Operation Optimization of Standalone Microgrids Considering Lifetime Characteristics of Battery Energy Storage System

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***Abstract*—Standalone microgrids with renewable sources and battery storage play an important role in solving power supply problems in remote areas such as islands. To achieve reliable and economic operations of a standalone microgrid, in addition to the consideration of utilization of renewable resources, the lifetime characteristics of a battery energy storage system also need to be fully investigated. In this paper, in order to realize the economic operation of a recently developed standalone microgrid on Dongfushan Island in China, an optimization model including battery life loss cost, operation and maintenance cost, fuel cost, and environmental cost is established to obtain a set of optimal parameters of operation strategy. Considering the lifetime characteristics of lead–acid batteries, a multiobjective optimization to minimize power generation cost and to maximize the useful life of lead–acid batteries has been achieved via the nondominated sorting genetic algorithm (NSGA-II). The results show that the proposed method can optimize the system operations under different scenarios and help users obtain the optimal operation schemes of the actual microgrid system.**

***Index Terms*—Lead–acid batteries, life characteristics, multiobjective, nondominated sorting genetic algorithm (NSGA-II), operation optimization, standalone microgrid.**

I. Introduction

IT IS usually difficult to extend the power grid on the mainland to far-separated islands due to a variety of reasons including economic factors and reliability issues. As a result, such areas are generally supplied by independent power systems where diesel generators are most widely employed [1]. Because of the high cost of fuel and transportation, the capacity of power supplies on those remote islands are very limited, which has greatly constrained the economic development of those regions in numerous aspects such as tourism, fisheries, etc. However, those areas are normally rich in renewable energy, which makes it promising to solve power supply problems by using renewable energy and establishing island microgrid systems. Meanwhile, the applications of renewable energy can also reduce pollution caused by traditional fossil fuel consumptions, which can further help protect the ecological and environmental systems of those island regions [2]. As an effective integration form of renewable distributed generations, microgrids have received widespread attention in recent years [3]–[5]. Today, microgrids have become more widely accepted and developed as they play an important role in solving the power supply problems on islands and in other remote areas [6]–[8].

Renewable energy sources such as wind, solar, and ocean energy are usually stochastic and intermittent [9]. It is critical to make effective use of renewable energy while keeping a stable, reliable, and economic operation of microgrid. Much effort has been made to pursue the optimal design and operation of a microgrid system. One of the focuses is the optimal sizing and structure to achieve economic operation [10], [11]. Similarly, much attention has already been paid to operation optimization issues. Fuel consumption minimization was discussed in [12] to get an optimal power sharing scheme of microgrid including combined heat and power (CHP), gas-engine, wind generator, and photovoltaic (PV). In [13], a new technique called “the jump and shift method” was developed to minimize operation costs and to reduce the emission level of a microgrid consisting of wind, PV, and battery banks. A method including a main algorithm and a secondary algorithm was proposed in [14] to optimize the sizing and control strategy of a wind–solar–diesel generator system. In [15], the scheduling problem of building energy supplies was considered to improve the energy efficiency of microgrid. A smart energy management system adopting a matrix real-coded genetic algorithm was proposed in [16] for optimal microgrid economic operation in order to minimize the microgrid operation cost. The optimal operation of an isolated system by a virtual power producer (VPP) was presented in [17] to decide the best management strategy to minimize the generation costs and to optimize the storage charging and discharging time.

A battery energy storage system is a core part in most remote power supply systems and it needs to be fully considered to ensure the efficient, safe, and stable operation of the whole system. However, the lifetime characteristics of a battery energy storage system have not been fully considered in many

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studies. It is a realistic problem encountered in the operation of the Dongfushan Island wind–solar–diesel–battery–seawater desalination project in Zhejiang Province, China, which was completed in April 2011. As a battery energy storage system usually has a short life cycle and high cost, a comprehensive optimization is difficult to realize and the optimization results are often one-sided without considering their lifetime characteristics, especially for lead–acid batteries which have many types and different constraints. Therefore, in the pursuit of minimizing operation cost, a full consideration should be given to the use of a battery energy storage system. Comprehensive studies are then needed to increase the renewable energy utilization and to extend the useful life of battery energy storage systems at the same time.

This paper discusses the economic optimization problem of a standalone wind–solar–diesel–battery microgrid system in which lead–acid batteries are used. With the full consideration of the lifetime characteristics of lead–acid batteries, a multiobjective optimization problem of minimizing power generation cost and maximizing the useful life of lead–acid batteries has been formulated. The optimization problem is solved using the nondominated sorting genetic algorithm (NSGA-II) to achieve the economic optimization considering the life loss cost, operation and maintenance cost, fuel cost, and the environmental cost.

This paper is organized as follows. Section II introduces the Dongfushan Island wind–solar–diesel–battery–seawater desalination project and the operation challenges to be addressed for the system. Section III formulates the optimization problem.Section IV describes the NSGA-II algorithm used in this paper. Section V presents and discusses the obtained results based on different conditions. The conclusion is given in Section VI

II. Background

Dongfushan Island, far from the mainland, is the farthest eastern inhabited island in China, and it once only relied on diesel generators to provide short-term power supply because of the difficulty and high cost of transportation. In order to improve the living quality of residents on the island and to make full use of the rich renewable energy resources there, the Dongfushan wind–solar–diesel–battery–seawater desalination project was started in September 2010 and completed in April 2011. The new system effectively solved the power and water supply problems for the island. The structure of the wind–solar–diesel–battery–seawater desalination system on Dongfushan Island is shown in Fig. 1. The system is composed of PV arrays (100 kW in total), seven wind turbines (WTs) (30 kW of each unit and a total of 210 kW), 480 lead–acid batteries (2 V/1000 Ah with a total of 960 kWh), and one diesel generator (200 kW).Table I summarizes the major components in the system. The original diesel generator serves as the backup power in the event of the failure of the newly finished system. Fig. 2 shows some photos of the actual system.

A master–slave control strategy in [18] is adopted in the Dongfushan Island microgrid system for power control. The lead–acid battery system and the diesel generator serve as the master control unit in turn to provide the reference voltage

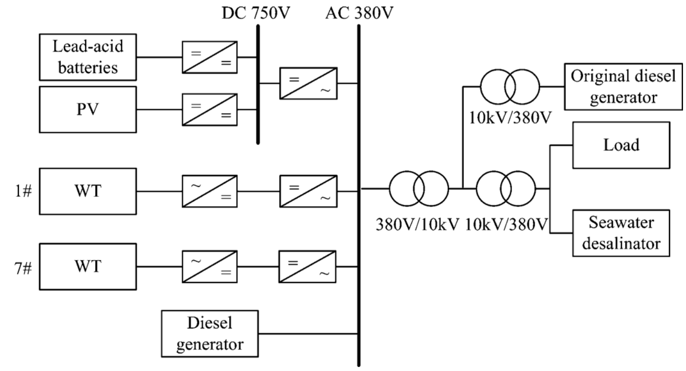

Fig. 1. Schematic diagram of the Dongfushan Island wind–solar–diesel–battery–seawater desalination system.

TABLE I
Components of the Microgrid System

Name	WT	PV	Diesel Generator	Lead-acid Battery
Type	30 kW	180 W	200 kW	2 V/1000 Ah
Quantity	7	556	1	480
Capacity	210 kW	100 kW	200 kW	960 kWh

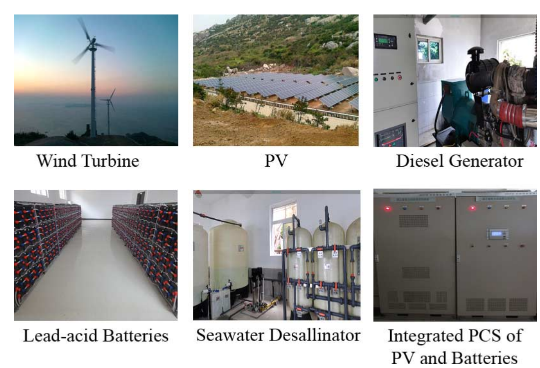

Fig. 2. Photos of the Dongfushan Island wind–solar–diesel–battery–seawater desalination system.

and frequency in accordance with the predetermined operation strategy. The schematic diagram of the operation strategy is shown in Fig. 3. In the figure, $\mathrm{SOC}_{\min}$ is the minimum-allowed state of charge (SOC) of batteries and is set to 0.5 in the Dongfushan Island system. $\mathrm{SOC}_{\mathrm{stp}}$ is the SOC set point at which the diesel generator stops. P_{ren} is the total output power of renewable energy. P_{load} is the total load demand. P_{excess} is the excess power set point of renewable energy that the batteries allow charging. P_{charge} is the charging power set point of batteries when the diesel generator operates.

The battery packs in the system are managed by its battery management system (BMS) based on individual battery monitoring modules (BMMs). The battery's SOC is measured and monitored by the BMS. When the battery's SOC is greater than $\mathrm{SOC}_{\min}$, the lead–acid batteries serve as the master control unit. At this time, the batteries can be in charge, discharge, or standby mode which is determined by P_{ren}, P_{load}, and P_{excess}. When P_{ren} is greater than P_{load}, and the excess power is greater than P_{excess}, the batteries are in charge mode. If the excess power is

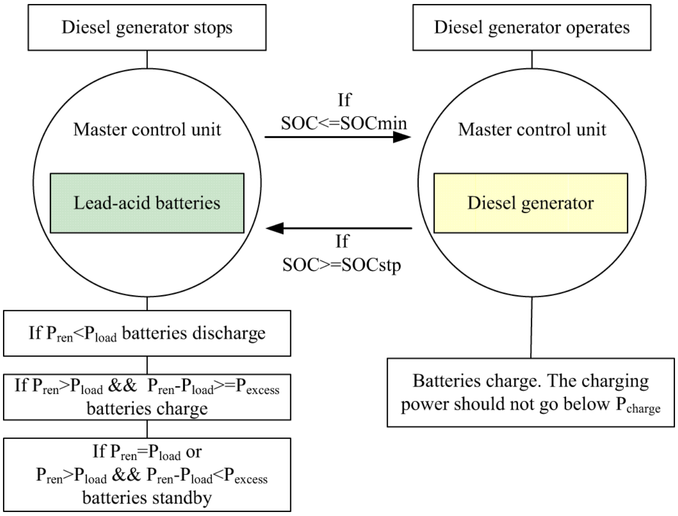

Fig. 3. Schematic diagram of the operation strategy for the Dongfushan system.

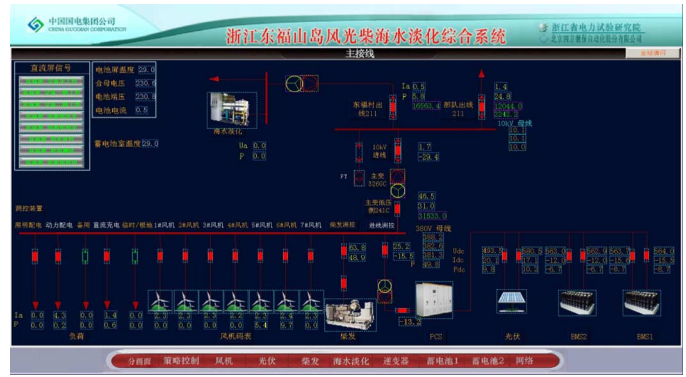

Fig. 4. Computer interface of the supervisory system for the Dongfushan wind–solar–diesel–battery–seawater desalination system.

less than P_{excess}, the batteries are in standby mode that they will not be charged. The extra amount of power will be dumped. An appropriate value of P_{excess} can reduce the number of shifts between charging and discharging which is beneficial to lead–acid batteries. When P_{ren} is smaller than P_{load}, batteries are in discharge mode.

If the battery's SOC is below its lower limit $\text{SOC}_{\min}$, the diesel generator starts as the master control unit while the lead–acid batteries turn into the charging process. The battery charging power should not go below P_{charge} which is guaranteed by the diesel generator to ensure the batteries work in a relatively stable charging status. When the SOC rises to SOC_{stp}, the diesel generator stops and the lead–acid batteries serve as the master control unit again.

The supervisory system gives orders and changes the operation modes automatically according to the state changes including the output power of PV, WT, diesel generator, and the lead–acid batteries, the SOC of lead–acid batteries, and the loads. The computer interface of the supervisory system is shown in Fig. 4. It is a key issue to determine the parameters of operation strategy in the light of actual conditions to ensure the economic operation of the microgrid system. Due to the difficulty and the high cost of shipping to the island, the system maintenance cost is expensive. Particularly, compared with the other components in the Microgrid, the lead–acid battery packs have the shortest life time. Moreover, if the batteries were not managed in an appropriate way, their life time could be significantly reduced. This could result in an even higher maintenance cost of the system. Therefore, the lifetime characteristics of lead–acid batteries should be given full consideration in the system design, operation, and maintenance.

From the environmental and economic point of view, it should reduce the operation of the diesel generator to maximize the utilization of renewable energy and to minimize the fuel cost. A diesel generator usually has a minimum power limit. Therefore, it is not necessary to charge the batteries to the maximum limit of SOC when the diesel generator operates if renewable sources are in good condition so that there is certain room for the batteries to be charged by the renewable sources. However, on the side of the battery, as renewable energy is stochastic and fluctuant, it is expected to appropriately prolong the operation of the diesel generator to guarantee that the batteries are charged to a relatively high level of SOC, which is beneficial to their useful life. It is known that the useful life of batteries is greatly influenced by their working conditions. If the batteries are replaced too often because of the short useful lifetime issue, it will cause great economic losses, especially for island regions with high transportation cost. The above two aspects (i.e., the maximum utilization of renewable sources and the longest lifetime of batteries) are contradictory under some conditions. Hence, it is suitable for using a multiobjective method to seek an optimal solution. The values of the set points, SOC_{stp}, P_{excess}, and P_{charge}, should be optimized for different conditions to extend the battery useful life and to minimize the generation cost at the same time.

III. Problem Formulation

A. Model of Generation Sources

1) WT Model: The approximate relationship between the output power of WT and wind speed can be used the following function, roughly [19]

$$P_{\text{wt}}(v)=\begin{cases}0, & v\le v_{\text{ci}}\ or\ v\ge v_{\text{co}}\\ \frac{P_{\text{rated-wt}}(v-v_{\text{ci}})}{(v_r-v_{\text{ci}})}, & v_{\text{ci}}\le v\le v_r\\ P_{\text{rated-wt}}, & v_r\le v\le v_{\text{co}}\end{cases} \quad (1)$$

where v_{ci} is cut-in speed, v_{co} is cut-off speed, v_r is the rated wind speed, $P_{\text{rated-wt}}$ is the rated output power of WT

$$P_{\text{out-wt}}\le P_{\text{wt}}(v). \quad (2)$$

$P_{\text{out-wt}}$ is the final actual output power of WT. The output power of WT can be adjusted according to demand.

2) PV Model: The output power of a PV can be calculated by its rated output power at the standard test condition, light intensity, and the operating ambient temperature [20]

$$P_{\text{pv}}=P_{\text{STC}}\frac{G_c}{G_{\text{STC}}}[1+k(T_c-T_{\text{STC}})]. \quad (3)$$

P_{pv} is the PV output power. The standard test condition (STC) means that solar irradiance G_{STC} is 1000 W/m^2, PV temperature T_{STC} is 25 °C, and relative atmospheric optical quality is AM1.5 condition. G_c is the irradiance of operating point, k is the power temperature coefficient, P_{STC} is the rated output power under STC, and T_c is the PV temperature of operating point.

The output power of the PV system can be adjusted by controlling its terminal voltage. So the output power can be expressed as

$$P_{\text{out-pv}} \leq P_{\text{pv}}. \tag{4}$$

$P_{\text{out-pv}}$ is the final actual output power of PV.

3) Lead–Acid Battery Model: The lead–acid battery storage system is one of the core parts of the wind–solar–diesel–battery microgrid system. The strategy of managing the lead–acid batteries significantly impacts the performance of the overall system.

At any given time, the SOC of the lead–acid battery system should be within a certain range. It can be expressed as

$$\text{SOC}_{\min} \leq \text{SOC} \leq \text{SOC}_{\max} \tag{5}$$

where $\text{SOC}_{\max}$ is the SOC upper limit, and $\text{SOC}_{\min}$ is the SOC lower limit. The output power of the lead–acid battery P_{bat} also has limits

$$P_{\text{cha-}\max} \leq P_{\text{bat}} \leq P_{\text{discha-}\max}. \tag{6}$$

$P_{\text{cha-}\max}$ is the maximum-allowed charging power, and $P_{\text{discha-}\max}$ is the maximum-allowed discharging power. P_{bat} is positive when discharging, and negative for charging.

The SOC value at time $t+\Delta t$ is determined by the SOC value at time t and the battery power during the time period. It can be expressed as

$$\text{SOC}_{t+\Delta t} = \text{SOC}_t - P_{\text{bat-}t} \times \frac{\Delta t}{C_{\text{bat}}}. \tag{7}$$

$P_{\text{bat-}t}$ is the battery power between t and $t+\Delta t$; and C_{bat} is the battery capacity. The SOC should be controlled within the range in (5). The charging efficiency and discharging efficiency are both assumed to be 90%, according to the practical situation of the Dongfushan Island system.

A weighted Ah ageing model [21] is employed to evaluate the lifetime of the lead–acid batteries in this paper. It is assumed that, under the standard conditions, a battery can achieve an overall Ah throughput until the end of the lifetime is reached. Deviations from the standard conditions result in a virtual increase (or decrease) of the physical Ah throughput. It has been reported that the effective cumulative lifetime of the lead–acid battery is associated with its operating SOC values [22]. Fig. 5 shows the effect of different operating SOC values on the effective cumulative lifetime of the lead–acid battery. For example, at an SOC of 0.5, removing 1 Ah from the battery is equivalent to removing 1.3 Ah from the lifetime cumulative total. However, at an SOC of 1, removing 1 Ah will result in only 0.55 Ah being removed from the effective cumulative total. This also indicates that lead–acid batteries should be operated at high SOC to optimize their lifetime.

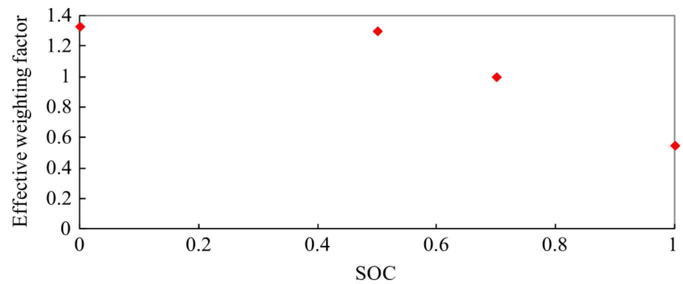

Fig. 5. Relationship between effective weighting factor and the SOC of lead–acid battery [22].

In addition, the following important conditions will also impose significant negative impacts on the lifetime of lead–acid batteries: i) operation at low SOC for a long period of time; ii) partial cycling at low SOC; iii) rare full charges; and iv) elevated temperature [23]. The main factor affecting the useful life of lead–acid batteries is the operating SOC when the temperature can be managed. Through the statistics of the value of operating SOC and the up-to-day cumulative Ah throughput, the life loss level can be evaluated.

4) Diesel Generator Model: Diesel generators generally serve as a backup power source. The fuel consumption (L/kWh) of the diesel generators is modeled as a linear function of their actual output power

$$F = F_0 \times P_{\text{rated-gen}} + F_1 \times P_{\text{gen}}. \tag{8}$$

$P_{\text{rated-gen}}$ is the rated output power. P_{gen} is the actual output power. F_0 and F_1 are the fuel consumption curve fitting coefficients. Based on the recommended values from [14], F_0 is set as 0.08415 and F_1 is 0.246.

Diesel generators usually have power limits which can be expressed as

$$k_{\text{gen}} P_{\text{rated-gen}} \leq P_{\text{gen}} \leq P_{\text{rated-gen}}. \tag{9}$$

The value of $k_{\text{-gen}}$ is set to 0.3 based on the manufacturers' suggestion of the Dongfushan Island system.

B. Economic Model

1) Generation Cost: The generation cost consists of two parts of cost from the diesel generator and from the renewable energy sources, respectively,

$$\begin{aligned} C_{\text{gen}} &= C_{\text{die}} + C_{\text{ren}} \\ C_{\text{die}} &= C_{\text{loss-die}} + C_{\text{om-die}} + C_{\text{fuel}} + C_{\text{po-die}} \\ C_{\text{ren}} &= C_{\text{loss-ren}} + C_{\text{om-ren}} - C_{\text{sub}}. \end{aligned} \tag{10}$$

C_{die} is the generation cost of diesel generator. $C_{\text{loss-die}}$ and $C_{\text{om-die}}$ are the diesel generator life loss cost, and the operation and maintenance cost, respectively. C_{fuel} is the fuel cost. $C_{\text{po-gen}}$ is the cost due to the pollution generated.

C_{ren} is the generation cost of renewable energy. $C_{\text{loss-ren}}$ and $C_{\text{om-ren}}$ are renewable generation equipment life loss cost, operation and maintenance cost, respectively. C_{sub} is generation subsidies of renewable energy.

2) Lead–Acid Battery Life Loss Cost: The effective cumulative Ah throughput can be generally employed to measure the life loss level of batteries. It can be expressed as

$$L_{\mathrm{loss}} = \frac{A_c}{A_{\mathrm{total}}}. \tag{11}$$

L_{loss} is the life loss of batteries. A_c is the effective cumulative Ah throughput in a certain period of time. A_{total} is the total cumulative Ah throughput in life cycle. A review of manufacturers' data for lead–acid batteries reveals an approximation that a battery size of Q Ah will deliver $390Q$ effective Ah over its lifetime [22].

A_c is related to the operating SOC and the actual Ah throughput A'_c. It can be expressed as

$$A_c = \lambda_{\mathrm{soc}} A'_c \tag{12}$$

where λ_{soc} is the effective weighting factor. As stated before, $\mathrm{SOC}_{\min}$ is set to 0.5 in this paper. And when SOC is greater than 0.5, the effective weighting factor is approximately linear with SOC, which can be expressed as

$$\lambda_{\mathrm{soc}} = k * \mathrm{SOC} + d. \tag{13}$$

In the equation, k and d are the two empirical parameters and their values can be determined based on Fig. 5.

The life loss cost C_{bl} can be expressed as

$$C_{\mathrm{bl}} = L_{\mathrm{loss}} C_{\text{init-bat}}. \tag{14}$$

$C_{\text{init-bat}}$ is the initial investment cost of batteries. In this way, C_{bl} is used to measure the life loss cost of batteries in certain duration.

C. Objectives

Multiobjective optimization is normally used to find a trade-off solution when there are different objectives, particularly when they are contradictory from each other. An optimal Pareto front can hopefully be established for a problem with multiple objectives. As discussed before, the development and management of the Dongfushan microgrid system is a multiobjective problem, which has the following two major objectives:

1) Objective 1: Minimize the Power Generation Cost: The power generation costs of the diesel generator and the renewable energy sources are included in objective 1 as

$$\min(C_{\mathrm{gen}}). \tag{15}$$

The higher utilization of renewable energy and the lower operation of the diesel generator, the smaller power generation cost is. The minimum cost of power generation is explored under this objective.

2) Objective 2: Minimize the Batteries Life Loss Cost: The total batteries life loss cost is the second objective

$$\min(C_{\mathrm{bl}}). \tag{16}$$

The higher the SOC of the batteries in general the smaller life loss cost will be.

The NSGA-II, discussed in Section IV, will be used to find the optimal solution (operation strategy) for the Dongfushan microgrid.

D. Constraints

Power generation and consumption should always be kept balanced, i.e.,

$$P_{\mathrm{load}} = P_{\mathrm{gen}} + P_{\text{out-pv}} + P_{\text{out-wt}} + P_{\mathrm{bat}}. \tag{17}$$

P_{bat} is the output power of the batteries, and positive means discharging and negative means charging. P_{load} is the load demand.

In addition, the constraints given in (2), (4), (5), (6), and (10) should also be satisfied. And the microgrid system should operate following the operation strategy described in Section II. $\mathrm{SOC}_{\mathrm{stp}}$, P_{excess}, and P_{charge} are the decision variables that are to be optimized.

IV. NSGA-II Algorithm

Numerous genetic algorithms (GAs) have been proposed in literature for solving multiobjective optimization problems. In this paper, the NSGA-II algorithm, which was proposed by Deb and other scholars [25], is used. In this algorithm, the population is sorted into different nondomination levels, and each solution is assigned fitness equal to its nondomination level [24]. The basic step of the NSGA-II algorithm is:

1) First generate the initial population P with size N. Then produce offspring population Q from P through genetic manipulation (crossover and mutation). And the two populations are combined to form population R.
2) Make classification of population R in accordance with Pareto rank on the basis of fitness. According to the principle of small Pareto rank and small intensity, individuals are selected to form new parent population P' with size N.
3) Generate offspring population Q' from P' through genetic manipulation. P' and Q' populations are combined to form new population R'. Repeat these steps in 2) and 3) until the algorithm meets the end condition.

$\mathrm{SOC}_{\mathrm{stp}}$, P_{excess}, and P_{charge} are the decision variables and their values will be optimized via this method. In the gene code of each individual in the population, there are five elements where the first three are the decision variables and the last two are the two objectives (i.e., Objective 1 and Objective 2).

The population size is chosen as 200 and the generation number is set as 20 in the paper. In genetic manipulation, the decision variables are crossed or mutated at a certain probability. The evaluated objectives that obtained by simulation are the fitness of the population. In the algorithm, the initial value of SOC is set as 0.6, $\mathrm{SOC}_{\min}$ is 0.5, and $\mathrm{SOC}_{\max}$ is 0.95, respectively. The simulation step is 1 h.

V. Results and Discussion

The output power of PV and WT can be obtained via the model given in Section III based on the actual measured solar irradiance, temperature, and wind speed. In Dongfushan Island,

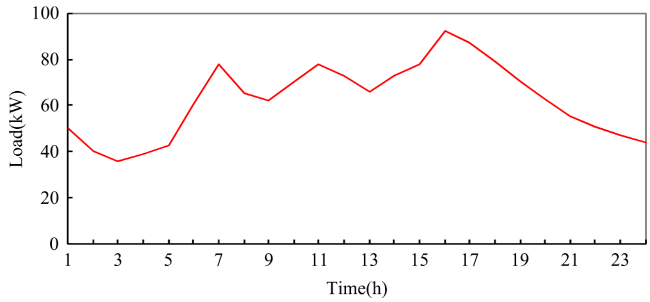

Fig. 6. Typical load demand of the island.

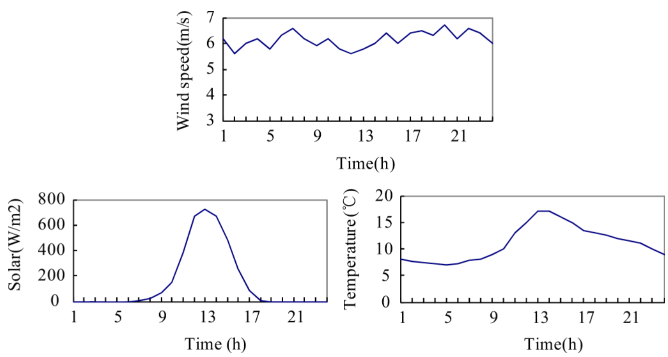

Fig. 7. Wind speed, solar radiation, and temperature profiles of the case with abundant renewable resources.

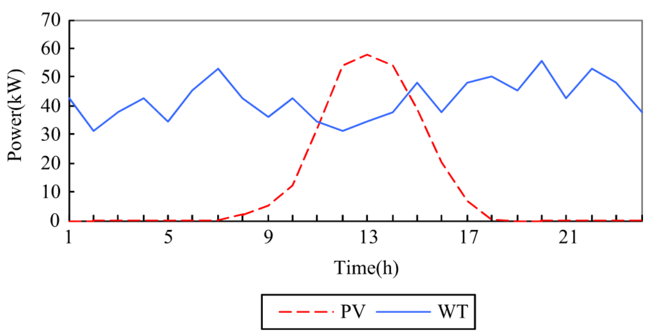

Fig. 8. Renewable output power profiles of the case with abundant renewable resources.

the data are the typical data chosen in the history measured data. The history measured data of the same period in the past are used to explore the optimal parameters in a certain period such as per day, per month, or per season.

There will be a different set of optimal values of $\mathrm{SOC}_{\mathrm{stp}}$, P_{excess}, and P_{charge} for different weather conditions. In order to compare and analyze the optimal parameters of operation strategy in different weather conditions, two typical cases with abundant renewable resources and short of renewable resources are selected as the examples in the following discussion. Fig. 6 shows the typical load demand on the island.

A. Abundant Renewable Resources

In this case, the wind speed and the solar radiation are in relatively good condition, which is shown in Fig. 7. The corresponding output power of WT and PV are shown in Fig. 8 which can be obtained based on (1) and (3). The conversion efficiency and other practical factors have been included in determining the output power of wind and PV. The optimal result obtained via the NSGA-II algorithm is shown in Fig. 9.

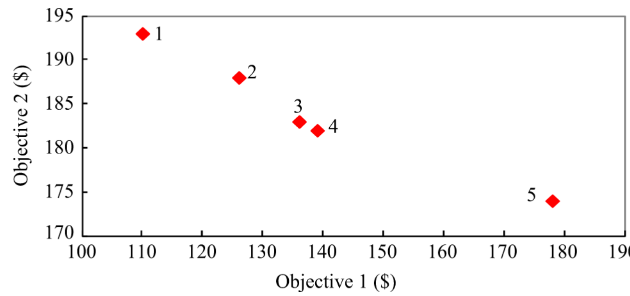

Fig. 9. Optimization results of the case with abundant renewables.

TABLE II
RESULTS OF THE CASE WITH ABUNDANT RENEWABLE RESOURCES

No.	SOC_{stp}	P_{charge} /kW	P_{excess} /kW	Objective 1 \$	Objective 2 \$
1	0.61	54	0	110	193
2	0.55	48	1	126	188
3	0.56	58	15	136	183
4	0.63	40	15	139	182
5	0.54	40	15	178	174

As shown in Fig. 9, the two objectives are in general conflict with each other. The detailed results of the five points shown in Fig. 9 are given in Table II. The optimized values of $\mathrm{SOC}_{\mathrm{stp}}$, P_{excess}, and P_{charge} for the five different operating strategies are given in the table. Because of the abundant renewable resources, the power generation cost and batteries life loss cost are relatively low. The system operation profiles of No. 1, 4, and 5, as an example, are shown in Figs. 10–12, respectively.

As shown in Figs. 10–12, the operation strategies with different parameters sure give different operation results/costs. For the operation scheme of No. 1, where $\mathrm{SOC}_{\mathrm{stp}}$ is set to 0.61, it is obvious that the operation time of the diesel generator reduces. Although the charging process of batteries is not sufficient relying on the diesel generator, it can be continued with renewable sources. However, the batteries have to discharge at a relative low SOC level which increases the life loss cost of the batteries. Moreover, P_{excess} is set to 0 which is helpful to make full use of renewable energy, but can cause adverse effects on the battery life.

For the operation scheme of No. 4, when $\mathrm{SOC}_{\mathrm{stp}}$ is set to 0.63, the charging process of batteries is more sufficient than the case of No. 1. It is helpful to set P_{excess} to 15 kW to avoid too frequent switching of batteries between the charging and discharging process, but it can cause waste of renewable sources. Therefore, it has a relatively high generation cost but a relatively low batteries life loss cost in this case.

For the operation scheme of No. 5, when $\mathrm{SOC}_{\mathrm{stp}}$ is set to 0.54, the charging process of batteries is less sufficient. When the battery SOC is less than $\mathrm{SOC}_{\mathrm{min}}$, the diesel generator has to operate again, which increases the generation cost. However, when the diesel generator operates, the batteries are in the charging process, which is helpful for the batteries to leave the low SOC range and to minimize the batteries life loss cost. But, it further increases the generation cost by setting P_{excess} to 15 kW. Therefore, under this scheme, the system relies more on

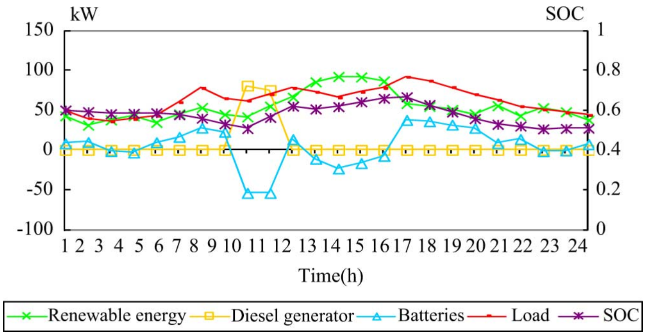

Fig. 10. System operation profiles under the operation strategy of No. 1 for the case with abundant renewable resources.

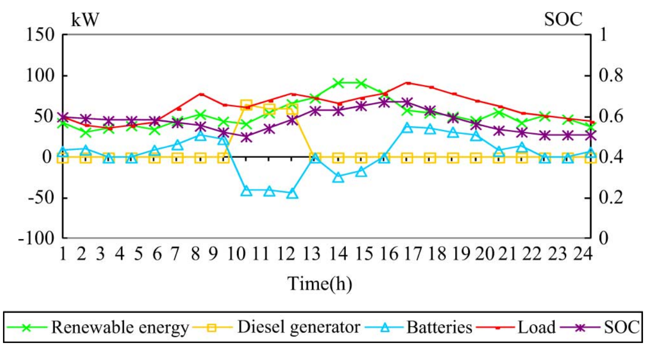

Fig. 11. System operation profiles under the operation strategy of No. 4 for the case with abundant renewable resources.

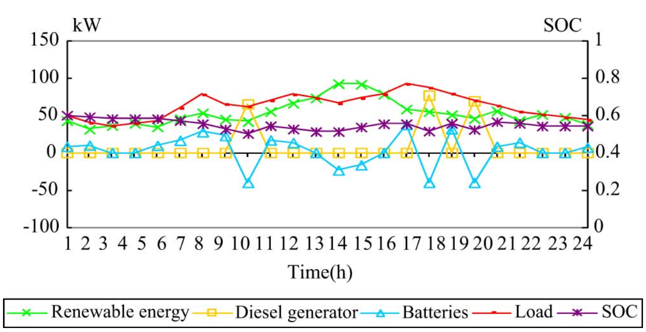

Fig. 12. System operation profiles under the operation strategy of No. 5 for the case with abundant renewable resources.

the diesel generator, which results in the highest generation cost but the lowest batteries life loss cost.

In general, it will increase the operation time of diesel generator and the power generation cost to minimize the batteries life loss cost. However, because of the abundant renewable resources, the reduction of life loss cost of batteries is limited by increasing the operation of the diesel generator. Therefore, it is not the best choice to increase the operation of the diesel generator too much in the case of abundant renewable resources.

An operation scheme can be determined based on the above three parameters, namely $\mathrm{SOC_{stp}}$, P_{excess}, and P_{charge}. To find an optimal operation scheme that balances the two objectives in (16) and (17), a weighting method is used to integrate the two objectives into one objective

$$\mathrm{Objective} = a_1 \times \mathrm{Objective1} + a_2 \times \mathrm{Objective2} \qquad (18)$$

TABLE III
RESULTS OF THE CASE WITH ABUNDANT RENEWABLE RESOURCES WITH ONE COMBINED OBJECTIVE

No.	SOC_{stp}	P_{charge} /kW	P_{excess} /kW	Objective $
1	0.61	54	0	152
2	0.55	48	1	157
3	0.56	58	15	160
4	0.63	40	15	161
5	0.54	40	15	176

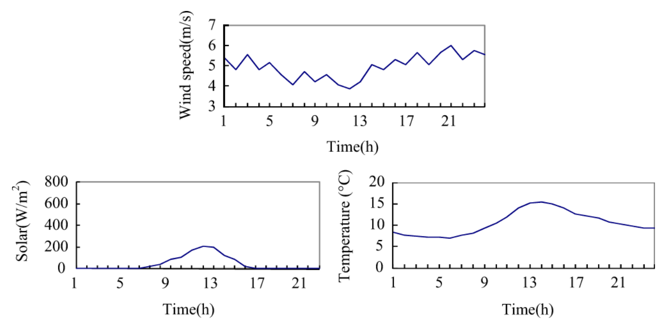

Fig. 13. Wind speed, solar radiation, and temperature profiles of the case short of renewable resources.

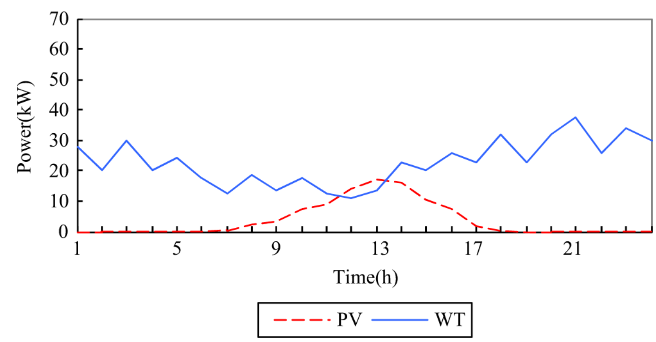

Fig. 14. Renewable output power profiles of the case short of renewable resources.

where a_1 and a_2 are the weight coefficients, and their sum is 1. In this study, the two objectives are treated as equally important, i.e., $a_1 = a_2 = 0.5$. The optimal schemes converted to one objective are shown in Table III.

It can be seen from Table III that in the case of abundant renewable resources, the scheme with a relatively high value of $\mathrm{SOC_{stp}}$ should be selected, such as 0.61. The scheme can reduce the power generation cost and protect the batteries from a reduced life time at the same time.

B. Short of Renewable Resources

In this case, the wind speed and the solar radiation are in relatively weak condition, shown in Fig. 13. The corresponding output power of WT and PV are shown in Fig. 14.

The optimization result is shown in Fig. 15. Similar to the case with abundant renewable resources, the pursuit of maximizing the utilization of renewable energy can push the batteries to work under less favorable conditions, which increase the batteries life loss. On the other hand, an appropriate increase of the operation time of the diesel generator can provide batteries a better condition to effectively reduce the battery life loss.

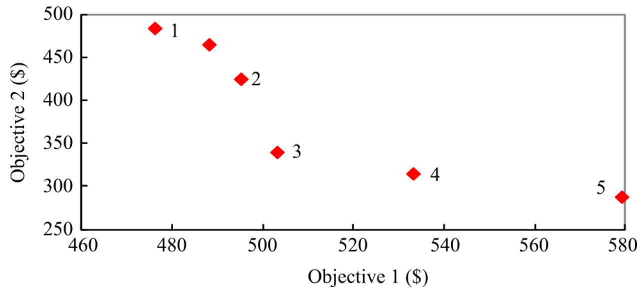

Fig. 15. Optimization result of the case short of renewable resources.

TABLE IV
OPTIMIZATION RESULTS OF THE CASE SHORT OF RENEWABLE RESOURCES

No.	SOC_{stp}	P_{charge} /kW	P_{excess} /kW	Objective 1 $	Objective 2 $
1	0.78	91	10	476	484
2	0.75	69	11	495	425
3	0.92	45	15	503	340
4	0.91	40	0	533	315
5	0.95	40	0	579	288

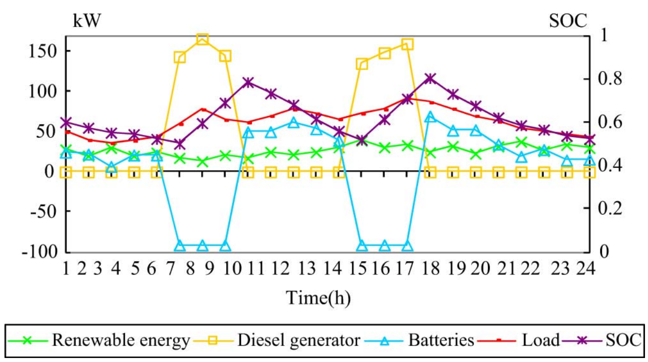

Fig. 16. System operation profiles under the operation strategy of No. 1 for the case short of renewable resources.

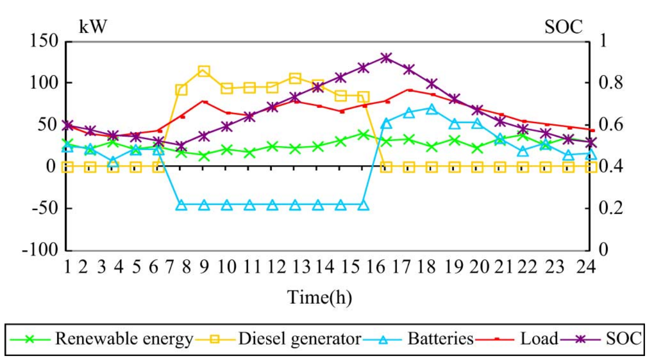

Fig. 17. System operation profiles under the operation strategy of No. 3 for the case short of renewable resources.

The optimization results are also given in Table IV, where different values of $\mathrm{SOC}_{\mathrm{stp}}$, P_{excess}, and P_{charge} are listed for the five different operation strategies. The detailed system operation profiles for the schemes of No. 1, 3, and 5 are given in Figs. 16–18 as examples.

Because of less renewable resources available, the diesel generator needs to provide more power. As shown in Figs. 16–18, the operation time of the diesel generator is obviously longer than the case of abundant renewable resources. Moreover, the battery management also relies more on the diesel generator. As a result, a relatively high value of $\mathrm{SOC}_{\mathrm{stp}}$ is needed for the system operation.

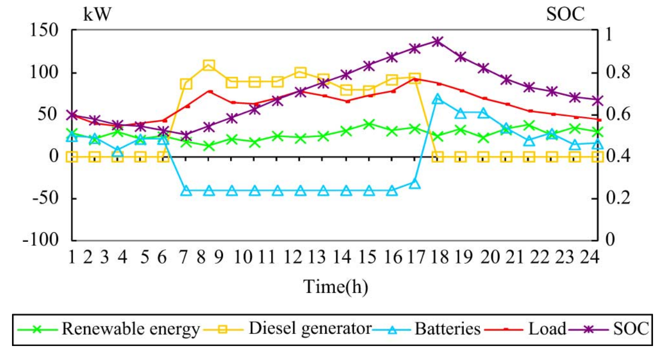

Fig. 18. System operation profiles under the operation strategy of No. 5 for the case short of renewable resources.

TABLE V
OPTIMIZATION RESULTS OF THE CASE SHORT OF RENEWABLE RESOURCES WITH ONE COMBINED OBJECTIVE

No.	SOC_{stp}	P_{charge} /kW	P_{excess} /kW	Objective $
3	0.90	45	15	422
4	0.90	40	0	424
5	0.95	40	0	434
2	0.74	69	11	460
1	0.74	91	10	480

TABLE VI
RESULTS OF THE BASE CASE IN BOTH RENEWABLE RESOURCES

Renewable Resources	Objective 1 $	Objective 2 $	Objective $
Abundant	240	247	243.7
Short of	616	489	552.5

Table V shows the results when the two objectives are combined together with the equal weighting factors, i.e., $a_1 = a_2 = 0.5$ in (18). For this case, the best operation scheme is No. 3. Compared to the case with abundant renewable resources, the total cost (the sum of the generation cost and the battery life loss cost) is higher than the case short of renewable resources.

The operation parameters such as $\mathrm{SOC}_{\mathrm{stp}}$, P_{excess}, and P_{charge} need to be adjusted according to the weather and load conditions achieve an optimized performance for different scenarios. In the Dongfushan microgrid, the parameters are optimized according to the forecast of weather condition and load in the future such as day-ahead. Through the real-time optimization, the microgrid is kept working in an optimized condition that the renewable energy is fully utilized while the batteries are effectively managed.

To further demonstrate the effectiveness of the proposed method, a base case study has been carried out with fixed typical control parameters in any situation that $\mathrm{SOC}_{\mathrm{stp}}$ is set to 0.9, P_{excess} is set to 0, and P_{charge} is set to 96 kW (charging power of 0.1 C). The detailed results of the base case in both scenarios of renewable resources are given in Table VI.

In the case of abundant renewable resources, compared with the base case, the result with optimal control parameters

(Table II, No. 1) can save 54.2% in generation cost and reduce 21.9% of battery life loss cost. The integrated one objective (Table III, No. 1) with equal weighting coefficients can reduce 37.6% of the overall cost. Meanwhile, in the case of a shortage of renewable resources, the result with optimal control parameters (Table IV, No. 3) increases 5.7% in generation cost but reduces 29.8% of battery life loss cost. The integrated one objective (Table V, No. 3) with equal weighting coefficients reduces the overall cost by 23.6%. These results demonstrate that the proposed method can effectively increase battery life and reduce generation cost via helping users obtain a set of optimal operation schemes of actual microgrid systems.

VI. Conclusion

This paper discusses the operation optimization of microgrids with renewable sources, diesel generators, and battery storage. The NSGA-II algorithm was used to find solutions for a multi-objective problem to minimize the generation cost and to minimize the battery life loss. A set of critical operation parameters can be found in real time for different operation conditions, i.e., weather conditions, load profiles, etc. The method was used for the Dougfushan Island microgrid which consists of wind, PV, diesel generators, and lead–acid batteries with a total generation capacity of 510 kW. Simulation studies have been carried out using the actual, measured data in Dongfushan Island for two typical cases: abundance and a shortage of renewable resources. The results show that the proposed method can help the system reduce the generation cost while maintaining the batteries in healthy working conditions.

Though the simulation studies carried out in this paper are for a recently finished project with lead–acid batteries as the energy storage technology and diesel generator as the backup power source, the method can be extended to microgrids with other energy storage and distributed generation technologies. We have used the method in implementing the Nanji Island project which is composed of 1000 kW WT, 500 kW PV, 1400 kW diesel generator, ultracapacitor, and LiFePO4 batteries. At present, we are also exploring the feasibility of developing a microgrid system using lithium–ion batteries and microturbines.

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