CrossMark

Integrated resources planning in microgrids considering interruptible loads and shiftable loads

Lan ZHU[1,2], Xueying ZHOU[2,3], Xiao-Ping ZHANG[4], Zheng YAN[1], Shuxin GUO[5], Longjun TANG[6]

MPCE

Abstract Demand response has the potential to bring significant benefits to the optimal sizing of distributed generation (DG) resources for microgrids planning. This paper presents an integrated resources planning model considering the impact of interruptible loads (IL) and shiftable loads (SL) in microgrids, which simultaneously deals with supply side and demand side resources and minimizes the overall planning cost of the microgrid. The proposed model can be applied to offer a quantitative assessment how IL and SL can contribute to microgrid planning. The pure peak clipping model with IL and SL is also provided for comparisons. Moreover, sensitivity analysis of parameters in the model is performed. Numerical results confirm that the proposed model is an effective method for reducing the planning cost of microgrids. It was also found that the major contributing factors of IL and SL have great impact on the economic benefits of the proposed model in low-carbon economy environments.

✉ Xueying ZHOU
  13916508874@163.com

  Lan ZHU
  Zhulant@163.com

  Xiao-Ping ZHANG
  X.P.Zhang@bham.ac.uk

  Zheng YAN
  yanz@sjtu.edu.cn

  Shuxin GUO
  guoshuxin026@163.com

  Longjun TANG
  tang_lj@ec.sgcc.com.cn

1 Introduction

In recent years, a great deal of technical, economic, and societal factors came together to cause microgrids to become one of the critical variations in shaping the electric power infrastructure in the near horizon [1]. Furthermore, the increasing penetration of renewable and other generation sources have been the driver for the development of microgrids. From a conceptual point of view, a microgrid is a small low/medium voltage distribution system with distributed energy sources and storage devices. Well-coordinated and managed microgrids can provide valuable benefits for both customers and utilities [2].

In the situation mentioned above, appropriate planning methods for microgrids is crucial to ensure benefits in

1 Department of Electrical Engineering, Shanghai Jiao Tong University, Shanghai 200240, China

2 School of Electrical Engineering, Shanghai University of Electric Power, Shanghai 200090, China

3 Pudong Power Supply Company, State Grid Shanghai Municipal Electric Power Company, Shanghai 200122, China

4 School of Electronic, Electrical and Systems Engineering, University of Birmingham, Birmingham B152TT, UK

5 Zibo Power Supply Company, State Grid Shandong Electric Power Grid Company, Zibo 255000, China

6 East Electric Power Dispatch and Control Sub-Center, State Grid Corporation of China, Shanghai 200000, China

🖄 Springer

STATE GRID
STATE GRID ELECTRIC POWER RESEARCH INSTITUTE

power grid operations, return of investments and environmental effects. Nowadays, considerable efforts have been placed on the analysis and methods for microgrids planning. In terms of planning and design models, in [3] a novel approach, which incorporates the robust optimization for microgrid planning, was presented and this approach uses a column and constraint generation framework to decide optimal locations, sizes and mix of dispatchable and intermittent distributed generators. In [4] a probabilistic minimal cut-set-based iterative methodology for the optimal planning of interconnection among microgrids with variable renewable energy sources was introduced. In terms of coordination planning of distribution networks and microgrids, in [5] a network planning algorithm for the planning of suburban MV cable networks with a high penetration of randomly located microgrids was formulated. In terms of economic analysis and planning of energy storage system, in [6] a cost minimization planning method for storage and generation considering both the initial investment cost and operational/maintenance cost was presented, while a distributed optimization framework to overcome the difficulty caused by the large size of the optimization problem was proposed.

Previous works have mostly taken the original load as the basis for the power balance in microgrids and have rarely taken into account the demand side response in the planning stage. Integrated resources planning (IRP) is to treat equally the various energy resources of supply side and demand side, as well as to optimize relevant costs and meet the availability constraints. IRP has played important roles on achieving energy conservation and emission reduction in large electric networks [7], while there have been few applications of IRP in microgrids. In this paper, an IRP method for microgrids planning combined with demand response (DR) is developed to decide the optimal sizing of DGs, which is based on the following reasons.

1) The load is specific and partially controllable in microgrids, which provides a convenient basis for the development of IRP studies in microgrids considering the load behavior during power grid operations.
2) The deployment of advanced metering infrastructure and communication technologies in the active power distribution network enable critical hardware conditions for this study.

According to the Federal Energy Regulatory Commission (FERC) in the USA, DR is defined as: changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high whole sale market prices or when system reliability is jeopardized [8]. By evaluating the different response modes of users, it can be divided into price-based DR and incentive-based DR. Direct load control (DLC), interruptible load (IL) and shiftable load (SL) are important techniques in incentive-based DR. In [9], we have expanded the idea of microgrid planning combined with direct load control behavior. In this paper, a study of IRP for microgrids considering the impact of IL and SL is carried out. IRP with IL and SL is different from the planning optimization with DLC in terms of the following aspects.

1) Application ranges

DLC is generally applicable to control terminal electrical equipment of residents or small business users. Air-conditioners and water heaters are typical controllable loads of DLC, which have the ability of heat storage [10].

IL and SL are usually applicable to industrial and commercial users and are generally not directly interrupted by the power dispatchers, but performed by users after being notified.

2) Optimization scheduling models

DLC is a technique to obtain a controllable load on/off schedule for shaving the system peak load, and various control strategy models and equivalent thermal parameter models for loads which need to be developed. In addition, DLC requires modeling the payback energy.

As for IL and SL, attention has been paid to the IL/SL contract, such as advanced notification time, interruption/translation duration, the number of interruptions/translations, minimum capacity of interruption/translation and the compensation scheme. The aforementioned aspects require further research on the impact of IL and SL on the microgrid planning, which is the motivation of this paper.

In fact, economic operations in microgrids considering DR have been investigated in [11–13] to solve energy and reserve scheduling problems. In [11], price-offer packages were proposed for different consumers to further encourage participants to contribute to DR programs. In [12], interruptible load was considered in probabilistic coordination of DERs on microgrid operations based on the hourly interruption cost for a variety of customers. In [13], a real-time shiftable loads scheduling algorithm was developed to make proper short-term scheduling to mitigate variability of deep renewable penetration and reduce reserve costs. In [14], another mechanism was designed to schedule a consumption plan for industrial customers based on the time of the day tariff. The aforementioned studies are under a given energy capacity for economic operation at a small time scale (12 or 24 hours). Being different from [11–14], our work aims to study planning optimization considering DR. Moreover, the planning period is a large time scale (N

years). For a long term microgrid planning period, demand response is an alternative to reduce the short-time peak load demand and hence reduce unnecessary investment expenditure. A greater calculation amount is required for the planning scheme. And there are some alternative planning tools which can be used as the decision support for investment and planning distributed energy resources in microgrids, such as the Hybrid Optimization Model for Electric Renewable (HOMER) and Distributed Energy Resources Customer Adoption Model (DER-CAM). However, the DR models of these software packages are comparatively simple and there is a lack of specific models for IL and SL, which is also a motivation of this paper. Furthermore, a carbon trading mechanism is considered in all the models.

The contributions of this paper are summarized as follows:

1) Based on time chronological load simulations, a novel method considering the impact of IL and SL is proposed for IRP in microgrids, which can be effectively applied to offer a quantitative assessment of the effect of IL and SL in microgrid planning. The framework of IRP considering IL and SL is established, together with a traditional planning model and pure peak clipping model for comparisons. The numerical examples demonstrate the advantages of the proposed method.

2) A concrete analysis about the impact of major contributing factors of IL and SL on IRP are presented, including changes of user bidding, the interruption/translation duration, etc.

3) The carbon trading mechanism is applied in all planning models. And a sensitivity analysis of the carbon trading price is also conducted, which can provide a reference for microgrids planning under low-carbon economy environments.

The rest of this paper is arranged as follows. In Section 2, the model for IL and SL is described. Subsequently, the IRP model considering IL and SL is formulated, meanwhile a pure peak clipping model is provided for comparisons in Section 3. Then numerical studies are analyzed which show the advantages of the proposed method in Section 4. Finally, the concluding remarks are given in Section 5.

2 Modeling of interruptible load and shiftable load control in planning

An annual load duration curve primarily reflects the cumulative time of different load values as shown in Fig. 1, which is usually used for IRP in the large power grid without taking into account the chronological load characteristics. However, the impact of IL and SL for changing the distribution of the time series power demand is required to be reasonably considered in microgrid planning. So an annual chronological load curve (as depicted in Fig. 2) is adopted in this paper.

IL is one of the techniques for DR and it is known that the customer enters into a contract with the power supply company or the independent system operator to reduce its demand when requested [15]. The grid benefits are from a decrease in its peak load and hence saving costly reserves, recovering quality of service and ensuring reliability. The commercial and industrial customer benefits are by means of a reduction in its energy costs and incentives offered by the contract. In [16], the IL management methods so far adopted by the utilities in many countries were summarized, which indicates that IL can be an effective option for the system operator to choose from its available Services with market settlement framework and proper contracting. The contents of IL contract consist of advanced notification time required, minimum curtailment and payment structure. The objectives of the pure problems of IL can be summarized as follows: the minimum purchase cost of IL in the power market [17, 18], the minimum cost commitment of IL for frequency response [19] and minimizing cost of the system operation considering IL [20–23]. Solution algorithms of IL optimization decision problems are as follows: the priority heuristic algorithm [18], the sensitivity-based method [19], dynamic programming method combined with heuristic rules [20], mixed-integer programming (MIP) method [21] binary particle swarm optimization algorithm [22], etc.

Meanwhile, SLs have also received increasing attention due to their ability in creating load flexibility and enhancing demand response programs. SL as a task will require a certain energy to be delivered over a specified time interval. As for SL, there are studies focused on optimizing the operation of SL with different objectives such as the minimum peak hourly load [24], the minimum system operating cost [25, 26] and maximizing the
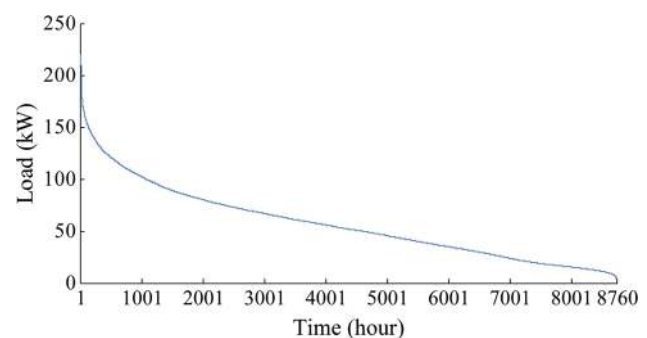

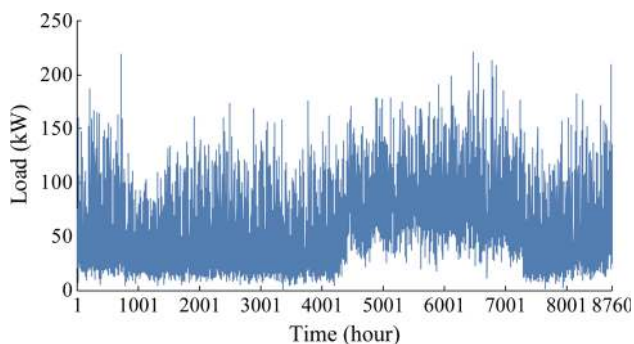**Fig. 1** Annual load duration curve

Fig. 2 Annual chronological load curve

customer's revenue for frequency regulation [27]. And the solving approaches of SL optimization are also developed, including integer linear programming (ILP) method [24], the glowworm swarm particles optimization algorithm [25], dynamic programming algorithm [26], etc.

In this paper, IL and SL are considered as optional power sources for microgrid planning. Therefore, the issue should not be treated as pure modeling for IL or SL and the mathematical description of IL and SL needs to be integrated in the overall planning model. The time-series value of load after IL and SL control can be represented as:

$$P'(t) = P(t) - \sum_{i=1}^{M} [S(i,t)C(i)] - P_{SL,out}(t) + P_{SL,in}(t)$$
$$\forall t = 1, 2, \ldots, N \tag{11}$$

where $P(t)$ is the project load for time period t; $P'(t)$ is the new load for time period t after IL and SL; N is the number of time periods per year (1 hour as a unit); M is the number of users for IL; $S(i,t)$ is 1 if user i is selected for providing IL during the period t and 0 otherwise; $C(i)$ is the IL capacity for user i; where $P_{SL,out}(t)$ is the curtailed load of SL for time period t, $P_{SL,in}$ is the increased load of SL for time period t.

The specific impact of IL and SL on IRP in microgrids will be illustrated in Section 3. In 2015, there were only 6 days of the daily maximum load which was more than 93.9% of the annual peak load in the Shanghai Power Grid. It would be a significant research undertaking to solve the aforementioned problem by load control. The ratios of peak-valley differences to the peak load for the past few years are shown in Fig. 3, which indicates that the ratios of peak-valley differences are still high in recent years, hence it is necessary to address these pressing issues by the active participation of a DR, such as IL and SL, etc.

3 Planning model

In this paper, the microgrid system is composed of wind turbines, solar cells, lead acid batteries, diesel generators and loads (partially controllable). The structure of the microgrid system is shown in Fig. 4. The microgrid is considered to ensure the operation occurs in an isolated mode. For IRP in microgrids, it is necessary to establish an appropriate model for each distributed generation (DG) in the microgrid. The specific DG models for wind turbines, solar cells, batteries, and diesel generator's energy can be found in [9].

In this section, the IRP model considering IL and SL is proposed. The pure peak clipping model is also given for comparison. It should be noted that, in this paper, we focus on how IL and SL can contribute to optimal capacity configuration of the microgrid during the planning stage and the specific day-ahead operation strategy is beyond the scope of this paper.

1) IRP model considering IL and SL

Both supply-side and demand-side resources are taken into consideration in the IRP.

2) Pure peak clipping model considering IL and SL

A two-stage plan considering IL and SL might be an alternative choice to reduce the complexity of optimization. In order to further compare their performances with the IRP model, the pure peak clipping model is presented. In doing so, the first step for this model is to minimize the peak load by using the IL and SL. The second step is to configure the capacity by the method of traditional microgrid planning in the light of the new load data.

3.1 IRP model for microgrid

We need to find the optimal portfolio of different types of microgrid resources (IL and SL as two types of power sources) so as to maximize the long-term economic profits. It is assumed that the quotation schemes of IL and SL users
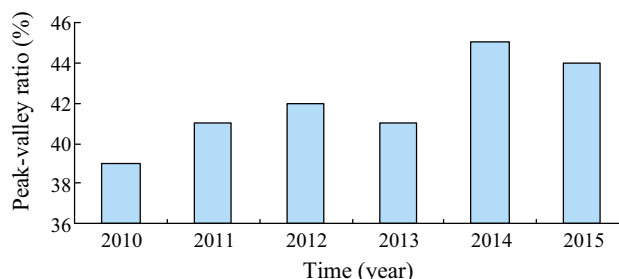

Fig. 3 Ratios of peak-valley differences to the peak load for the last six years
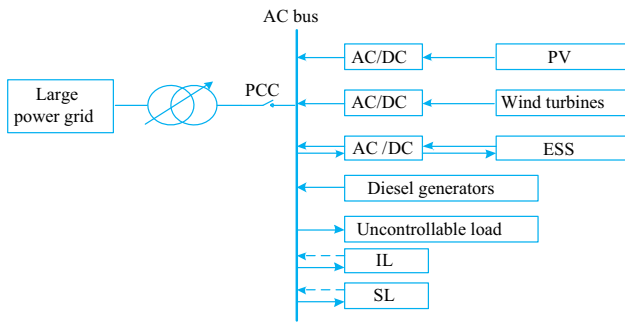
Fig. 4 Structure of the proposed microgrid

are known and user data can be obtained on the basis of the investigation.

3.1.1 Decision variables

Decision variables are defined as:

$$X_1 = [S_W, S_{PV}, S_{DE}, S_{SB}, P_{DE}(t), P_{SB}(t), P_{SL,out}(t),$$
$$P_{SL,in}(t), S(i,t), C(i), T_d(i)] \quad (2)$$

where $S_W, S_{PV}, S_{DE}, S_{SB}$ denote the capacity of wind turbines, photovoltaic batteries, diesel generators and the energy storage batteries respectively; $P_{DE}(t), P_{SB}(t)$ are the output power of the diesel generators and energy storage batteries; $T_d(i)$ is the duration of the interruption for user i each time.

3.1.2 Objective function

The objective for IRP in microgrids considering IL and SL is to minimize the total cost of the microgrid, which is represented as:

$$F_1 = \min(Z_W + Z_{PV} + Z_{SB} + Z_{DE} + Z_{IL} + Z_{SL} + Z_C) \quad (3)$$

where $Z_W, Z_{PV}, Z_{SB}, Z_{DE}, Z_{IL}, Z_{SL}, Z_C$ are the total cost of wind turbines, photovoltaic batteries, the energy storage batteries, diesel generators, IL, SL and the cost of carbon trading respectively, which can be calculated as:

$$\begin{cases} Z_W = Z_{W,init} + Z_{W,rep} + Z_{W,O\&M} \\ Z_{PV} = Z_{PV,init} + Z_{PV,rep} + Z_{PV,O\&M} \\ Z_{SB} = Z_{SB,init} + Z_{SB,rep} + Z_{SB,O\&M} \\ Z_{DE} = Z_{DE,init} + Z_{DE,rep} + Z_{DE,fuel} + Z_{DE,O\&M} \\ Z_{IL} = Z_{IL,init} + Z_{IL,comp} \\ Z_{SL} = Z_{SL,init} + Z_{SL,comp} \\ Z_C = K_C \left(\sum_{t=1}^{J} \sigma P_{DE}(t)\Delta T - \varepsilon \sum_{t=1}^{J} \eta P_{sum}(t)\Delta T \right) \end{cases} \quad (4)$$

where $Z_{W,init}, Z_{W,rep}, Z_{W,O\&M}$ are the initial investment, the replacement cost, the operation and maintenance cost of

wind turbines; $Z_{PV,init}, Z_{PV,rep}, Z_{PV,O\&M}$ are the initial investment, the replacement cost, the operation and maintenance cost of photovoltaic batteries; $Z_{SB,init}, Z_{SB,rep}, Z_{SB,O\&M}$ are the initial investment, the replacement cost, the operation and maintenance cost of energy storage batteries; $Z_{DE,init}, Z_{DE,rep}, Z_{DE,fuel}, Z_{DE,O\&M}$ are the initial investment, the replacement cost, the fuel cost and the operation and maintenance cost of diesel generators; $Z_{IL,init}, Z_{IL,comp}$ are the investment cost and the price compensation of IL; and $Z_{SL,init}, Z_{SL,comp}$ are the investment cost and the compensation cost of SL; K_C is the price of carbon trading; σ is the carbon emission coefficient of the diesel engine; $P_{DE}(t)$ is the output power of the diesel generators; ΔT is the time interval between t and $t-1$; ε is the correction coefficient of the load rate; η is the carbon emission benchmark for 1 MWh; $P_{sum}(t)$ is the total output power of the microgrid for time period t; and J is the planning horizon.

3.1.3 Constraints

1) Power balance constraints

At the time period of t, the sum of all the power generated by the DGs (include ESS) is no less than the adjusted load in the microgrid, which is expressed as:

$$P_W(t) + P_{PV}(t) + P_{SB}(t) + P_{DE}(t) \geq P(t)$$
$$- \sum_{i=1}^{M} [S(i,t)C(i)] - P_{SL,out}(t) + P_{SL,in}(t) \quad (5)$$
$$\forall t = 1, 2, \ldots, N$$

where $P_W(t), P_{PV}(t)$ are the output power of wind turbines and photovoltaic batteries.

2) Capacity constraints

The capacities of the DGs are required to meet the upper bound constraints, which are denoted by:

$$S_W \leq S_{Wmax} \quad (6)$$

$$S_{PV} \leq S_{PVmax} \quad (7)$$

$$S_{SB} \leq S_{SBmax} \quad (8)$$

$$S_{DE} \leq S_{DEmax} \quad (9)$$

where $S_{Wmax}, S_{PVmax}, S_{SBmax}, S_{DEmax}$ denote the upper capacity of wind turbines, photovoltaic batteries, the energy storage batteries and diesel generators.

3) Output power constraints

The output power for each DG should be within its capacity, as shown in the following:

$$P_W(t) \leq S_W \quad \forall t = 1, 2, \ldots, N \quad (10)$$

$$P_{PV}(t) \leq S_{PV} \quad \forall t = 1, 2, \ldots, N \tag{11}$$

$$P_{DE}(t) \leq S_{DE} \quad \forall t = 1, 2, \ldots, N \tag{12}$$

4) Battery operating constraints

The allowable limits of SOC are determined by (13). Constraint (14) is associated with charge and discharge power limits. And the maximum charge rate of the battery limit is shown in (15) [28].

$$S_{\min} \leq S(t) \leq S_{\max} \quad \forall t = 1, 2, \ldots, N \tag{13}$$

$$P_{SB\min} \leq P_{SB}(t) \leq P_{SB\max} \quad \forall t = 1, 2, \ldots, N \tag{14}$$

$$-P_{SB}(t) \leq [S_{\max} - S(t)]\alpha_c, \quad \forall t = 1, 2, \ldots, N \tag{15}$$

where $S(t)$ is the remaining capacity of the battery; $S_{\min}, S_{\max}$ are the minimum and maximum values of the remaining battery capacity; $P_{SB\min}, P_{SB\max}$ are the lower bound and upper bound of the battery charging power; and α_c is the maximum battery charge rate.

5) Load curtailment constraints

The curtailment capacity of user i should be lower or equal to the maximum amount of its offers.

$$C(i) \leq C_{\max}(i) \quad \forall i = 1, 2, \ldots, M \tag{16}$$

where $C_{\max}(i)$ is the upper bound of the interruptible capacity for user i.

6) Interruption duration constraints

The interruption duration of user i needs to be within the maximum allowed value.

$$T_d(i) \leq T_{d\max}(i) \quad \forall i = 1, 2, \ldots, M \tag{17}$$

where $T_{d\max}(i)$ is the upper bound of the interruption duration for user i each time.

7) Total number of interruptions constraints

The total number of interruptions of user i should not be more than the maximum allowable number of interruptions per year.

$$\sum_{t=1}^{N} \frac{S(i,t)\Delta T}{T_d(i)} \leq y(i) \quad \forall i = 1, 2, \ldots, M \tag{18}$$

where $y(i)$ is the maximum allowable number of interruptions per year for user i.

8) Interruption time interval constraints

The time interval between two load interruptions is restricted to meet its upper bound.

$$\sum_{t}^{t+n(i)} U(i,t) \leq 1 \quad \forall t = 1, 2, \ldots, N - n(i), \forall i = 1, 2, \ldots, M \tag{19}$$

where $U(i,t)$ is 1 if each load interruption for user i starts from the period t and 0 otherwise; $n(i)$ is the minimum time interval requirement between two interruptions for user i.

9) SL balance constraints

$$\sum_{t \in T_1} P_{SL,out}(t) = \sum_{t \in T_2} P_{SL,in}(t) \tag{20}$$

where T_1, T_2 represents the peak load periods and the off-peak load periods respectively.

3.2 Pure peak clipping model considering IL and SL for microgrid

IL and SL are directly used for reducing or shifting the peak load as much as possible in the pure peak clipping model. In combination with the load data after clipping, the traditional planning is employed for the resources allocation. Because the process of the second step is the same as the traditional planning model, only the mathematical model of the first step is shown here.

3.2.1 Decision variables

Decision variables are defined as:

$$X_2 = [P'_{\max}, S(i,t), C(i), T_d(i), P_{SL,out}(t), P_{SL,in}(t)] \tag{21}$$

where $P'_{\max}$ is the maximum load for the microgrid after IL and SL.

3.2.2 Objective function

The objective is to minimize the peak load of the microgrid, which is formulated as:

$$F_2 = \min P'_{\max} \tag{22}$$

3.2.3 Constraints

For the pure peak clipping model, related constraints of IL and SL are the same as (16)–(20). In addition, new constraints are given.

1) The maximum load constraints:

The peak load after IL and SL is always greater than the level of system load at any time, which are formed by:

$$P'_{\max} \geq P(t) - \sum_{i=1}^{M} [S(i,t)C(i)] - P_{SL,out}(t) + P_{SL,in}(t)$$
$$\forall t = 1, 2, \ldots, N$$

$$(23)$$

4 Numerical examples

4.1 Data for the microgrid

In this section, numerical examples are provided to illustrate the performance of the proposed method. The maximum load of the considered microgrid is 221 kW. The forecasting data for wind and solar come from a region in Shanghai, China. The region is at longitude 121°4ı East and latitude 31°2ı North. Prediction data of solar and wind power resources are available by using the forecasting data from HOMER software. The average irradiance is 4.161 kWh/m^2/d, and the average wind speed is approximately 3.7 m/s. The planning period for the microgrid is 25 years. According to the Shanghai Emissions trading scheme, the average price of carbon trading is 4.6205 $/ton [29]. The carbon emission benchmark is 0.7478 ton/MWh [30], which takes into consideration an average of the operating margin emission factor and build margin emission factor. The carbon emission coefficient of the diesel engine is 1.052 ton/MWh [31].

Table 1 shows the upper limit for the capacity of the distributed generation, which is subject to regional restrictions, such as natural conditions, the installation space, etc. The selection of diesel capacity is regardless of the actual product capacity number.

The corresponding economic parameters are specified in Tables 2 and 3. The price of diesel fuel is 1.1804 $/L, and the investment cost for IL is 165 $/kW [32] in the simulation.

Table 4 represents the IL bidding offer for two groups of users [18]. Table 5 shows the price compensation of one group of SL users [33].

And an analysis of multiple groups of users participating in IL and SL will be provided in the later subsection, respectively.

4.2 Results

In this paper, the proposed models are classified as mixed integer linear programming optimization problems, which can be solved by LINGO software.

In Table 6, the results for the traditional planning model, IRP model, and pure peak clipping model under the load data are depicted in Case 1, Case 2 and Case 3, respectively.

As shown in Table 6, the total cost for Case 3 during the planning period is less than that for Case 1. And the overall planning cost for Case 2 is less than that for Case 3. It clearly demonstrates that IRP considering IL and SL can achieve more economic benefits than the traditional planning model and pure peak clipping model. Because the pure peak clipping model is only to minimize the peak load, not considering comprehensive economic characteristics of the microgrid energy, this results in the peak load only attaining the minimum value, whereas the total cost may increase.

As for the planning allocation results from Table 6, the capacity of both the wind turbines and photovoltaic cells have reached their maximum available capacity, because there is no fuel cost and lower operation and maintenance cost for wind turbines and photovoltaic cells compared with the diesel engine. The maximum available capacity is chosen for the storage battery because the charging and discharging characteristics of the storage battery can be applied to balancing the fluctuation characteristics of the intermittent power supply and serving for peak load shifting. The capacities of the diesel engines are primarily different in all cases. Because of IL and SL participating in the planning, a corresponding decrease in the capacity and the output power of the diesel engine is realized. IL capacities reach the upper limits in all cases with IL measures, which show a significant impact of IL on the outcomes of microgrid planning. And partial loads are shifted from peak hours to off-peak hours by SL.

4.3 Analysis and discussions

In this section, an in-depth analysis of major contributing factors of IL and SL on IRP are illustrated. Case 2 is regarded as the base case for comparison. Sensitivity analysis of parameters in the IRP model is investigated.

Table 1 Capacity upper limit of various DGs

DG	Wind turbine (kW)	PV cell (kW)	Energy storage (kWh)	Diesel engine (kW)
Capacity upper limit	33	100	100	210

Table 2 DGs parameters of various DGs

DGs	Size (kW)	Capital ($)	Replacement ($)	O&M ($/year)	Lifetime (year)
PV cell	1	1011	842	10	20
Wind turbine	1	1882	1569	50	20
Diesel engine	1	345	288	0.05	1.7

Table 3 DGs parameters of lead acid battery

Quantity	Capital ($)	Replacement ($)	O&M ($/year)	Lifetime (year)
1 (1.2 kWh)	230	192	50	8

Table 4 Bidding offer for two groups of IL users

Group	Total number of interruptions	Interruption duration (h)	Capacity (kW)	Compensation costs ($/kWh)
1	2	2	20	0.24
2	2	4	18	0.224

Table 5 Bidding offer for one group of SL users

Group	Time for curtailed load	Starting time for increased load	Ending time for increased load	Capacity (kW)	Compensation costs ($/kWh)
1	20:00	1:00	3:00	10	0.06

4.3.1 Changing the IL users bidding

The introduction of power market reform has promoted a modest growth for bidding freedom. Based on Case 2, the bidding prices for two groups of users are adjusted to 10 times (Case 7), 20 times (Case 8) and 30 times (Case 9) respectively. The planning results are presented in Table 7.

It can be seen that higher prices of bidding will result in more costs in the microgrid planning and the user can receive more compensation for load interruption. Even as the bidding costs increase, the optimization result of IL capacity, total number of interruptions and interruption duration remain unchanged. Based on calculation results, only when the bidding prices grow to 15 times, will the users for Group 2 be unable to participate in IL. Meanwhile, when the bidding costs are more than 27 times, all users cannot be involved in IL and the total cost of the IRP will be equal to the traditional planning. Therefore, IRP provides a preferable economic benefit.

4.3.2 Changing the total number of IL interruptions

On the basis of Case 2, the total number of interruptions for two groups of users are changed to 1 (Case 10) / 3 (Case 11) /4 (Case 12); Table 8 shows the new results of the IRP method. Note that the rise in the number of interruptions leads to a decrease for the overall planning costs. And the total numbers of interruptions of the three cases all attain the upper limit, which indicates that IL is a better choice.

4.3.3 Changing the IL interruption duration

Based on Case 2, the interruption duration for two groups of users is adjusted to 4 hours (Case 13) and 8 hours (Case 14), respectively. Table 9 shows the new results and the solution.

Herein, longer interruption duration corresponds to greater economic benefit. The maximum value of interruption duration of IL is selected in the optimization program. The choice of 4 actual situations of factory timetables in China is conducive to the implementation of IL measures.

Table 6 Planning results of three models under the load data

Case	IL			SL			Wind turbine (kW)	PV cell (kW)	Energy storage (kWh)	Diesel engine (kW)	Total planning costs ($)
	Capacity (kW)	Total number of interruptions	Interruption duration (hour)	Total number of translations	Time period of curtailed load (hour)	Time period of increased load (hour)					
1	–	–	–	–	–	–	33	100	100	198	5440318
2	Group1: 20 Group2: 18	Group1: 2 Group2: 2	Group1: T6572-6573; T6789-6790 Group2: T714-717; T6861-6864	3	T1820 T6476 T8732	T1825 T6483 T8738	33	100	100	186	5413489
3	Group1: 20 Group2: 18	Group1: 2 Group2: 2	Group1: T6475-6476; T6788-6789 Group2: T714-717; T6570-6573	4	T212 T6116 T6140 T8732	T218 T6121 T6145 T8737	33	100	100	188	5418449

4.3.4 Multiple groups of users participating in IL

In reality, there could be more users participating in IL. It assumed that five groups of users sign the IL contract to take part in IL. And the bidding schemes for multiple groups of users are presented in Table 10.

In Table 11, planning results of five groups of IL users (all the users in Table 10) are shown in Case 15.

When the number of users participating in IL is increased, the total cost of the IRP is decreased. The optional numbers of users all reach the upper limit, together with the maximum amount of interruption times and interruption duration. The specific load curtailment for each of the users is determined by comprehensive situations of the interruption capacity, interruption duration, user bidding and load characteristics. It can be seen that if conditions permit, a greater number of users participating in IL will play a greater role in load curtailment.

4.3.5 Changing the SL users bidding

The end users are becoming aware of the energy resource they can manage and are now able to take part in the sustainable operation of the microgrids. And the microgrid should be able to recognize customer choice for different price compensation accordingly.

Based on Case 2, the price compensation for SL is adjusted to 10 times (Case 16), 20 times (Case 17) and 30 times (Case 18), respectively. The planning results are also presented in Table 12. The total planning cost increases with the rise in the price compensation. And SL users can obtain more economic benefit for load translation. Nevertheless, as the bidding costs increase, the total number of translations and shiftable duration are basically unchanged. So jointly planning SL for IRP potentially results in a more economic energy system.

4.3.6 Changing the translation period

Based on Case 2, the time for the curtailed load is changed from 20:00 to 8:00. And the time region for the increased load is adjusted from 1:00–3:00 to 11:00–13:00. The optimization results with different translation periods are presented in Table 13. Along with a rise in the number of translations, the overall planning cost of Case 19 is more than that of Case 2. In the daytime, the output power of solar is comparatively abundant, which indicates the demand for peak decrement is comparatively weak. The translation period of Case 19 is not considering the comprehensive situation of renewable energy characteristics of the microgrid, which results in the total cost increase.

4.3.7 Multiple groups of users participating in SL

Actually, there could be more users participating in SL in electricity markets. It is supposed that two groups of users take part in SL for IRP. The price compensation

Table 7 Planning results comparison after raising biddings for two groups of IL users

Case	IL (kW)	Diesel engine (kW)	Total planning costs ($)	Compensation cost for group ($)	Total number of interruptions	Interruption duration (hour)
7	Group1: 20 Group2: 18	188	5426815	15102	Group1: 2 Group2: 1	Group1: T6572-6573; T6788-6789 Group2: T714-717
8	Group1: 20 Group2: –	193	5435696	8100	Group1: 1 Group2: –	Group1: T716-717 Group2: –
9	–	198	5440318	–	–	–

Table 8 Planning results comparison after changing the total number of interruptions for two groups of IL users

Case	IL (kW)	Diesel engine (kW)	The total planning costs ($)	Total number of interruptions	Interruption duration (hour)
10	Group1: 20 Group2: 18	190	5426421	Group1: 1 Group2: 1	Group1: T717-718 Group2: 6788-6791
11	Group1: 20 Group2: 18	178	5391558	Group1: 3 Group2: 3	Group1: T717-718; T6572-6573; T8732-8733 Group2: T6474-6477; T6788-6791; T6860-6863
12	Group1: 20 Group2: 18	172	5375329	Group1: 4 Group2: 4	Group1: T716-717; T6573-6574; T6788-6789; T6861-6862 Group2: T717-720; T6474-6477; T6812-6815; T8730-8733

Table 9 Planning results comparison after changing interruption duration for two groups of IL users

Case	IL (kW)	Diesel engine (kW)	The total planning costs ($)	Total duration of interruption (hour)	Interruption duration (hour)
13	Group1: 20 Group2: 18	186	5417926	Group1: 4 Group2: 4	Group1: T714-717; T6571-6574 Group2: 6786-6789; T8729-8732
14	Group1: 20 Group2: 18	186	5409552	Group1: 8 Group2: 8	Group1: T6469-6476; T6572-6579 Group2: T714-721; T6788-6795; T6469-6476

details for two groups of SL users are shown in Table 14.

In Table 15, planning results of two groups of SL users are shown in Case 20. The total cost of IRP is reduced with the increase of the number of SL users. And the alternative numbers of SL users all achieve their maximum. And the SL users of Group 2 reach the upper limit of translation times due to greater optional translation capacity. It can be seen that if a larger amount of users participating in SL, the savings in planning costs will be more favorable for the microgrid.

Table 10 Bidding offers of multiple groups of IL users

Group	Total number of interruption (year)	Interruption duration (hour)	Capacity (kW)	Compensation costs ($/kWh)
1	2	2	20	0.24
2	2	4	18	0.224
3	2	2	22	0.208
4	3	4	23	0.192
5	4	4	17	0.256

Table 11 Planning results comparison of multiple groups of IL users

Case	IL (kW)	Diesel engine (kW)	The total planning costs ($)	Total number of interruptions	Interruption duration (hour)
15	Group1: 20 Group2: 18 Group3: 22 Group4: 23 Group5: 17	166	5364723	Group1: 2 Group2: 2 Group3: 2 Group4: 3 Group5: 4	Group1: T716-717; T6573-6574 Group2: T6115-6118; T6788-6791 Group3: T6789-6790; T6861-6862 Group4: T714-717; T6475-6478; T6645-6648 Group5: T5922-5925; T6571-6574; T6811-6814; T8730-8733

Table 12 Comparison of planning results after raising biddings for one group of SL users

Case	Diesel engine (kW)	The total planning costs ($)	The compensation cost for SL ($)	Total number of translations	The time period of curtailed load (hour)	The time period of increased load (hour)
16	186	5413773	1950	2	T6476 T8732	T6482 T8738
17	186	5414073	2250	2	T6476 T8732	T6482 T8739
18	189	5420952	–	–	–	–

Table 13 Comparison of planning results after changing the translation period for one group of SL users

Case	Diesel engine (kW)	The total planning costs ($)	The compensation cost for SL ($)	The capacity of translation (kW)	Total number of translations	The time period of curtailed load (hour)	The time period of increased load (hour)
19	189	5422087	1725	10	5	T2072 T2120 T2552 T3248 T7640	T2077 T2123 T2555 T3253 T7465

Table 14 Bidding offer for two groups of SL users

Group	Time for the curtailed load	Starting time for the increased load	Ending time for the increased load	Capacity (kW)	Compensation costs ($/kWh)
1	20	1	3	10	0.06
2	20	1	3	20	0.08

Table 15 Comparison of planning results of multiple groups of SL users

Case	Diesel engine (kW)	The total planning costs ($)	The capacity of translation (kW)	Total number of translations	The time period of curtailed load (hour)	The time period of increased load (hour)
20	184	5410689	Group1: 10 Group2: 20	Group1: 2 Group2: 5	Group1: T212;T6140 Group2: T1820; T6116; T6476; T8684; T8732	Group1: T217; T6145 Group2: T1825; T6121; T6483; T8691; T8738

Table 16 Comparison of planning results after raising carbon trading prices

Case	IL			SL			Diesel engine (kW)	The total planning costs ($)
	Capacity (kW)	Total number of interruptions	Interruption duration (hour)	Total number of translations	The time period of curtailed load (hour)	The time period of increased load (hour)		
21	Group1: 20 Group2: /	Group1: 1 Group2: /	Group1: T6572-6573; Group2: /	2	T6476 T8732	T6482 T8738	193	5439318

4.3.8 Changing the price for carbon trading

In response to increasing resources and environmental constraints domestically, together with fulfilling international commitments for greenhouse gas emissions abatement, local carbon emissions trading pilots have been launched in China. The monthly price fluctuation is large and the average prices of each pilot differs significantly [34]. To compare the effects of IL and SL in different carbon trading prices, the price for carbon trading is adjusted to 10 times (Case 21) based on Case 2. The planning results are described in Table 16. According to Case 21, SL and IL users can still take part in IRP when the bidding for them is adjusted simultaneously to 30 times (more than Case 2). The critical value for IL bidding cost is increased by enhancing the price for carbon trading. It is also indicated that higher carbon trading prices are helpful for promoting the impact of IL and SL in a low-carbon economy environment.

5 Conclusion

In this paper, an IRP method combined with the impact of IL and SL is presented for microgrids planning. Compared with the traditional microgrid planning model and the pure peak clipping model with IL and SL, IRP considering IL and SL has shown advantages in reducing microgrid planning costs. This method has broadened the application of demand response in actual practices. Moreover, a reference is provided to microgrids planning based on operational simulations and with the active participation of interruptible loads and shiftable loads.

A time series modeling of IL and SL for 8760 hours based on an annual chronological load curve is applied, which can reveal a more truthful impact of load behavior.

Then, the proposed method as a systematic method can be effectively applied to a quantitative assessment of the effect of IL and SL in microgrid planning. The sensitivity analysis results show that when there is an increase in the number of both IL and SL users, the total number of

interruptions, the interruption duration, and suitable translation duration economic benefits of IRP will increase. And IL and SL can play a bigger role in a low-carbon economy environment.

Further work will more deeply investigate IL and SL, together with other types of DR participating in IRP. Moreover, uncertainties regarding the load control will be considered in microgrid planning.

References

[1] Zhao B, Dong X, Bornemann J (2015) Service restoration for a renewable-powered microgrid in unscheduled island mode. IEEE Trans Smart Grid 6(3):1128–1136

[2] Khodaei A, Bahramirad S, Shahidehpour M (2015) Microgrid planning under uncertainty. IEEE Trans Power Syst 30(5):2417–2425

[3] Wang Z, Chen B, Wang J et al (2015) Robust optimization based optimal DG placement in microgrids. IEEE Trans Smart Grid 5(5):2173–2182

[4] Che L, Zhang X, Shahidehpour M et al (2015) Optimal interconnection planning of community microgrids with renewable energy sources. IEEE Trans Smart Grid 8(3):1054–1063

[5] Millar RJ, Kazemi S, Lehtonen M et al (2012) Impact of MV connected microgrids on MV distribution planning. IEEE Trans Smart Grid 3(4):2100–2108

[6] Yang P, Nehorai A (2014) Joint optimization of hybrid energy storage and generation capacity with renewable energy. IEEE Trans Smart Grid 5(4):1566–1574

[7] Zheng Y, Hu Z, Wang J et al (2014) IRSP (integrated resource strategic planning) with interconnected smart grids in integrating renewable energy and implementing DSM (demand side management) in China. Energy 76(C):863–874

[8] Federal Energy Regulatory Commission (2012) Assessment of demand response and advanced metering staff report. http://www.ferc.gov/legal/staff-reports/12-20-12-demand-response.pdf

[9] Zhu L, Yan Z, Lee WJ et al (2015) Direct load control in microgrids to enhance the performance of integrated resources planning. IEEE Trans Ind Appl 51(5):3553–3560

[10] Qin Z, Xifan W, Jianxue W et al (2008) Survey of demand response research in deregulated electricity markets. Autom Elect Power Syst 32(3):97–106

[11] Aghajani GR, Shayanfar HA, Shayeghi H (2015) Presenting a multi-objective generation scheduling model for pricing demand response rate in micro-grid energy management. Energy Convers Manag 106:308–321

[12] Alharbi W, Raahemifar K (2015) Probabilistic coordination of microgrid energy resources operation considering uncertainties. Elect Power Syst Res 128(4):1–10

[13] Subramanian A, Garcia MJ, Callaway DS et al (2013) Real-time scheduling of distributed resources. IEEE Trans Smart Grid 4(4):2122–2130

[14] Kinhekar N, Padhy NP, Li F et al (2016) Utility oriented demand side management using smart AC and micro DC grid cooperative. IEEE Trans Power Syst 31(2):1151–1160

[15] Huang KY, Chin HC, Huang YC (2004) A model reference adaptive control strategy for interruptible load management. IEEE Trans Power Syst 19(1):683–689

[16] Zhong H, Xie L, Xia Q (2013) Coupon incentive-based demand response: theory and case study. IEEE Trans Power Syst 28(2):1266–1276

[17] Haghighat H, Kennedy SW (2012) A bilevel approach to operational decision making of a distribution company in competitive environments. IEEE Trans Power Syst 27(4):1797–1807

[18] Wang J, Wang X, Wang X (2005) Study on model of interruptible load contract in power market. Proc CSEE 25(9):11–16

[19] Bhana R, Overbye TJ (2016) The commitment of interruptible load to ensure adequate system primary frequency response. IEEE Trans Power Syst 31(3):2055–2063

[20] Yang L, He M, Vittal V et al (2016) Stochastic optimization-based economic dispatch and interruptible load management with increased wind penetration. IEEE Trans Smart Grid 7(2):730–739

[21] Aminifar F, Fotuhi-Firuzabad M, Shahidehpour M (2009) Unit commitment with probabilistic spinning reserve and interruptible load considerations. IEEE Trans Power Syst 24(1):388–397

[22] Pedrasa MAA, Spooner TD, MacGill IF (2009) Scheduling of demand side resources using binary particle swarm optimization. IEEE Trans Power Syst 24(3):1173–1181

[23] Bruno S, Dassisti M, La Scala M et al (2014) Predictive dispatch across time of hybrid isolated power systems. IEEE Trans Sustain Energy 5(3):738–746

[24] Zhu Z, Tang J, Lambotharan S et al (2012) An integer linear programming based optimization for home demand-side management in smart grid. Innovative smart grid technologies (ISGT), 2012 IEEE PES, Washington, DC, USA, 16–20 Jan 2012, 5pp

[25] Graditi G, Silvestre MLD, Gallea R et al (2015) Heuristic-based shiftable loads optimal management in smart micro-grids. IEEE Trans Ind Inform 11(1):271–280

[26] Tasdighi M, Ghasemi H, Rahimi-Kian A (2014) Residential microgrid scheduling based on smart meters data and temperature dependent thermal load modeling. IEEE Trans Smart Grid 5(1):349–357

[27] Han S, Han S, Sezaki K (2010) Development of an optimal vehicle-to-grid aggregator for frequency regulation. IEEE Trans Smart Grid 1(1):65–72

[28] Lilienthal P (2011) HOMER V.2.68beta. Boulder, CO, USA: HOMER ENERGY, LLC. http://www.homerenergy.com/

[29] Shanghai Environment and Energy Exchange (2015) Shanghai carbon market report. http://www.cneeex.com/searchresult_detail.jsp?main_artid=7146

[30] Climate Change Department of National Development and Reform Commission (2014) Baseline emission factors for regional power grids in China. http://www.ccchina.gov.cn/archiver/cdmcn/UpFile/Files/Default/20150204155537627092.pdf

[31] Sarge SM, Höhne GWH, Hemminger W (eds) (2014) Calorimetry: fundamentals, instrumentation and applications. Wiley, Weinheim

[32] Wang B, Li Y, Gao C (2009) Demand side management outlook under smart grid infrastructure. Autom Elect Power Syst 33(20):5–14

[33] Schneider F, Klabjan D, Thonemann UW (2013) Incorporating demand response with load shifting into stochastic unit commitment. Social Science Electronic Publishing, New York

[34] Zhao X, Jiang G, Nie D et al (2016) How to improve the market efficiency of carbon trading: a perspective of China. Renew Sustain Energy Rev 59:1229–1245

Lan ZHU received the B.S. degree from Northeast Dianli University, Jilin, China, in 2000, and the M.S. degree from North China Electric Power University, Beijing, China, in 2003, both in electrical engineering. She is currently working towards the Ph.D. degree at Shanghai Jiao Tong University, Shanghai, China. Since 2004, she has been with Shanghai University of Electric Power, Shanghai, where she is currently an Associate Professor with the College of Electrical Engineering. Her current research interests include power system analysis and control, microgrid, renewable energy, and demand response.

Xueying ZHOU received the B.S. and the M.S. degrees from Shanghai University of Electric Power, Shanghai, China, in 2014 and 2017, respectively. She is an engineer in Pudong Power Supply Company of State Grid Shanghai Municipal Electric Power Company. Her research interests include microgrid, demand response and power grid operation.

Xiao-Ping ZHANG received the B.Eng., M.Sc., and Ph.D. degrees in electrical engineering from Southeast University, China, in 1988, 1990, 1993, respectively. He worked at China State Grid EPRI (formerly NARI) on EMS/DMS advanced application software research and development between 1993 and 1998. From 1998 to 1999 he was visiting UMIST. From 1999 to 2000 he was an Alexander-von-Humboldt Research Fellow with the University of Dortmund, Germany. He was then an Associate Professor in the School of Engineering at the University of Warwick, U.K. He is currently a Reader in Electrical Power Systems at the University of Birmingham, Birmingham, U.K., and he is also Director of the University Institute for Energy Research and Policy. He is coauthor of the monograph Flexible AC Transmission Systems: Modeling and Control (Springer, 2006).

Zheng YAN received the B.Sc. degree from Shanghai Jiao Tong University, Shanghai, China, in 1984, and the M.Sc. and Ph.D. degrees from Tsinghua University, Beijing, China, in 1987 and 1991, respectively, all in electrical engineering. Before joining the Electrical Engineering Department, Shanghai Jiao Tong University, Shanghai, China, in 2004, as a Full Professor, he was on research cooperation with Ibaraki University in Japan (1994–1996), Cornell University (1997–2001), and University of Hong Kong (2001–2004). His research interests are in application of optimization theory to power systems and power markets, and dynamic security assessment.

Shuxin GUO received the B.S. degree from Shanghai University of Electric Power, Shanghai, China, in 2014. Since 2014, she has been an engineer in Zibo Power Supply Corporation of State Grid Shandong Electric Power Corporation. Her research interests include the field of power market.

Longjun TANG received the B.S. degree from Northeast Dianli University, Jilin, China, in 2000, and the M.S. degree from Zhejiang University, Zhejiang, China, in 2003. He is a senior engineer in East Electric Power Dispatch and Control Sub-Center of State Grid Corporation of China. His research interests include power system security and stability analysis and power grid dispatching operation.