Robust optimization for energy transactions in multi-microgrids under uncertainty

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HIGHLIGHTS

- Formulated the multi-microgrid (MMG) operation as a transaction commitment problem.
- Designed a two-stage robust optimization based MMG coordinated operation approach.
- Described discrete feature of energy interactive behaviour among multiple microgrids.
- Mitigated the disturbances of uncertainties in renewable energy.
- Reduced frequent energy exchange between the MMG and the grid.

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ABSTRACT

Independent operation of single microgrids (MGs) faces problems such as low self-consumption of local renewable energy, high operation cost and frequent power exchange with the grid. Interconnecting multiple MGs as a multi-microgrid (MMG) is an effective way to improve operational and economic performance. However, ensuring the optimal collaborative operation of a MMG is a challenging problem, especially under disturbances of intermittent renewable energy. In this paper, the economic and collaborative operation of MMGs is formulated as a unit commitment problem to describe the discrete characteristics of energy transaction combinations among MGs. A two-stage adaptive robust optimization based collaborative operation approach for a residential MMG is constructed to derive the scheduling scheme which minimizes the MMG operating cost under the worst realization of uncertain PV output. Transformed by its KKT optimality conditions, the reformulated model is efficiently solved by a column-and-constraint generation (C&CG) method. Case studies verify the effectiveness of the proposed model and evaluate the benefits of energy transactions in MMGs. The results show that the developed MMG operation approach is able to minimize the daily MMG operating cost while mitigating the disturbances of uncertainty in renewable energy sources. Compared to the non-interactive model, the proposed model can not only reduce the MMG operating cost but also mitigate the frequent energy interaction between the MMG and the grid.

1. Introduction

Microgrids (MGs) integrated with distributed renewable energy generations and storage systems can effectively improve energy utilization and reduce environmental pollution \cite{1–3}. Recently, as the technologies of roof-top PV and Electric Vehicle (EV) grow in popularity, the deployment of residential MGs is increasing \cite{4,5}. Multiple neighbouring MGs appear in a local area and can be interconnected to form a multi-microgrid (MMG) for better energy performance \cite{6–8}. Different from a single MG, for a MMG, energy can be exchanged not only with the grid but also among MGs, which makes the operation process of MMGs more complex. Moreover, most existing operating approaches for MMGs are based on deterministic conditions, which is hard to adapt to randomness of renewable energy sources (REBs). Overall, complicated mechanism and uncertainties in MMG operation may lead to various problems, such as low energy efficiency, high operation cost and frequent interaction with the grid. Therefore, in order to improve robustness and economy of MMG operation, it is necessary to design an effective operation method to coordinate the operation of multiple MGs and immunize against randomness of REBs.

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B. Zhang et al.  


### Nomenclature

#### Indices

- \( i,j \) index of MGs
- \( t \) index of hours

#### Sets

- \( G \) set of MGs, \( i,j \in G \), \( G=[1,2,\ldots,n] \)
- \( T \) set of time intervals, \( t \in T, T=[0,1,\ldots,23] \)
- \( T_p \) intervals when the EV is plugged, \( T_p \subseteq T, T=[0,T+1,\ldots,T_2-1] \)

#### Binary variables

- \( r(i,j,t) \) binary variable of MG \( i \) related to the power exchange status between MG \( i \) and MG \( j \), \( r(i,j,t)=1 \) if MG \( i \) purchases power from MG \( j \) at time \( t \), \( r(i,j,t)=0 \) otherwise
- \( s(i,j,t) \) binary variable of MG \( i \) related to the power exchange status between MG \( i \) and MG \( j \), \( s(i,j,t)=1 \) if MG \( i \) sells power to MG \( j \) at time \( t \), \( s(i,j,t)=0 \) otherwise
- \( u(i,t) \) binary variable of MG \( i \) related to the power exchange status between MG \( i \) and the grid, \( u(i,t)=1 \) if MG \( i \) purchases power from the grid at time \( t \), \( u(i,t)=0 \) otherwise
- \( v(i,t) \) binary variable of MG \( i \) related to the power exchange status between MG \( i \) and the grid, \( v(i,t)=1 \) if MG \( i \) sells power to the grid at time \( t \), \( v(i,t)=0 \) otherwise
- \( z(i,t) \) binary variable related to charging status of EV in MG \( i \), \( z(i,t)=1 \) if EV in MG \( i \) is charging at time \( t \), \( z(i,t)=0 \) otherwise
- \( w(i,t) \) binary variable related to discharging status of EV in MG \( i \), \( w(i,t)=1 \) if EV in MG \( i \) is discharging at time \( t \), \( w(i,t)=0 \) otherwise

#### Continuous variables

- \( T C \) expected daily total cost of multiple MGs (CNY)
- \( p_{gb}(i,t) \) power that MG \( i \) purchases from the grid at time \( t \) (kW)
- \( p_{gs}(i,t) \) power that MG \( i \) sells to the grid at time \( t \) (kW)
- \( p_{ev}(i,t) \) charging power of EV in MG \( i \) at time \( t \) (kW)
- \( p_{es}(i,t) \) discharging power of EV in MG \( i \) at time \( t \) (kW)
- \( SOCe_v(i,t) \) state of charge of EV in MG \( i \) at time \( t \) (
- \( p_{op}(i,t) \) actual power output of PV in MG \( i \) at time \( t \) (kW)

#### Parameters

- \( \Delta_\tau \) duration of time intervals. In this paper, \( \Delta_\tau=1 \) h.
- \( \Delta_p(i,t) \) predicted power output of PV in MG \( i \) at time \( t \) (kW)
- \( \Delta_r(i,t) \) deviation from the predicted PV power output in MG \( i \) at time \( t \) (kW)
- \( \Gamma(i) \) budget of uncertainty of PV in MG \( i \)
- \( P_{rt}(i,t) \) predicted load demand in MG \( i \) at time \( t \) (kW)
- \( C_{pv}(i) \) O&M cost of PV in MG \( i \) (CNY/kW h)
- \( C_{ev}(i) \) charging/discharging cost of EV in MG \( i \) (CNY/kW h)
- \( a_{ser} \) service charge of exchange between MGs (CNY)
- \( b_{ser} \) service charge of exchange between MG and the grid (CNY)
- \( c_{ev}(i) \) electricity price among MGs at time \( t \) (CNY/kW h)
- \( c_{gb}(i) \) purchasing electricity price from the grid at time \( t \) (CNY/kW h)
- \( c_{gs}(i) \) selling electricity price to the grid at time \( t \) (CNY/kW h)
- \( \text{cost}_{el}(i) \) electricity cost of MG \( i \) in the MMG without energy exchanging (CNY)
- \( p_{gb}^{\text{max}} \) exchanging power limit between MGs (kW)
- \( p_{gs}^{\text{max}} \) purchasing power limit from the grid (kW)
- \( p_{gs}^{\text{max}} \) selling power limit to the grid (kW)
- \( \text{t}_1 \) the time at which EVs are plugged in
- \( \text{t}_2 \) the time at which EVs depart
- \( P_{gb}^{\text{max}}(i) \) maximum charging power of EV in MG \( i \) (kW)
- \( P_{es}^{\text{max}}(i) \) maximum discharging power of EV in MG \( i \) (kW)
- \( \eta_{gb}(i) \) charging efficiency of EV in MG \( i \) (%)
- \( \eta_{es}(i) \) discharging efficiency of EV in MG \( i \) (%)
- \( C_{gb}(i) \) capacity of battery in EV in MG \( i \) (kW h)
- \( SOC_{\text{nom}}^G(i) \) maximum state of charge of EV in MG \( i \) (%)
- \( SOC_{\text{min}}^G(i) \) minimum state of charge of EV in MG \( i \) (%)
- \( SOC_{\text{nom}}^G_L \) initial state of charge of EV in MG \( i \) at time \( t_1 \) (%)
- \( SOC_{\text{min}}^G_L \) users’ desired SOC of EV in MG \( i \) at time \( t_1 \) (%)

### 1.1. Literature review

Recently, there have been increasing researches focusing on MMG operation approaches. According to energy interaction relationships among MGs, these researches can be classified into non-interactive [9–15] and interactive [16–19]. For non-interactive MMGs, MGs directly exchange energy with the grid without considering local energy interaction. To avoid electricity exchange peaks, decentralized energy scheduling strategies between a multi-microgrid system and the grid are studied in [9,10]. To simultaneously maximize the interests of the MMG, the distribution network operator (DNO) and the grid, [11] develops a multi-objective approach, [12,13] propose bi-level optimization methods, and [14] designs a distributed economic model predictive control scheme. Besides economic objectives, [15] also considers security guarantee in its proposed new modeling framework by dynamically estimating the power interchange between MMGs and a DNO. From the perspective of future smart grids, the joint operation with energy interaction among MGs is preferable to the independent operation of single MGs, which ensures greater operation benefits and energy efficiency. A metakmetic algorithm based approach for a building-level microgrid cluster is presented in [16] to achieve local sharing of cooling energy. Similarly, an augmented multi-objective particle swarm optimization framework for the same system is developed in [17] to achieve thermal energy sharing among MGs. In [18,19], connection between MGs is considered in MMG optimal scheduling to enable their power sharing in an interconnected operation mode. These researches demonstrate that interactive operation methods can improve economy and operation performance, therefore, how to more effectively guide and motivate energy transactions among MGs becomes hot research topics.

To optimize energy transactions among multiple MGs, several energy trading modes have been designed, which can be generally classified into competitive modes [20,21] and cooperative modes [22–26]. By passing the profit margin of each MG to energy service provider, the competitive situation of multiple MGs is formulated as a bi-level problem [20]. Considering different consumer preferences and loads in buildings, the non-cooperative game theory is introduced in the joint operation of multiple buildings with PV systems [21]. However, for most competitive modes, the overall efficiency of MMGs is not considered, which may lead to energy waste. Therefore, cooperative modes among multiple MGs are investigated based on flexible price mechanisms. Such as, [22] defines Lagrange multipliers as dynamic purchase prices for power transactions among MGs. [23] proposes a distributed energy trading method for a MMG based on dual decomposition, in which energy prices are adjusted according to the law of demand. Along this line, a parallel optimization strategy for multiple buildings is developed by introducing Lagrange multipliers for energy exchange in all transmission lines [24]. In [25], an interactive energy game matrix is
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