1, 2, \dots, k)$, $x_{j_{opt}}^-(j=k_1+1, k_1+2, \dots, n)$. Then, the final object value can be obtained:

$$f_{opt}^\pm = [f_{opt}^-, f_{opt}^+] \quad (13)$$

and

$$x_{j_{opt}}^\pm = [x_{j_{opt}}^-, x_{j_{opt}}^+].$$

Considering the variety of the uncertainty problem, using interval linear programming algorithm can build a model which includes battery, wind turbine, PV, and microgrids and build the optimal operation model of the microgrid. This model uses the operation cost as the object function, and can optimize the operation of a microgrid in a day.

4.1. Object function

If the object is to minimize the operation cost of a day, then it can be represented by the following equations:

$$\sum_{t=1}^T C_t = \sum_{t=1}^T (C_{wd,t} + C_{pv,t} + C_{fl,t} + C_{ex,t} + C_{bt,t}) \quad (14)$$

$$C_{wd,t} = c_{wd,t} \cdot P_{wd,t} \quad (15)$$

$$C_{pv,t} = c_{pv,t} \cdot P_{pv,t} \quad (16)$$

$$C_{fl,t} = c_{fl,t} \cdot P_{fl,t} \quad (17)$$

$$C_{sb,t} = c_{bid,t} \cdot P_{bid,t} - c_{bdc,t} \cdot P_{bdc,t} \quad (18)$$

$$C_{ex,t} = c_{buy,t} \cdot P_{buy,t} - c_{sell,t} \cdot P_{sell,t} \quad (19)$$

where T is the operation time, C_t is the total operation cost of the system at time t . C_t includes the operation cost of fuel cell, wind turbine, battery, and energy exchange cost of power system. The above items are represented by the following symbols, respectively: $C_{fl,t}$, $C_{wd,t}$, $C_{pv,t}$, $C_{sb,t}$ and $C_{ex,t}$. $P_{buy,t}$ and $c_{buy,t}$ represent the purchase power and energy purchase cost. $P_{sell,t}$ and $c_{sell,t}$ represent the sell power and energy sell income. $P_{wd,t}$, $P_{pv,t}$, $P_{fl,t}$ represent the output power of wind turbine, PV, and fuel cell at time t . $c_{wd,t}$, $c_{pv,t}$, $c_{fl,t}$ represent the operation maintenance cost of wind turbine, PV, and fuel sell. $c_{bid,t}$, $c_{bdc,t}$ represent the charging and discharging cost of battery. $P_{bid,t}$, $P_{bdc,t}$ represent the charging and discharging power of battery at time t .

4.2. Constraints

1. The constraint of microgrid power equation:

$$\sum_{t=1}^m (P_{wd,t} + P_{pv,t} + P_{fl,t} + P_{bid,t} + P_{buy,t} = P_{L,t} + P_{bdc,t} + P_{sell,t}) \quad (20)$$

where $P_{L,t}$ represents the forecast power load of microgrid at time t and the network loss is neglected.

2. The constraint of controllable micropower supply system:

$$P_{i,min} \leq P_i \leq P_{i,max} \quad (21)$$

where $P_{i,min}$, $P_{i,max}$ represent the minimum and maximum power output of micropower supply system i , respectively.

3. The constraint of maximum exchange energy between microgrid and the connected distribution system:

$$P_{e.min} \leq P_{ex.t} \leq P_{e.max} \quad (22)$$

where $P_{ex.t}$ is the difference between purchase electrical energy and sold electrical energy; $P_{e.min}, P_{e.max}$ are the nether and upper value of exchange power between power system and microgrid.

4. The constraints of fuel cell ramp rate:

$$\Delta t \cdot \Delta \underline{P}_f \leq P_{f,t+1} - P_{f,t} \leq \Delta t \cdot \Delta \bar{P}_f \quad (23)$$

where $\Delta \bar{P}_f, \Delta \underline{P}_f$ are the upper and lower ramp rates of fuel cell. Δt is the time interval of unit time.

5. The operation constraint of battery:

The capacity of battery should satisfy the following constraints:

$$S_{min} \leq SOC_t \leq S_{max} \quad (24)$$

When SOC reaches the maximum value ($S_{max} = 100\%$), the controller of the battery control the battery stop charging, when SOC reaches the minimum value, the controller control the battery stop discharging. And, the S_{min} is set to be 30% usually.

When consider the operation characteristic of battery, the energy capacity state should be same at the beginning and end of the dispatch process:

$$E_{bat}(0) = E_{bat}(T) \quad (25)$$

$$\begin{cases} 0 \leq P_{b.ch.t} \leq P_{b.ch.max} X_t \\ 0 \leq P_{b.disch.t} \leq P_{b.disch.max} Y_t \\ X_t \in \{0,1\}, Y_t \in \{0,1\} \end{cases} \quad (26)$$

where $P_{b.ch.max}, P_{b.disch.max}$ are the maximum charging and discharging power of battery, respectively.

The battery can only work at charging state or discharging state, therefore, the battery should meet the following constraint:

$$\begin{cases} X_t + Y_t \leq 1 \\ X_t \in \{0,1\}, Y_t \in \{0,1\} \end{cases} \quad (27)$$

4.3. Numerical analysis

The microgrid test system used is shown in **Figure 5**. The microgrid is connected to external distribution grid through a static switch at the point of common coupling (PCC). Wind turbine (WT), PV (PV), battery (BT), and fuel cell (FC) are included in the system. MV, LV means medium voltage, low voltage distribution grid and LD means routine load. The rated capacities of BT and FC are 300 and 100 kWh, respectively. The initial energy (the capacity at the time $t = 0$) in BTs is set 100 kWh. The maximum power rise rate and the maximum power drop rate of FC are 15 and 10 kW/h.

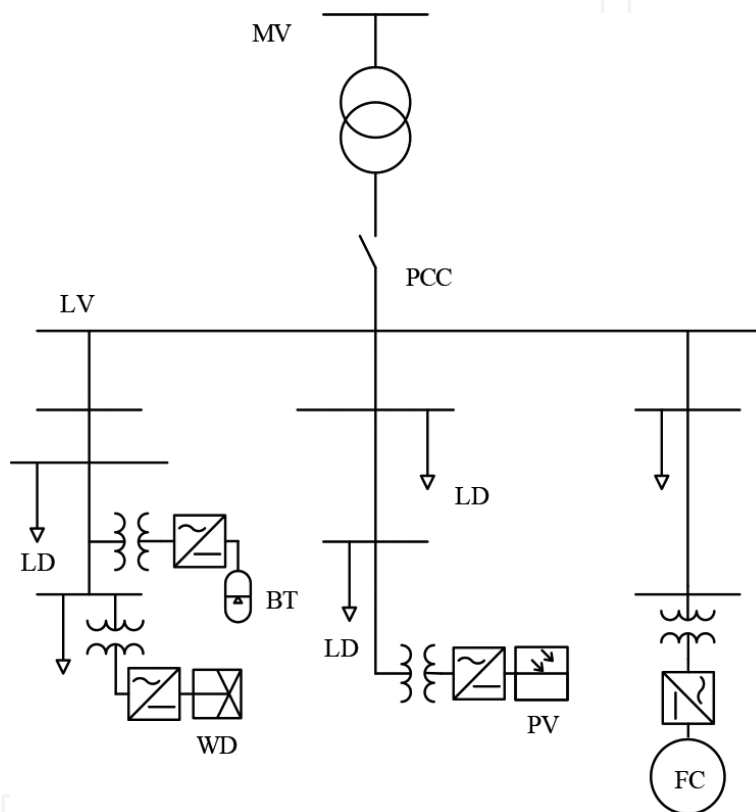


Figure 5. Architecture of a microgrid test system.

The price parameters of WT, PV, BT, and FC are shown in **Table 2**.

DG	WT	PV	FC	BT	
				Charging	Discharging
Price (yuan/kWh)	0.52	0.75	0.6	0.4	0.6

Table 2. Price parameters.

The objective of the model is to optimize the economic cost of one-day operation of the system. Using the interval models of DG output under uncertainty and the prediction intervals of wind

speed and illumination intensity, the prediction intervals of WT and PV power is obtained through Eqs. (1)–(4). The prediction curves are shown in **Figures 6** and **7**. The cloud cover index $[I]$ follows the following principle: $[I] = [0.8, 1.0]$ for cloudless days, $[I] = [0.5, 0.8]$ for cloudy days, $[I] = [0.1, 0.3]$ for rainy and snowy days. The load prediction curve of the system is shown in **Figure 8**. The load curve has peak, valley, and flat at different time periods. The power electricity is bought and sold using time-of-use prices. The power price curve is shown in **Figure 9**.

1. The impact of BT on the system

In this case, the DG power outputs are intervals predicted as before and the load fluctuates in interval [95%, 105%]. The system operation costs without and with BT are compared below.

The power output intervals of FC without and with BT are shown in **Figures 10** and **11**. The bought and sold power intervals of FC without and with BT are shown in **Figures 12** and **13**. The one-day system operation costs are: [2431.51, 2917.86] *yuan* without BT, and [2357.24, 2855.32] *yuan* with BT. It can be seen that there exists overlap between the two cost intervals, which reflects the impact of DG uncertainty on the economic system operation. Due to the uncertainty of DG and load prediction, the comparison of system operation costs without and with BT is uncertain. However, for this system the system operation cost without BT is larger than that with BT from the aspect of interval number comparison. So it is concluded that based on the BT parameters used in this system, the participation of BT in the microgrid can decrease the system operation cost and partly improve the system economy. With different BT parameters, the conclusion may be different and even opposite, but the uncertainty analysis method still holds.

2. The impact on system operation caused by load fluctuation

Taking into consideration work and rest regime of various industries, people's life law, and weather change, load varies by 30% of the peak load between one day and night. Therefore, based on forecasting load, different levels of load fluctuation (namely, 10, 20, and 30% of load peak) are used to analyze the impact on system operation.

The impact on economic operation of microgrid caused by the uncertainty of load prediction is shown in **Table 3**. It can be seen from **Table 3** that system operation cost is relatively stable when load fluctuation is small. With the strengthening of load fluctuation, system operation cost interval widths are also on the increase. So, the size of load fluctuation has a direct impact on the uncertainty of the system operation cost interval.

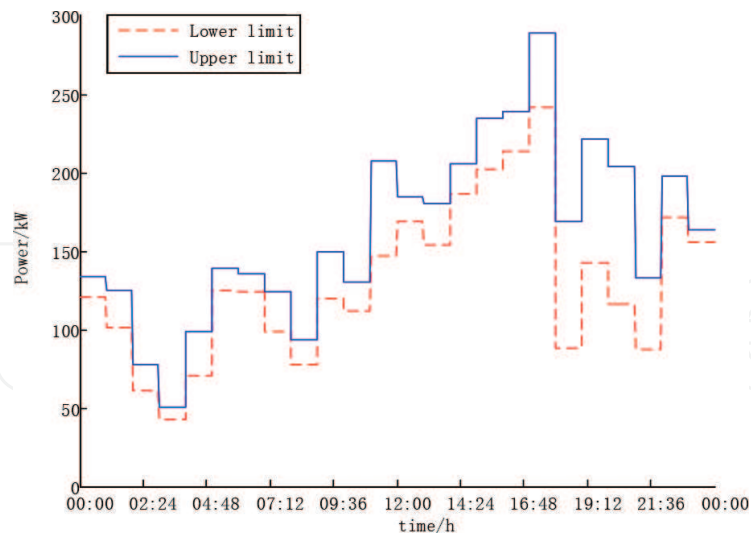


Figure 6. Prediction intervals of wind power.

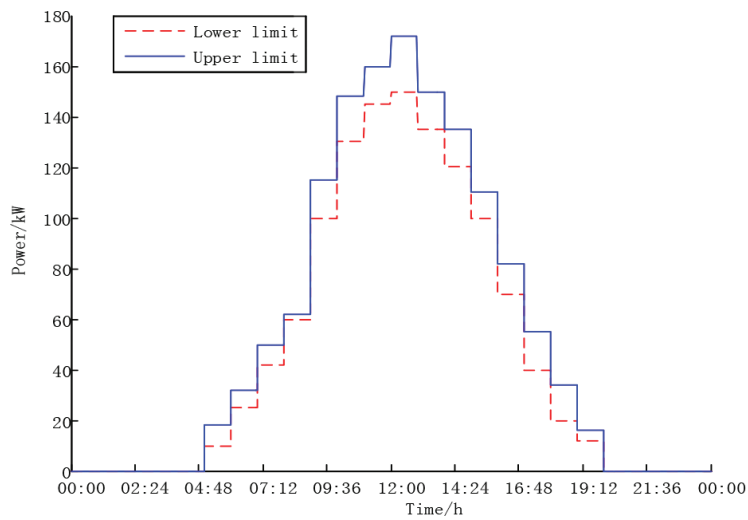


Figure 7. Prediction intervals of PV battery power.

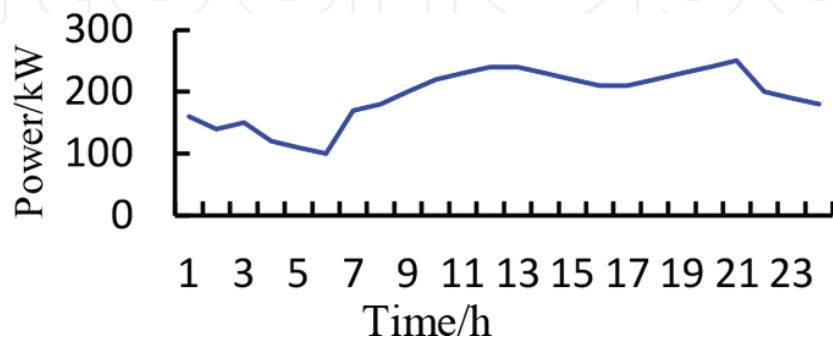


Figure 8. The load prediction curve of the system.

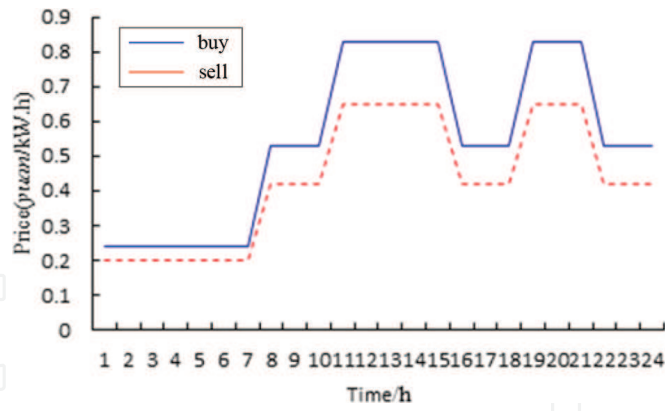


Figure 9. Power price curve.

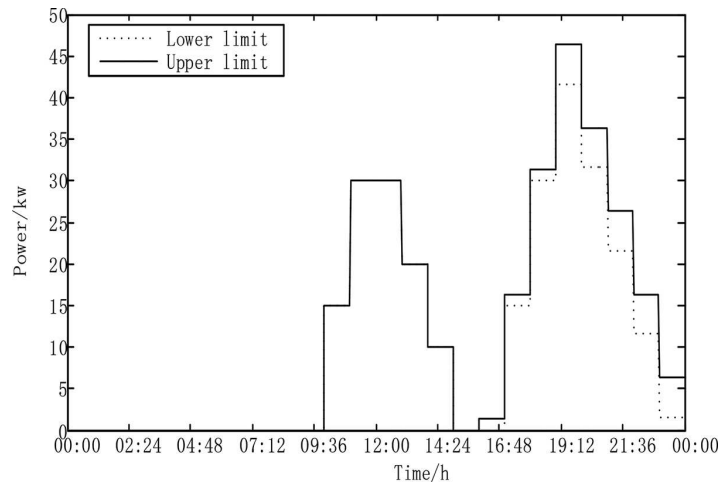


Figure 10. Power output intervals of FC without BT.

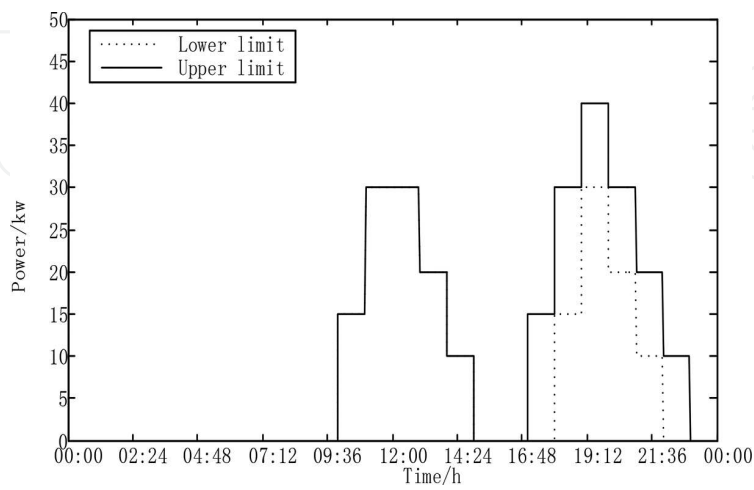


Figure 11. Power output intervals of FC with BT.

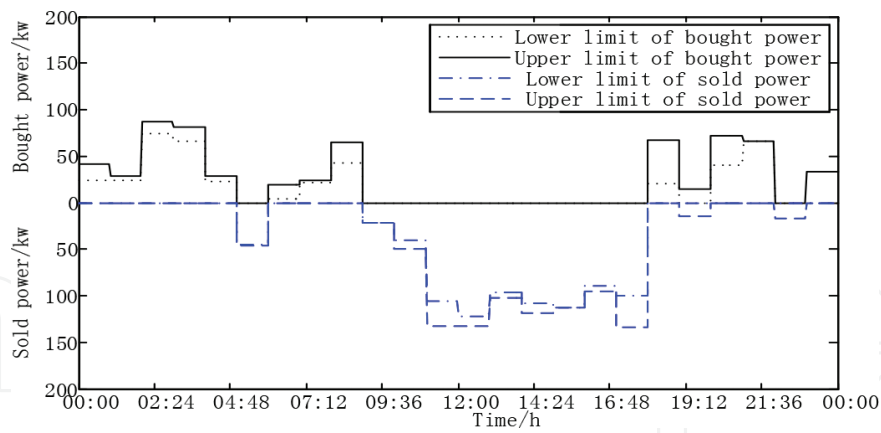


Figure 12. Bought and sold power intervals of FC without BT.

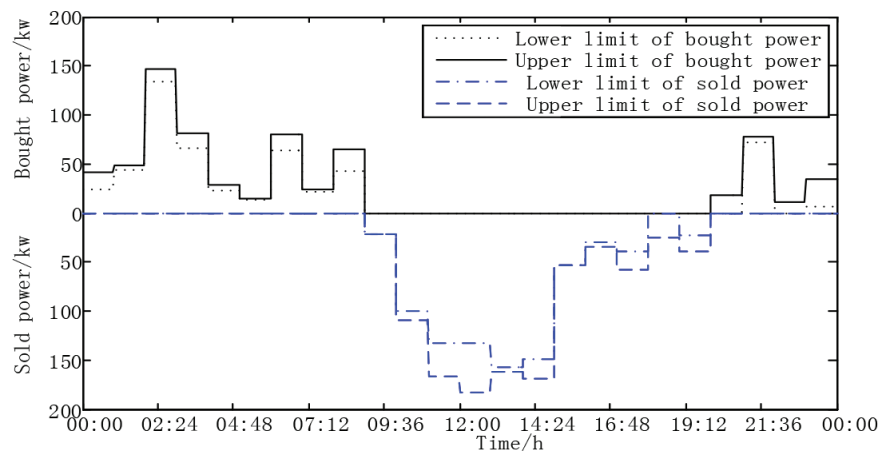


Figure 13. Bought and sold power intervals of FC with BT.

Load fluctuation (%)	System operation cost of a day (yuan)
0	[2596.08, 2624.43]
10	[2357.24, 2855.32]
20	[2120.79, 3088.71]
30	[1894.29, 3328.94]

Table 3. System operation cost under different load prediction fluctuation.

Figures 14–19 show battery charge and discharge power, fuel cell power output, power purchase interval, and power sale interval corresponding to 0% and 20% of load fluctuation. By comparing two figures, it can be seen load is supplied by upper grid and wind turbine and fuel cells do not work during load valley periods (00:00–6:00) because of time-of-use price. If the SOC of storage battery is less than 100%, it can absorb extra power to adjust active power

during other periods. It should be noted that power purchase interval and storage battery charging interval corresponding to 20% of load fluctuation are larger than 0%. In conclusion, load fluctuation levels can have impact on power purchase interval width and storage battery charging interval width during load valley periods.

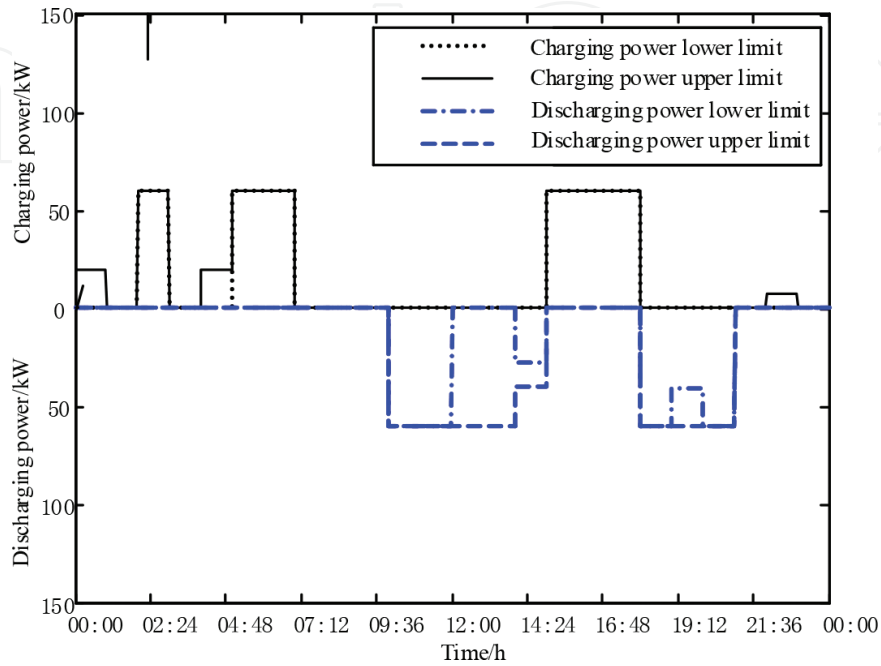


Figure 14. Storage battery charging intervals corresponding to 0% of load fluctuation.

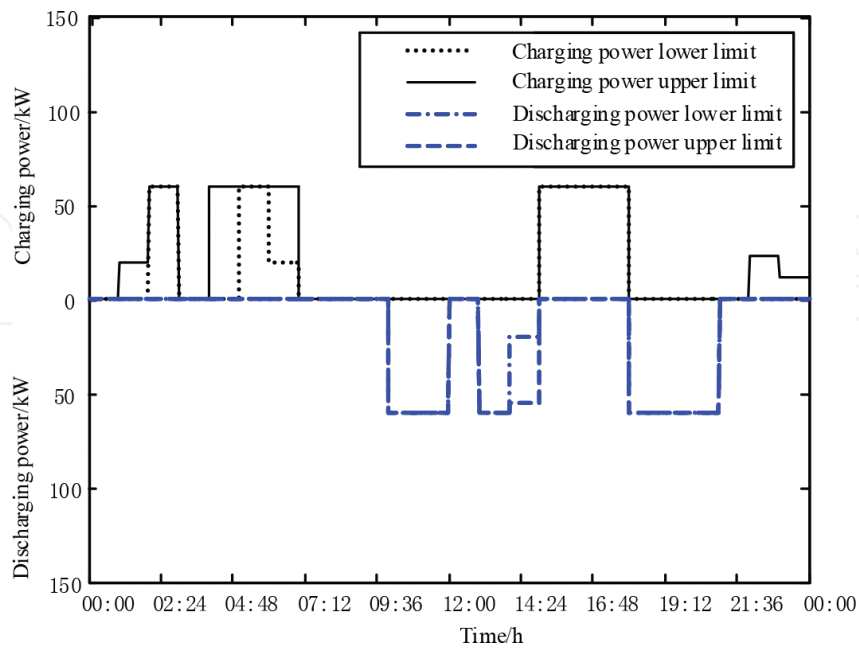


Figure 15. Storage battery charging intervals corresponding to 20% of load fluctuation.

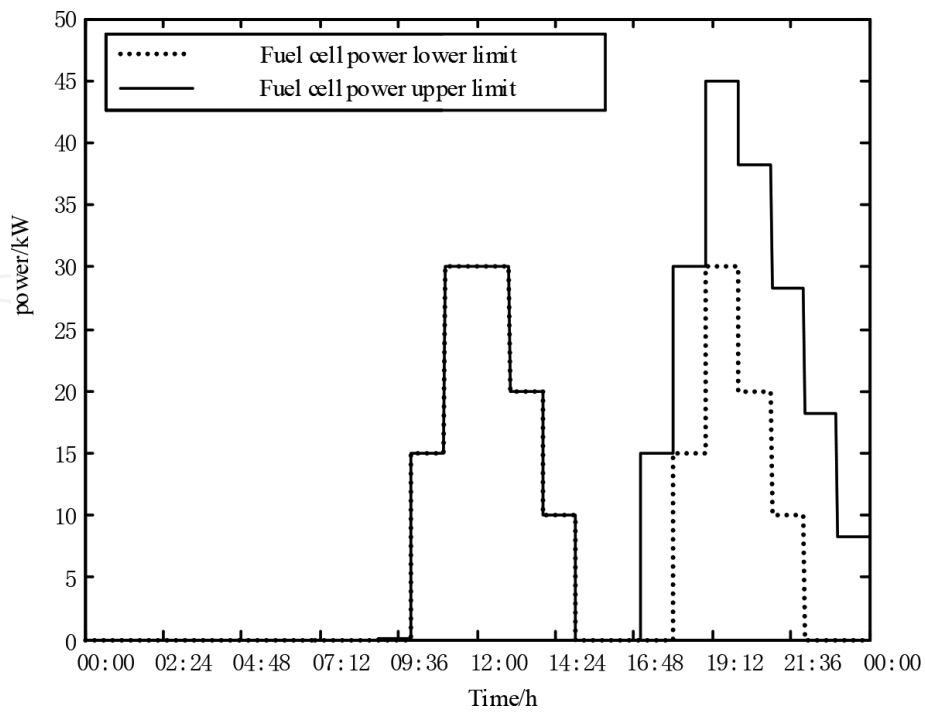


Figure 16. Fuel cell power intervals corresponding to 0% of load fluctuation.

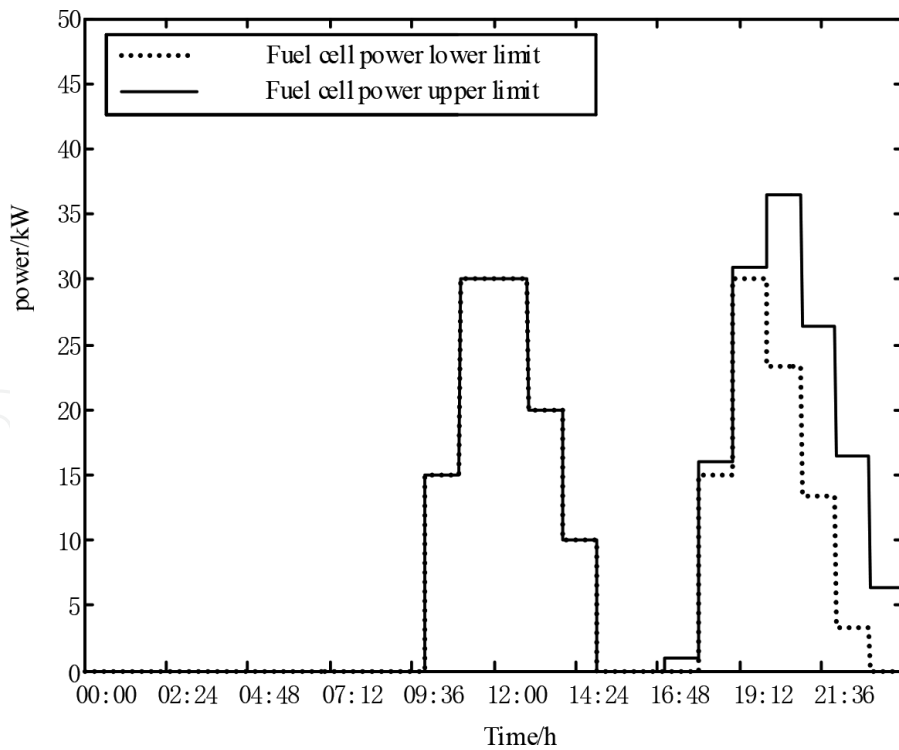


Figure 17. Fuel cell power intervals corresponding to 20% of load fluctuation.

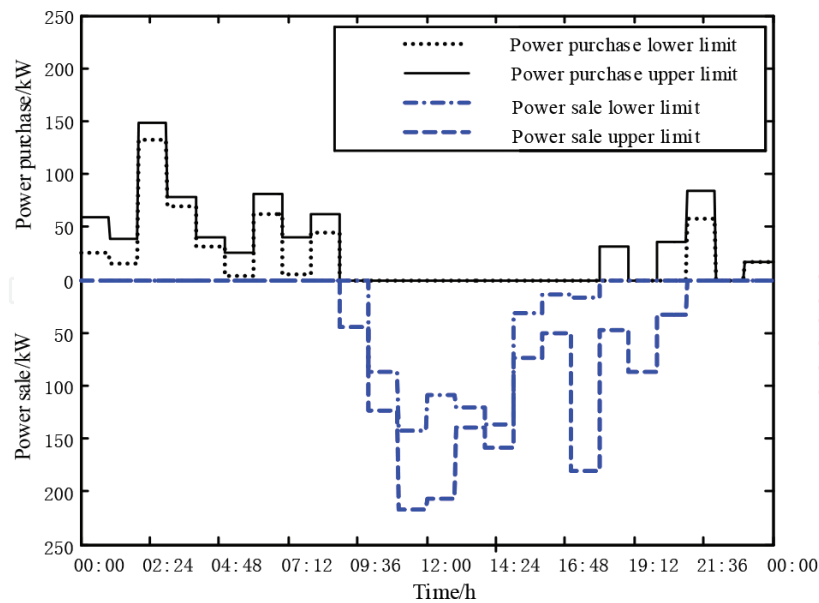


Figure 18. Power purchase and sale intervals corresponding to 0% of load fluctuation.

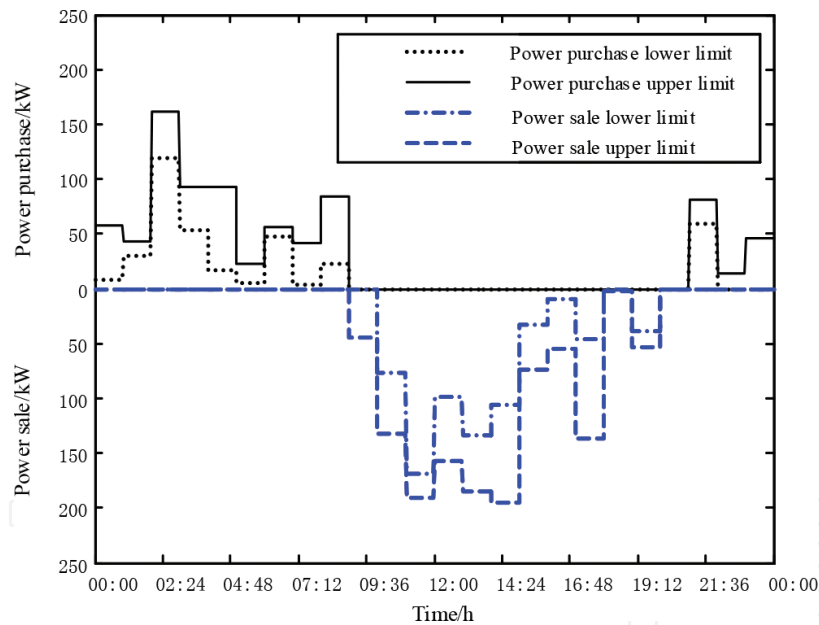


Figure 19. Power purchase and sale intervals corresponding to 20% of load fluctuation.

During load peak and normal periods, generation cost and discharging cost are lower than power purchase cost, and they still do not reach their maximum output, so generation unit can decide whether to generate more power and sale it to grid compared with the power sale price in order to obtain the optimal economic operation. During load peak periods (9:00–14:00 and 18:00–20:00), load fluctuation is relieved by the adjustment of storage batteries and fuel cells, and power purchase is not affected largely. During load normal periods (15:00–17:00), storage batteries are in charging condition and microgrid sale power, because WTs and PVs can supply

load and microgrid has extra power. The extra power of microgrid is stored in storage batteries and sold to grid, so different levels of load fluctuation has larger impact on power sale for storage batteries during load normal periods.

5. Conclusions

In this chapter, the characteristics of DGs and ESSs are studied and the mathematical models are established specifically. Different operational control strategies of microgrid under different operation modes are analyzed and an economic operation optimization method is proposed considering uncertainties of DGs in microgrid. The effects of the uncertainty property of DERs and user loads in microgrid on the economic optimization of microgrid are demonstrated. In order to characterize these uncertainties in microgrid, the randomness and intermittent of the wind speed and solar radiation intensity are described in interval forms and then the output prediction interval values of the wind turbines and PVs are obtained. Based on the interval model of load uncertainty, a microgrid economic optimization model based on interval optimization method is proposed. Meanwhile, combined with the time-of-use characteristic, issue of the power exchange with the external grid has been considered. Taking the effects analysis of ESSs on the economic operation of the system as an example, this chapter discusses the impacts of uncertainty of renewable energy power and load power on optimization results, as well as the effects of the degree of load uncertainty or load fluctuation on scheduling results. The results verify the robustness of the proposed method and model, and show the effectiveness in dealing with uncertainty optimization problem.

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