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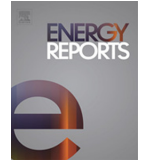
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Day-ahead economic dispatch of microgrid based on game theory

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Abstract

Utility and users are two important subjects in power dispatching, and each participant wants to maximize its benefits. That is to say, utility and users are engaged in an interest game with each other. In this paper, a day-ahead economic dispatch strategy which can solve mixed integer programming problem based on game theory is proposed. First, build the model of the microgrid. Second, set optimization objectives of utility and users and analyze constraints. Last, propose a dispatch strategy to ensure that utility and users gain the maximum benefits. A case study verifies the effectiveness of the proposed approach.

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Keywords: Day-ahead dispatch; Microgrid; Dispatch strategy; Game theory; Mixed integer programming

1. Introduction

Microgrids with users equipped with photovoltaic and batteries are promoted and applied increasingly widely. A microgrid is frequently includes a utility and several users, and power exchange generally exists among utility and all users. Much research has been done on the optimization of microgrid. Zhang et al. [1] proposes a parallel optimization strategy based on model predictive control and game theory to reduce the negative impacts introduced by the uncertainties of the loads and renewable energy resources. Luo et al. [2] proposes a two-stage optimization approach for microgrid energy management: one is the economic dispatching stage and the other one is the real-time adjusting stage. Cominesi et al. [3] proposes a two-layer strategy for dispatch of microgrid: the high level runs at a slow timescale and the low level runs at higher frequency.

In this paper, a day-ahead economic dispatch strategy is proposed. Because the system in this paper is a multi-participant system, and each participant's interests are in conflict, a strategy based on game theory is elaborated. The contributions of this paper include: (1) Consider the price of electricity as an independent variable in the optimization. (2) Establish the model of utility and users and abstract the scheduling problem as the mixed integer programming problem. (3) Propose a strategy based on game theory that can ensure each participant achieve their own optimization goals respectively.

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Nomenclature

$P_{GE}(t)$	Power of generator at time t
$U_{GE}(t)$	Running state of generator at time t
P_{GE}^{\min}	Minimum power of generator
P_{GE}^{\max}	Maximum power of generator
R_{GE}^{\max}	Maximum ramp up and down power of generator
C_{GE}	Running cost of generator
a, b, c	Coefficients of fuel cost of generator
c^{up}	Coefficients of start-up cost of generator
T	Optimization period
Δt	Optimization interval
$P_{(u)BT, ch}(t)$	Charging power of battery of User u at time t
$P_{(u)BT, dis}(t)$	Discharging power of battery of User u at time t
$U_{(u)BT, ch}(t)$	Charging state of battery of User u at time t
$U_{(u)BT, dis}(t)$	Discharging state of battery of User u at time t
$P_{(u)BT, ch}^{\max}$	Maximum charging power of battery of User u
$P_{(u)BT, ch}^{\min}$	Minimum charging power of battery of User u
$P_{(u)BT, dis}^{\max}$	Maximum discharging power of battery of User u
$P_{(u)BT, dis}^{\min}$	Minimum discharging power of battery of User u
$E_{(u)BT}(t)$	Energy level of battery of User u at time t
$\mu_{(u)BT}$	Self-discharging rate of battery of User u
$\eta_{(u)BT, ch}$	Charging efficiency of battery of User u
$\eta_{(u)BT, dis}$	Discharging efficiency of battery of User u
$C_{(u)BT}$	Running cost of battery of User u
$c_{(u)BT, ch}$	Coefficients of charging cost of battery of User u
$c_{(u)BT, dis}$	Coefficients of discharging cost of battery of User u
$P_{in}(t)$	Total amount of electricity purchased from all users of utility
$P_{out}(t)$	Total amount of electricity sold to all users of utility
$p_{in}(t)$	Price of electricity purchased from all users of utility
$p_{out}(t)$	Price of electricity sold to all users of utility
$P_{(u)in}(t)$	Amount of electricity purchased from utility of User u
$P_{(u)out}(t)$	Amount of electricity sold to utility of User u
$P_{(u)load}(t)$	Load of User u at time t
F_{ut}	Benefit of utility
$F_{us(u)}$	Cost of User u
$\varepsilon_{ut}, \varepsilon_{us(u)}$	Stop criteria of the algorithm

The rest of this paper is organized as follows. Section 2 shows the model of the microgrid and devices in it. Section 3 proposes the day-ahead dispatch strategy based on game theory to balance interests of multi participants. Section 4 completes a simulation to verify the effectiveness of proposed strategy. Section 5 draws the conclusions of the whole analysis and research.

2. Models of microgrid

In this paper, a microgrid consists of two subjects, users and utility. Users are allocated with photovoltaic and batteries, and utility generates power by generator. The structure of this microgrid is shown in Fig. 1. Utility sell electricity to users, while users can sell electricity to utility when their power is surplus. It is noteworthy that

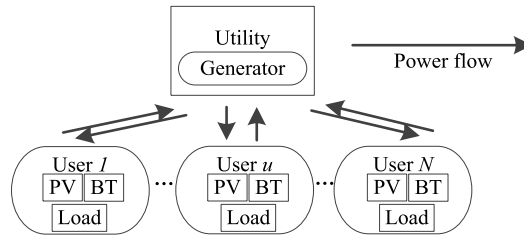


Fig. 1. Structure of microgrid.

no direct exchange of electricity exists between any two users, while utility plays the role of medium of power interaction. Loads of users are all non-dispatchable. In the whole microgrid, dispatchable devices are generator of utility and batteries of users. In addition, power output of photovoltaic and loads are fluctuating and need to be predicted.

2.1. Utility

Utility sells electricity generated by generator to users in microgrid. The parameters of generator are running state, maximum and minimum power, maximum ramp up and down power, as shown in (1) and (2) [4].

$$U_{GE}(t) P_{GE}^{\min} \leq P_{GE}(t) \leq U_{GE}(t) P_{GE}^{\max} \tag{1}$$

$$-R_{GE}^{\max} \leq P_{GE}(t) - P_{GE}(t-1) \leq R_{GE}^{\max} \tag{2}$$

The running cost of generator includes fuel cost and start-up cost, which is shown in (3).

$$C_{GE} = \sum_{t=1}^T [(a(P_{GE}(t))^2 + bP_{GE}(t) + c)] + \sum_{t=1}^T [\max(U_{GE}(t) - U_{GE}(t-1), 0) \cdot c^{up}] \tag{3}$$

2.2. User u

Users are satisfied by power from utility and their own PV and batteries. The parameters of batteries are maximum charging/discharging power, charging/discharging state, state of charge, as shown in (4) to (7) [5].

$$U_{(u)BT,ch}(t) P_{(u)BT,ch}^{\min} \leq P_{(u)BT,ch}(t) \leq U_{(u)BT,ch}(t) P_{(u)BT,ch}^{\max} \tag{4}$$

$$U_{(u)BT,dis}(t) P_{(u)BT,dis}^{\min} \leq P_{(u)BT,dis}(t) \leq U_{(u)BT,dis}(t) P_{(u)BT,dis}^{\max} \tag{5}$$

$$U_{(u)BT,ch}(t) + U_{(u)BT,dis}(t) \leq 1 \tag{6}$$

$$E_{(u)BT}(t) = E_{(u)BT}(t-1) (1 - \mu_{(u)BT})^{\Delta t} + [P_{(u)BT,ch}(t) \eta_{(u)BT,ch} - P_{(u)BT,dis}(t) / \eta_{(u)BT,dis}] \Delta t \tag{7}$$

In order to guarantee the dispatch of the next cycle, SOC of batteries at the beginning of a cycle is equal to that at the end of a cycle.

$$E_{(u)BT}(t) |_{t=0} = E_{(u)BT}(t) |_{t=T} \tag{8}$$

The running cost of battery is shown in (9).

$$C_{(u)BT} = \sum_{t=1}^T [P_{(u)BT,ch}(t) c_{(u)BT,ch} + P_{(u)BT,dis}(t) c_{(u)BT,dis}] \tag{9}$$

PV and loads in microgrid are undispachable.

3. Day-ahead economic dispatch

3.1. Objectives of utility and users

Utility and users are two kinds of players in the power market of microgrid in this paper. Conflicts are existed between the interests of the two sides, because each player in market wants its benefit maximized. Utility pursues

maximum profit, while users try to minimize their electricity cost, as shown in (10) and (11) respectively.

$$\max F_{ut} = \sum_{t=1}^T [p_{out}(t) P_{out}(t) - p_{in}(t) P_{in}(t)] - C_{GE} \quad (10)$$

$$\min F_{us(u)} = \sum_{t=1}^T [p_{out}(t) P_{(u)in}(t) - p_{in}(t) P_{(u)out}(t)] + C_{(u)BT} \quad (11)$$

3.2. Constraints

Constraints of optimization include two kinds, device characteristic constraints and system operation constraints. Device characteristic constraints have been described above, and system operation constraints of utility and user u are shown in (12) and (13).

$$P_{out}(t) = P_{in}(t) + P_{GE}(t) \quad (12)$$

$$P_{(u)out}(t) + P_{(u)load}(t) = P_{(u)in}(t) + P_{(u)BT}(t) \quad (13)$$

3.3. Dispatch strategy

Day-ahead dispatch of microgrid is based on game theory in this paper. To be specific, utility is the leader in this game, and it has the right to determine the price of electricity, include electricity purchased from users and sold to users. After the price is announced by utility, users draw up plans accordingly. These plans publish the quantity of electricity purchased from utility and sold to utility. After that, utility adjusts its strategy to maximize its profit accordingly. And then, users adjust their strategies. The process continues until the each player is satisfied in this game, and the game reaches the equilibrium point. The dispatch strategy is as follows:

- Step 1: Initialize, and set a counter k recording number of iterations. Calculate the optimum solution of utility, then price of electricity is obtained;
- Step 2: All users work out their own plan according to the price obtained from the utility, then total quantity of electricity purchased and sold by all users is obtained;
- Step 3: $k = k + 1$. Utility makes optimization again based on the newly updated quantity of electricity of all users, then a new price is calculated correspondingly.
- Step 4: All users make optimization again based on the latest price, and tell the total quantity of electricity to utility;
- Step 5: Go to Step 3 until $|F_{ut}(k+1) - F_{ut}(k)| \leq \varepsilon_{ut}$ and $|F_{us(u)}(k+1) - F_{us(u)}(k)| \leq \varepsilon_{us(u)}$ are satisfied.

4. Case study

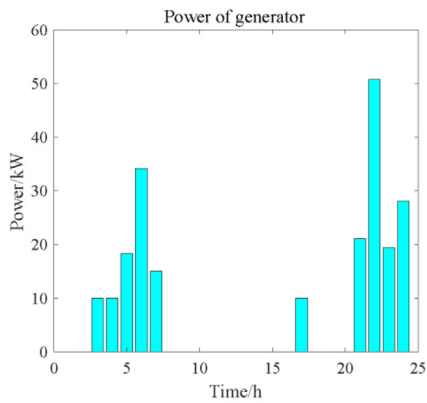
In this paper, to verify the day-ahead economic dispatch strategy, a microgrid with one utility and two users is used as a case. The parameters of equipment in this microgrid are shown in Table 1. To maintain transaction order, utility should set limited price of electricity, and limited price of both purchased and sold are set as 3 in this paper. The simulation was run on a 64-bit PC with 2.50-GHz CPU and 4-GB RAM, and was coded in MATLAB R2017a. We set Δt as 1 h and T as 24 h. Data for PV and loads are from SSTECH project.

Day-ahead generation plan and price of electricity of utility are shown in Fig. 2. Day-ahead economic dispatch of users are shown in Fig. 3.

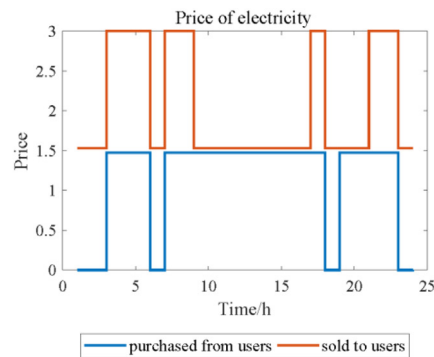
From Fig. 2(b), we can clearly see that price of electricity is fluctuant over time, which is caused by fluctuations in electricity demand of users in this microgrid. Utility adjusts the output of generator over and over again to satisfy users for more benefits, and Fig. 2 is the final day-ahead schedule for generator. From Fig. 3, we can see that batteries play an important role in reducing the cost because they stabilize fluctuations to a large extent. In addition, users purchase or sell electricity to minimize their costs. Results of this case study demonstrates that the strategy proposed in this paper is effective.

Table 1. Parameters of equipment.

Generator of utility	Maximum power: 100 kW
Battery of User 1	Maximum charging power: 50 kW Maximum discharging power: 50 kW State of charge: 20%–90% Maximum capacity: 100 kWh
Battery of User 2	Maximum charging power: 100 kW Maximum discharging power: 100 kW State of charge: 20%–90% Maximum capacity: 200 kWh

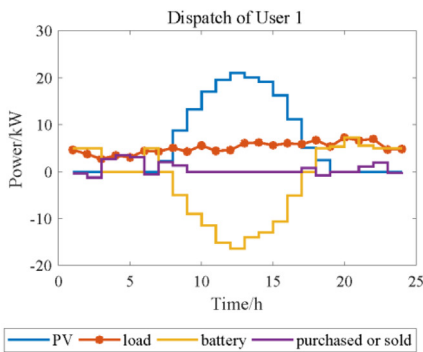


(a) Power of generator of utility

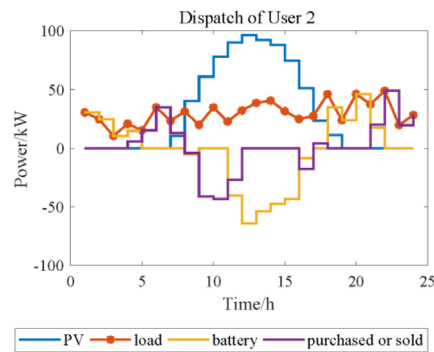


(b) Price of electricity.

Fig. 2. Scheduling results of utility.



(a) Dispatch of User 1



(b) Dispatch of User 2

Fig. 3. Scheduling results of users.

5. Conclusions

This paper focus on a microgrid which consists of two important and common entities: utility and users. Utility pursue higher profits, while users want lower costs, thus the two entities are in the game state. Therefore a day-ahead dispatch based on game theory is proposed. In this strategy, price of electricity is considered as an independent variable and it is the message transmitted in the game. Utility informs all users of electricity price and all users inform utility of their amount of electricity purchased and sold. Each participant makes optimization according to

the information from others. The case study demonstrates the effectiveness and practicability of the optimization approach.

Acknowledgments

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