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Optimal Sizing of DGs and Storage for Microgrid with Interruptible Load Using Improved NSGA-II

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***Abstract*—The rapid development of distributed generation (DG) has deeply transferred the power utilization style. Microgrid is developed for better absorption of distributed generation and has been researched in recent years. Interruptible load (IL) is another method to absorb the randomness and waviness of wind and solar energy, and is considered in this paper for more reliable and efficient deployment of DGs and storage in microgrid. A multi-objective optimization model is proposed for microgrid power sources construction with distributed generation, storage and interruptible load. Objectives of the model are economic cost, environmental cost and annual interruption duration. The model is solved by employing improved NSGA-II with the input of temperature, light intensity, wind speed, and load curve. The case study shows that the Pareto optimal front which covers the optimal solutions under different circumstances is effectively obtained. Thus the supervisor can select the final scheme with full consideration of different objectives. The impacts of IL on economic and environmental cost are also analyzed and demonstrated with many aspects.**

Keywords—microgrid; interruptible load; distributed generation; improved NSGA-II

I. INTRODUCTION

Distributed Generation (DG) and demand response are two significant features and driving forces of Smart Grid [1]. Interruptible Load (IL) is an important measure of demand response with fast response and high user enthusiasm, and is employed to maintain the balance between the supply and demand of active power at a lower cost [2]. The focus of intense debates on IL application lies in electricity market pricing and grid scheduling.

In the electricity market pricing, [2] summarizes the current and potential interruptible load application methods, as well as the economy of the combination with DGs in optimizing energy configuration. Reference [3] reveals the great economic benefits brought by IL which not only effectively suppresses volatility of the node price, but also reduces network losses and electricity cost. The bidding behavior of generation companies and distribution companies is studied in [1], and an electricity market game model of DGs and IL with incomplete information is built and solved with Improved Co-Evolution Algorithm.

For grid scheduling optimization, [4] observes the peaking performance of IL in a wind farm containing large-capacity coal-fired units. When the output of wind turbines reaches the minimum and the load demand the opposite, the compensation cost of IL is lower than peaking cost of coal-fired units. Under this circumstance, IL is called while coal-fired units are still peaking margin. Reference [5] focuses on energy optimization of a microgrid containing IL, where IL is confined to cooling or heating use and one winter day is adopted as an example for optimization. One defect which hinders the wind power from being fully utilized is the absence of energy storage. When the output of wind turbines reaches the maximum, a low load demand and a tie-line power delivery restriction will waste the surplus. User experience is an important and often neglected issue in calling for IL during microgrid energy optimization. Conventional optimization goals of using IL are to minimize the total compensation cost and interrupt frequency. The study is usually a multi-user multi-period problem, while [6] casts a light on user experience issue through introduce of individual concern. It restricts the total interrupt length, single interrupt duration as well as the interval between interrupts for an individual IL, which is quite meaningful in dealing with IL participation experience.

This paper proposes an optimal sizing model of DGs and storage for microgrid with the participation of IL. Microgrid is a meaningful attempt to change the way we get access to power, and this cannot be achieved without the effort from the demand side. The method and solution proposed in this paper can be used for future study and planning reference.

II. MODEL OF DG, STORAGE, AND IL IN A MICROGRID

A. A Microgrid Considering DGs, Storage, and IL

An increasing number of DGs serve our need of electricity. While the DG characteristics of randomness and waviness are quite maladaptive to traditional power utilization, the emergence of microgrid offers new

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opportunities. A microgrid is usually made up by DGs, storages and loads. As the involvement of power user is often emphasized, the response of demand side is accounted, namely interruptible load. At the same time, a microgrid is usually small and can be seen as an IL, making the whole grid a multi-fractal system. The similar architecture on each level may best reflect the practice and help optimize the power dispatch.

This paper mainly focuses on the plan and design of the inside architecture of a microgrid, accounting for the IL involvement and optimizing the size of DGs and storages. The microgrid includes multiple kinds of DGs along with inverters and controllers, such as wind turbines, PV arrays, micro gas turbines, diesel generators and fuel cells.

The constraint in dispatch is a balance between supply of units and need of loads, as shown in (1).

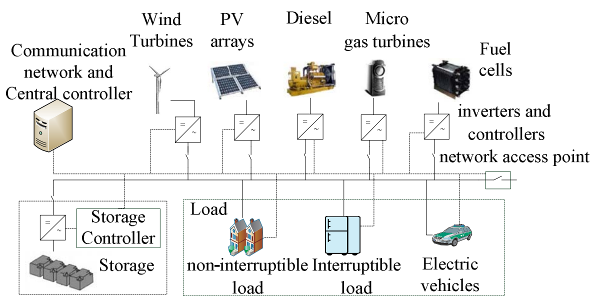

Fig 1 DG model

$$\sum_{i=1}^{N} P_i(t) = L_{total}(t) \tag{1}$$

$P_i(t)$ indicates output of the *ith* DG and $L_{total}(t)$ the load at interval t.

B. DG Models

1) Wind Turbine

Output of wind turbines depends on wind speed v, and this relationship can be approximated with (2) and (3) [7].

$$P_{wt} = \begin{cases} 0, & 0 \le v \le v_{ci} \\ n_{wt} p_r \eta(v), & v_{ci} \le v \le v_r \\ n_{wt} p_r, & v_r \le v \le v_{co} \\ 0, & v_{co} \le v \end{cases} \tag{2}$$

$$\eta(v)=(v-v_{ci})/(v_r-v_{ci}) \tag{3}$$

In the following content, Bergey Excel wind turbines from Bergey Windpower [8] are employed for modeling and optimization. According to its factory data, rated power p_r equals to 10kW, and cut-in speed v_{ci}, rated wind speed v_r, cut-out speed v_{co} equal to 2.5m/s, 12m/s, 18m/s, respectively. And the output of wind turbines is denoted as P_{wt}.

2) PV Array

Output of PV arrays is expressed in (4) [9], which depends on the installation number n_{PV} and the efficiency η_{PV} at time t. The efficiency is related to light G_a, temperature T_a and wind speed v, as shown in (5) [9]. And the temperature T_c is defined in (6) and (7) [9], while c_1, c_2, and c_3 are constant coefficients.

$$P_{PV} = n_{PV} p_{STC} \eta_{PV} \tag{4}$$

$$\eta_{PV} = (1 + k(T_c - T_{STC}))G_a / (G_{STC}) \tag{5}$$

$$T_c = T_a + \alpha G_a \tag{6}$$

$$\alpha = f(v) = c_1 + c_2 \exp(c_3 v) \tag{7}$$

According to MSX-83 photovoltaic parameters from Solarex, the power temperature coefficient k is -0.5%, STC stands for Standard Test Condition with illumination of 1kW/m^2 (1 sun) at spectral distribution of AM1.5, cell temperature is 25℃, and p_{STC} equals to 83W [10].

C. Storage Model

Battery capacity is temperature dependent, and this relationship can be approximated with (8) [11]. The temperature coefficient λ_C is normally set as 0.6% [11]. Actual amount of storage of current period depends on previous period state and the storage and extraction of current period, as expressed by (9).

$$C_{bat} = C_{STC}[1+\lambda_C(T_{bat} - T_{STC})] \tag{8}$$

$$E_{bat,t+1} = E_{bat,t} + P_{in}\Delta t - P_{out}\Delta t \tag{9}$$

While battery assistant dispatchers in better tracking changes in generator output and load demand, several constraints should be accented to protect and prolong life expectancy of batteries. There are two main constraints. One is about state of charge (SOC), namely the charged amount should never exceed the upper and lower limit of battery utilization. Equation (10) [11]expresses this constraint, with C_{max}=100%C_{bat} and C_{min}=20%C_{bat} normally. The other is about charging rate, which is given an upper limit for longevity for battery life, as shown in (11) (Δt =1h).[11].

$$C_{min} \le E_{bat} \le C_{max} \tag{10}$$

$$\begin{cases} P_{in} \le 0.2 C_{bat} / \Delta t \\ P_{out} \le 0.2 C_{bat} / \Delta t \end{cases} \tag{11}$$

The case below adopts VRB-50 vanadium battery stack from GEFC, whose standard rated capacity C_{STC} is 50kWh, charge efficiency η_{bat} is 72%, and hourly rate of self-discharge σ is 0.01% [8].

D. Interruptible Load Model

The load in microgrid can be divided as interruptible and non-interruptible. IL can adjust its need and tolerate power supply being cut off in extreme situation. The model here represents the adjustable load in an authentic way.

In this paper, the interruptible and conventional loads comprise the total load demand. And load curve of microgrid is obtained. Under electricity market circumstance, the interruptible part is compensated by the price ordered by IL [12]. The IL recycling purchase bill depends on the interrupted capacity during the cut-off period. The IL altogether can be treated as a virtual power plant (VPP). When the IL is cut off, the VPP generates exactly the same amount of power, whereas the output of VPP remains zero. The output of VPP comprised by IL can be expressed as (12).

$$P_{IL}(t)=\begin{cases} 0 & x(t)=0 \\ n(t)p_{IL} & x(t)=1 \end{cases} \tag{12}$$

While $x(t)$ is a binary variable, with 1 standing for using IL and 0 for not. $n(t)$ represents the number of ILs used during interval t. p_{IL} represents the capacity of a single interruptible load, expressed as (13).

$$\begin{gathered}(n(t)-1)p_{IL}\Delta t < E_{lack,t} \le n(t)p_{IL}\Delta t \\ n(t)\in\{1,2,\cdots,n_{IL}\}\end{gathered} \tag{13}$$

While $E_{lack,t}$ is the lacking amount of electricity before the use of ILs during interval t.

As for the dispatcher of microgrid, a compromise between constructions of DG and development of IL is of considerable benefit, taking account for construction and operation costs of DGs, as well as IL recycling purchase. As for conventional loads, a certain level of reliability and security is sought after. As for IL, shorter interrupted period and lower interrupt frequency are always preferred.

Calling for IL is subject to constraints of single interrupt duration and interval between interrupts [6]. Normally, the model of IL is abstracted and the mentioned constraints are proposed accordingly. In this paper, IL is considered as a whole and some constraints are considered as follows.

The interval between interrupts is confined as (14) [6].

$$\begin{gathered}|j-i|\ge T_{\min} \\ if \quad x(i-1)=1, x(i)=0 \quad and \quad x(j-1)=0, x(j)=1\end{gathered} \tag{14}$$

While T_{min} is the minimum interval between interrupts.

A limit is prescribed to the interrupt duration of IL at a time, expressed as (15) [6].

$$\begin{gathered}\sum_{m=1}^{T_{\max}} x(t+m) \le T_{\max} \\ if \quad x(t-1)=0, x(t)=1\end{gathered} \tag{15}$$

While T_{max} is the maximum interrupt duration.

III. Optimal Planning Issue For Microgrid With Complicated Components

A. Economy Objective

1) Equivalent annual installation cost

The installed cost contains two parts, namely the unit cost and the installation cost, both paid before utilization. When the problem is considered in years, the initial installation cost requires a transfer into equivalent annual cost, as shown in (16) [13] with r being calculated by (17) [13].

$$C_{b,i}=(C_{1,i}+C_{2,i})r(1+r)^{l_i}/((1+r)^{l_i}-1) \tag{16}$$

$$r=RD(1-T)+E(1-D) \tag{17}$$

While $C_{b,i}$, $C_{1,i}$, $C_{2,i}$ and l_i are the equivalent annual cost, unit cost, installation cost and lifespan of the *ith* kind of DGs respectively, and r is equal to 6.7% calculated by (17) [13].

2) Fuel cost

Micro gas turbine, fuel cell and diesel depend on fuel for generation, and the cost is expressed in (18) [8].

$$C_{f,i}=K_{f,i}W_i \tag{18}$$

$C_{f,i}$, $K_{f,i}$ and W_i are the fuel costs, fuel costs factor and annual generation capacity of the *ith* kind of DGs respectively.

3) Compensation expense of IL

The IL is one form of demand side response which can be cut off under certain conditions stipulated in contracts or other arrangements [14]. The IL usually provides certain amount of energy with notification in advance and compensation by power amount. The notification time and cut-off amount are decided through consultation with dispatcher, as well as the compensation price. Therefore, the fuel cost of VPP is the same as the compensation for IL.

$$C_{IL}=K_{IL}W_{IL} \tag{19}$$

Usually, there are two kinds of interruptible load schemes: interruptible load with low price (ILL) and interruptible load with high compensation (ILH) [14], with ILL facing many cut-offs and ILH at the risk of a sudden cut-off. Therefore, in this paper the interruptible load is compensated equally, and its benefits are profound in terms of user experience.

4) Operation and maintenance cost

Operation and maintenance cost of DG is proportional to its installed capacity, as shown in (20) [8].

$$C_{m,i}=K_{m,i}P_i \tag{20}$$

$C_{m,i}$, $K_{m,i}$ and P_i are the maintenance costs, maintenance costs factor and capacity of the *ith* kind of DGs respectively.

Economy is a crucial requirement in microgrid planning, and from the different components of cost comprising the total expenditure of the whole full life-cycle of microgrid mentioned above, the total cost can be described as (21) and its minimum is searched, which makes up one of the objectives in arrangement of DGs and storage.

$$\min C_{econ}=\sum_{i=1}^{N}(C_{b,i}+C_{f,i}+C_{m,i}) \tag{21}$$

B. Environmental Objective

Environmental costs are comprised of environmental loss and pollution penalty, as expressed in (22) [15]. The environmental loss refers to environment degradation caused by pollution and ecological damage caused by excessive recourse consumption. The pollution penalty means exactly the mulct for pollutant emission [15]. The pollutant emissions coefficient, environmental loss, and pollution penalty of different DGs are obtained from [15].

$$C_{e,i} = \sum_{j=1}^{m} E_{j,i} W_i (V_{1j} + V_{2j}) \tag{22}$$

$E_{j,i}$ is the emission factor of the *jth* kind of pollutants of the *ith* kind of DGs, V_{1j} and V_{2j} are the environmental loss and pollution penalty of the *jth* kind of pollutants respectively.

The objective is set to minimize the total annual environmental cost of the microgrid, as shown in (23).

$$\min C_{envi} = \sum_{i=1}^{N} C_{e,i} \tag{23}$$

C. Annual Interruption Duration Objective

Customer satisfaction is necessary for a quality-ensured service, so it is for IL. Calling for IL excessively frequently may bring too much inconvenience even with compensation. In this paper, annual interruption duration is minimized to show solicitude for user satisfaction. As the optimization is dealt by the hour and considered for a year, a total of 8760 hours, the object may be shown in (24).

$$\min N_{IL} = \sum_{t=1}^{8760} x(t) \tag{24}$$

D. Multi-objective Optimization Problem

From the modeling and analysis above, the multi-objective problem is established with practical constraints considered, as shown in (25) and (26)

Objects are listed as follows.

$$\min \quad [C_{econ}, C_{envi}, N_{IL}] \tag{25}$$

Constraints are listed as follows

$$\begin{gathered}
\sum_{i=1}^{N} P_i(t) = L_{total}(t) \\
P_i(t) \le n_i p_i(t) \\
C_{min} \le E_{bat} \le C_{max} \\
P_{in} \le 0.2 C_{bat} / \Delta t \\
P_{out} \le 0.2 C_{bat} / \Delta t \\
|\, j-i \,| \ge T_{\min} \quad if\ x(i-1)=x(j)=1, x(i)=x(j-1)=0 \\
\sum_{m=1}^{T_{\max}} x(t+m) \le T_{\max} \quad if\ x(t-1)=0, x(t)=1
\end{gathered} \tag{26}$$

IV. NSGA-II Algorithm

A. NSGA-II Key Technologies

Fast and elitist non-dominated sorting in genetic algorithms (NSGA-II) is a new multi-objective genetic algorithm [16]. NSGA-II employs fast non-dominated sorting and crowding distance estimate for measurement of the individuals. Comparison operators are proposed for filtrations, thus avoiding the target bias in population selection. Compared with the non-dominated sorting genetic algorithm (NSGA) [17], the computational complexity has significantly decreased. The adoption of elitist strategy in NSGA-II protects non-dominated individuals of parents from disappearing and improves the convergence rate as a result.

B. Improved NSGA-II Applied to the Planning

In this paper, NSGA-II is applied and adapted to the optimal sizing of microgrid containing distributed generation, energy storage devices and interruptible load.

1) Gene encoding and population initialization.

Decision variables here are the capacity of wind turbines, PV arrays, storage devices, micro-turbines, diesels, fuel cells and IL. The capacity of one single unit is determined, which is supposed as P_i for the *ith* kind of DGs. Therefore, capacity of DG is discrete and can be represented by number of units installed. Same goes for IL as the user is confronted with limited schemes of interrupt contracts. Therefore, the chromosome here is a 7-dimension integer discrete variable, with each gene bit represents the number of corresponding units for distributed power generation capacity.

As there is no explicit upper bound of the installed number of each distributed power units, the initialization of the population is rather difficult. The complex coupling relationship between the variables may also hinder the initialization. A random initialization cannot be competent to ensure a quick and sound converge, as the feasible solutions in initial population are rare and a large number of individuals stay away from the optimal area. Under this circumstance, the following methods are adopted in this paper to improve the population quality during initialization.

a) Decision variables estimate

The upper capacity bound of the *ith* DG is speculated by assuming that it is the only distributed power installed and it should be adequate for the peak load $P_{load,max}$.

$$n_{i,\max} = \left\lceil P_{load,\max} / p_i \right\rceil \tag{27}$$

Among them, p_i represents the unit capacity of the *ith* DG.

Interruptible load capacity has an upper bound due to its limited proportion of the total load. The maximum proportion allowed is set to be δ.

$$n_{IL,\max} = \left\lceil \delta P_{load,\max} / p_{IL} \right\rceil \tag{28}$$

Besides, the installation portfolio should contribute an output between the average load $P_{load,ave}$ and the peak load.

$$P_{load,ave} \le \sum_{i=1, i\ne 3}^{7} n_{i,\max} p_i \le P_{load,\max} \tag{29}$$

b) Initial population improvement

Preliminary estimates of decision variables cannot completely remove infeasible solutions in microgrid annual state computation. To further on increasing feasible solutions and improving the initial population quality, non-dominated sorting is applied to the initial population generation [18].

Firstly, a population P with $2N$ individuals is randomly generated, and P is filtered based on feasibility. Then $P0$ with N individuals is selected from P according to the results of fast non-dominated sorting and crowding distance estimate.

2) Mutation

Non-uniform mutation [19] is adopted with appropriate changes. Individual $n = (n_1,...,n_i,...,n_7)$ converts to $n' = (n_1',\cdots,n_i',\cdots n_7')$, and variation point is obtained as below. rnd(2) is the result of randomly generated positive integer taking congruence 2.

$$n_i' = \begin{cases} n_i + \Delta(g, y_i) & rnd(2) = 0 \\ n_i - \Delta(g, y_i) & rnd(2) = 1 \end{cases} \tag{30}$$

With y_i is the initial step of the *ith* kind of DGs, $\Delta\ (g,y_i)$ decreases along with evolution generation g ascending. The modification is due to the fact that the upper bound is difficult to determine and that the vicinity of the original feasible solution is a place with greater probability of obtaining new solutions. Since the decision variables in this paper is discrete, $\Delta\ (g,y_i)$ should represent a non-uniform distributed random variable on $[1, y_i]$ and the probability close to 1 increase along with, which can ensure NSGA-II algorithm able to produce new individuals in the final evolution. Here, set the maximum evolution generation to be G_{max}. Taking into account of impact of different distributed power units installed on target vector, y_i is delivered as the sensitivity of f_1 to each variable. ω is the increasing rate coefficient. rand is the result of randomly generated number on [0,1].

$$\Delta(g, y_i) = (y_i - 1)\exp(1 - G_{\max} / (G_{\max} + 1 - g))rand + 1 \tag{31}$$

$$y_i = \omega(\partial f_1 / \partial n_i) \tag{32}$$

3) Selection mechanism

NSGA-II tends to get trapped in local optimal solution with multimodal complex problems. As the existence of priority between the two evaluation index, fast non-dominated sorting and crowding distance, the individuals with higher non-dominated level possesses a higher survival rate when selecting individuals from the union of current generation R_t to parent set of next generation P_{t+1}. As a result, the population of the dominated individuals rapidly increases while that of other non-dominated layers suffers disaster. The vertical diversity of populations faces great loss.

Elitist strategy [20] is adopted for this headache, which first non-dominated filters R_t and settles the number of non-dominated layers K, then limit the maximum number of individuals each layer reserved, N_i, according to (33). q is the decay rate on [0,1], while N is the population size. This method can ensure the vertical diversity of populations through maintaining number of individuals belonging to each layer.

$$N_i = Nq^{i-1}(1-q)/(1-q^K) \tag{33}$$

4) Battery utilization

The operation of the microgrid is considered for a year, a total of 8760 hours. Assuming that distributed power output and load remain constant in an hour, the output of distributed power per hour can be observed as below.

$$E_{p,t} = P_{wt}(t)\Delta t + P_{PV}(t)\Delta t \tag{34}$$

$E_{p,t}$ is the total output of PV and wind turbines at time .

Charging and discharging state of the battery at time t is influenced by $E_{p,t}$ and $E_{load,t}$ Battery charge and discharge rate is another limitation. Besides, battery charge at time t-1 should be taken into account for battery endurance. Specifically, when $E_{p,t} > E_{load,t}/\eta_{inv}$, battery start to be charged, as shown in (35).

$$\begin{aligned} &E_{bat,t} = E_{bat,t-1}(1-\sigma) + \Delta E \\ &\Delta E = \min((E_{p,t} - E_{load,t}/\eta_{inv})\eta_{bat}, C_{\max} - E_{bat,t-1}(1-\sigma), P_{in,\max}\Delta t) \end{aligned} \tag{35}$$

When $E_{p,t} < E_{load,t}/\eta_{inv}$, battery will be discharged, as shown in (36)

$$\begin{aligned} &E_{bat,t} = E_{bat,t-1}(1-\sigma) - \Delta E \\ &\Delta E = \min(E_{load,t}/\eta_{inv} - E_{p,t}, E_{bat,t-1}(1-\sigma) - C_{\min}, P_{out,\max}\Delta t) \end{aligned} \tag{36}$$

$E_{bat,t}$ and $E_{load,t}$ is battery capacity and the electricity consumed by load at time , η_{inv} is inverter efficiency, $P_{in,max}$ and $P_{out,max}$ is the maximum charge and discharge rate.

5) IL utilization

As can be found from (36), the limitation on battery charge and discharge rate, as well as battery charge block fully satisfaction of power requirements with only renewable and storage. The distributed power delivery order is fuel cells, micro-turbines, IL, and diesels, which is quite obvious due to fuel costs. Therefore, the IL utilization state can be expressed as below, while its utilization amount is determined by IL amount and power shortage.

$$\begin{aligned} &x(t) = \begin{cases} 0 & E_{lack,t} = 0 \\ 1 & E_{lack,t} > 0 \end{cases} \\ &E_{lack,t} = E_{load,t}/\eta_{inv} - E_{p,t} \\ &\qquad - (E_{bat,t} - (1-\sigma)E_{bat,t-1}) - E_{fc,t} - E_{mgt,t} \end{aligned} \tag{37}$$

$E_{fc,t}$ and $E_{mgt,t}$ represent the output of fuel cells and micro gas turbines respectively at time t.

V. Case Study

In this paper, NSGA-II is used to optimize the size of DGs and storage for microgrid with IL. The candidate DGs for microgrid can be wind turbines, PV arrays, micro-turbines, fuel cells, storage and diesels. The IL in the microgrid can be regarded as a virtual plant in microgrid scheduling. The DGs cost parameters are listed in Table I [8]. The statistical data of temperature, wind speed, light intensity and daily load in this case is that of a local area for the year 2011. The corresponding information is shown in Fig 2.

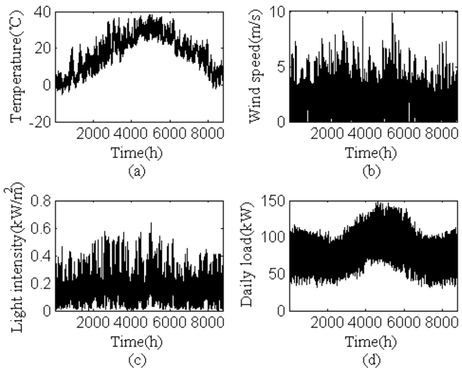

Fig 2 Parameters for the case: (a) is temperature, (b) is wind speed, (c) is light intensity, and (d) is load curve.

A. Results Analysis

The Pareto optimal front obtained is demonstrated in Fig 3, with the corresponding meaning of the labels listed in Table II. The Pareto optimal front is comprised by three specific parts as follows.

1) f_2=0, fuel cells, diesels and micro gas turbines are not adopted in planning.

2) f_3=0, interruptible loads are not adopted in planning.

3) $f_2 \neq 0, f_3 \neq 0$, several kinds of DG are adopted.

The distribution of the optimal front has a significant track characteristic. According to the definition of Pareto optimal solution, the border f_2=0 is a curve where only PV, wind turbines, batteries and IL are adopted, while the border f_3=0 is a curve where IL are relieved. This track characteristic can help the comparison between optimization solutions set under different premise.

As shown in Fig 3, an optimal solution set is obtained through multi-objective optimization, on the contrary to the unique solution obtained in single-objective optimization. Each solution in the set performs better than others on at least one objective, shown by Table III. Therefore, schemes which meet certain tendencies can be adopted accordingly. For example, when the project is cost-sensitive, the option with the smallest economic cost and passable environmental requirements and interruptible load conditions like Scheme 1 is preferred. When environmental protection requirements of the area are high, Scheme 6 and similar cases are preferred as their low environmental costs. However, when users require higher electricity quality, schemes like Scheme 2 which economic and environmental costs are less accounted make more sense.

TABLE II THE CORRESPONDING MEANING OF THE LABELS IN FIG 3

Labels	Meaning of the labels
f_2=0	diesels, fuel cells and micro gas turbines are not adopted in the optimal solution
f_3=0	ILs are not adopted in the optimal solution
Type1	the number of diesels, fuel cells and micro gas turbines in the optimal solution is 0,0,5
Type2	the number of diesels, fuel cells and micro gas turbines in the optimal solution is 0,0,4
Type3	the number of diesels, fuel cells and micro gas turbines in the optimal solution is 0,0,3

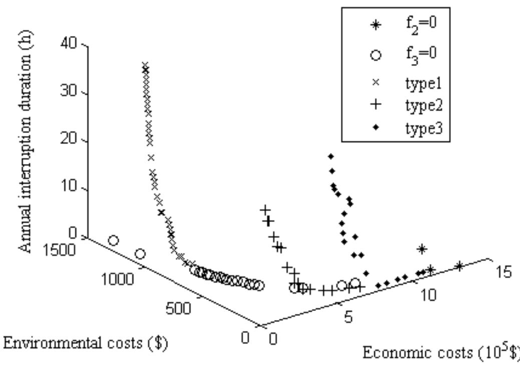

Fig 3 The Pareto optimal front

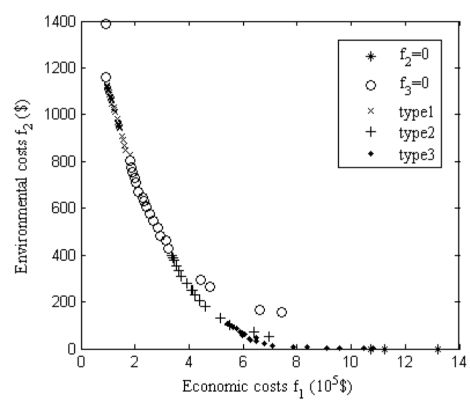

Fig 4 Environmental costs with economic costs

The reason that a solution set is obtained rather than a single solution is the conflicts between objectives. As shown in Fig 4, economic costs and environmental costs always present an inverse relationship with or without IL. PV and wind turbines which have a fluctuate and random output require a large installation for reliability, which is quite obvious from the comparison between Scheme 1 and 6. In

TABLE I BASIC INFORMATION OF SELECT DGS

DG	Type	Unit capacity (kW)	Unit cost ($/kW)	Installation cost ($/kW)	Maintenance cost ($/(kWa))	Fuel cost ($/(kWh))
WT	WD-10	10	2805	3250	5.7	0
PV	MSX-83	0.083	5175	1500	14.3	0
Storage	VRB-50	50(kWh)	1100	200	7.0	0
Diesel	DE-k-60	60	290	574	26.5	0.145
Fuel cell	PAFC-O-200	200	3500	3000	26.5	0.025
MGT	MTL-C-30	30	1200	1333	119.0	0.045
IL	--	1	0	0	0	0.05

TABLE III PART OF THE PARETO OPTIMAL SOLUTIONS

No	WT	PV	Storage	Diesel	Fuel cell	MGT	IL	$f_1(10^5\$)$	$f_2(\$)$	f_3(h)
1	0	906	1	0	0	5	6	1.357	969.5	8
2	0	2082	1	1	0	4	0	1.846	773.1	0
3	2	7113	5	0	0	4	1	4.620	179.5	3
4	26	7276	15	0	0	4	5	6.967	52.45	3
5	54	9580	28	0	0	3	2	10.81	2.04	3
6	0	24336	11	0	0	0	0	13.22	0	0

the perspective of economic cost, contradiction between installment cost and fuel&environment cost also exists. More PV and wind turbines lead to high investment and low fuel&environment cost, and vice visa. When IL is adopted, it is regarded as a virtual power plant which reduces economic costs and increases the environmental costs, which further maintains the inverse relationship between economic costs and environmental costs.

B. The Impact of IL on Economic Costs

As shown in Fig 5, when IL is concerned, relationship between annual interruption duration and the economic costs possesses a gradient relationship with multiple tracks. Each track represents a portfolio of diesels, fuel cells, and micro gas turbines and takes up its corresponding economic costs range. On each track, the economic costs decline along with the increase in annual interruption duration. There are mainly two reasons.

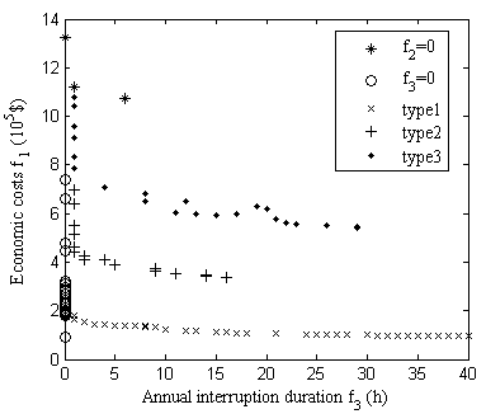

Fig 5 The economic costs with annual interruption duration

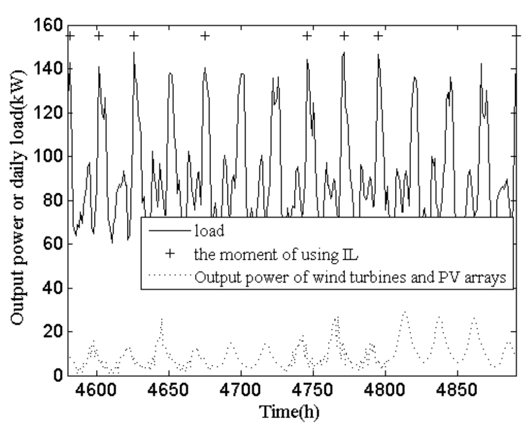

Fig 6 Load curve, the total amount of photovoltaic and wind power generation with the moment of using IL(under Scheme 1).

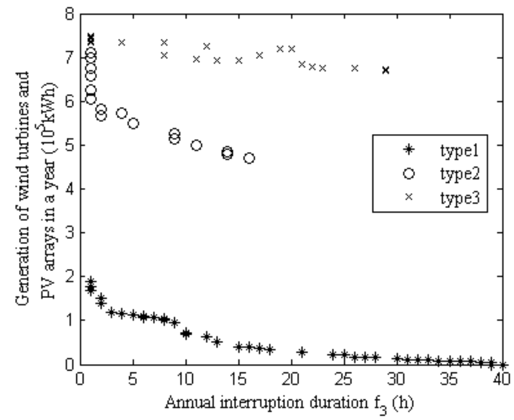

Fig 7 The total amount of PV and wind power generation with annual interruption duration

Firstly, IL is zero-cost in investment and maintaining aspect. It is also quite flexible and less prone to meteorological states such as light, compared to other renewable generation. IL will generate in short term as an alternative power source of PV and wind turbines at the load peak. As shown in Fig 6, this is also the case when PV or wind turbines go through a sudden decrease, exerting IL for peaking. The substitution effect of IL at load peak reduces the installment requirement of the renewable, thus reducing the economic costs.

Secondly, on each track, the installation of PV and wind turbines declines along with the increase in annual interruption duration. This will result in the decline in the spare capacity of micro gas turbines, and this trend goes on till a new micro gas turbine is in need, which means a jump to another track. In the scope of economic costs, micro gas turbines is able to substitute PV and wind turbines in large-scale. The difference in investment cost between them lead to the phenomenon that each track takes up its corresponding economic costs range.

C. The Impact of IL on Environmental Costs

As shown in Fig 8, Relationship between the environmental costs and annual interruption duration is quite similar to that between annual interruption duration and the economic costs. With the gradient relationship with multiple tracks and its meaning remains the same, the trend is an ascending one at this time. This is mainly because that IL may fail to fill the gap at the load peak when it functions as an alternative source, and micro gas turbines and other kinds of controllable DGs will cover the shortage. When the annual generation capacity and utilization of the latter increase, the environment costs will also be mounting, which is shown in Fig 9.

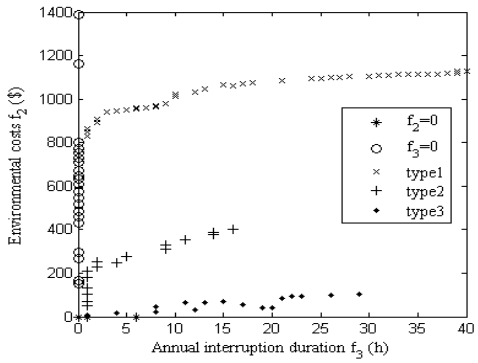

Fig 8 The environmental costs with annual interruption duration

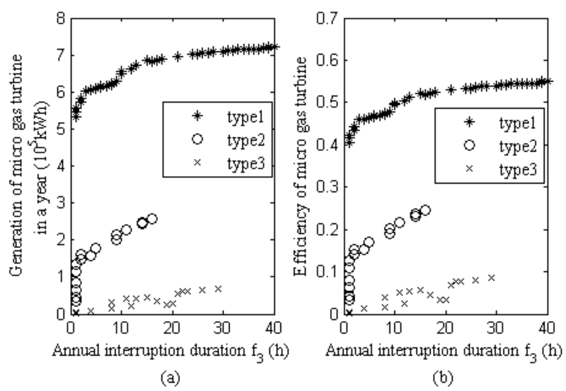

Fig 9 The total amount of micro gas turbine generation (a) and efficiency of micro gas turbine (b) with annual interruption duration

VI. Conclusion

The paper optimizes the power sources in a microgrid with interruptible loads (IL) by using NSGA-II. A multi-objective optimization model is proposed for microgrid construction. Objective functions of the model are economic cost, environmental cost and annual interruption duration. The Pareto optimal front covers the optimal solutions under three circumstances, which is (1) without diesels, fuel cells and micro gas turbines; (2) without IL and (3) full utilization. The final planning scheme is selected from the optimal set and settled with full consideration of requirements of different objectives. The impacts of IL on economic and environmental costs can be concluded as follows. The relationship between annual interruption duration and the economic/environmental costs possesses a gradient relationship with multiple tracks. On each track, the economic costs decline along with the increase in annual interruption duration, while the environmental costs ascend. These impacts are demonstrated by annual generation capacity of PV and wind power, annual generation capacity and utilization of micro gas turbine, as well as the moment of using IL.

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