Study on Minimum Annual Electricity Bill of a Campus Microgrid Using the Sparrow Search Algorithm and Bin Packing Method

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***Abstract*—This paper aims to solve the minimum annual electricity bill problem of a campus microgrid with distributed generation and a battery energy storage system via the proposed optimal hybrid approach with sparrow search algorithm (SSA) and bin packing method (BPM). First, the hourly, daily, monthly, and annual electricity bill computing modules were built. The historical electrical consumption and photovoltaic generation were analyzed to statistic the net load distribution and duration over one year. Next, the time-of-use rate for high-voltage customers with demand charge and energy charging of Taipower for the high-voltage campus microgrid was formulated as an optimization function and coded in python language. The charging and discharging schedule of the 1 MW/1.26 MWh battery energy storage system (BESS), according to the annual net load, were considered in this minimum annual electricity bill problem. We obtained the optimal contract capacity and the corresponding minimum annual electricity bill. The optimal hybrid approach was applied to solve this optimization problem. The results demonstrate that the proposed method could effectively solve the annual minimum electricity bill problem.**

Keywords—Microgrid, Bin Packing Method, Sparrow Search Algorithm, Minimum Cost

I. Introduction

The swarm optimization algorithm is typically used for engineering optimal applications; it is effective and can rapidly solve the minimum operational cost in power systems [1-2]. Among these algorithms, the sparrow search algorithm has been verified in the coordinated dispatch of combined heat and power in microgrids [3], the optimal dispatch strategy of microgrid energy storage [4], and the scheduling strategy of regionally integrated energy systems [5]. Furthermore, the bin packing method is also used to solve the scheduling problem of energy storage systems [6-7]. As such, this study combined the sparrow search algorithm and bin packing method as a hybrid approach, coded in python language, to solve a minimum annual electricity bill problem for a campus microgrid, a high-voltage customer of Taipower in Taiwan. The first task of this study was to analyze the total annual electricity consumption and photovoltaic generation per hour in one year. The analysis elicited 8,760-hour net electrical consumption data, which is the load demand minus the photovoltaic generation. This was used as the net load demand for solving this problem. The rate of electricity fee is vital in this study; the time-of-use rate for 11.4 kV high-voltage customers of Taipower is composed of demand charge and energy charge as shown in TABLE I [8]. Therefore, the demand charge per kW is different in summer and non-summer. Moreover, the energy charge per kWh in peak and off-peak periods from Monday to Sunday differs as well.

Additionally, if the customer's metered maximum demand is more than the contracted capacity, the demand charge of the excess within 5% of the contracted capacity is charged at one of the rates of contracted capacity; the demand charge of the excess within 10% of the contracted capacity is double the rate of contracted capacity, and an excess over 10% of the contracted capacity is charged triple the rate. According to the annual net load and time-of-use rate, the proposed hybrid approach will solve the minimum yearly electricity bill. The rest of this paper is divided into four sections. Section 1 introduces the background and objectives of this study. Section 2 describes the study problem. Section 3 discusses the numerical results. Section 4 presents our conclusions.

TABLE I. TIME-OF-USE RATE FOR 11.4 KV HIGH-VOLTAGE CUSTOMERS OF TAIPOWER

UNIT: NTD

Classification					Summer (Jun. 1 ~Sep. 30)	Non-summer (All other days of the year)
Demand Charge	Regular Contracted Demand			Per kW Per Month	223.60	166.90
	Non-Summer Contracted Demand				-	166.90
	Saturday Partial-Peak Period Contracted Demand				44.70	33.30
	Off-Peak Period Contracted Demand				44.70	33.30
Energy Charge	Monday to Friday	Peak Period	07:30~22:30	Per kWh	4.00	3.86
		Off-Peak Period	00:00~07:30 22:30~24:00		1.68	1.56
	Saturday	Partial-Peak Period	07:30~22:30		1.97	1.87
		Off-Peak Period	00:00~07:30 22:30~24:00		1.68	1.56
	Sunday & Off-Peak day	Off-Peak Period	00:00~24:00		1.68	1.56

II. PROBLEM DESCRIPTION

A. The Proposed Approach

Figure 1 illustrates the proposed approach for an optimal contracted capacity and a minimum annual electricity bill. The load demand and photovoltaic generation were measured from the smart meters and transmitted to the InfluxDB by kW per second. The metering data were computed into the net load in kW per hour. The BESS's state of charge (SoC) and the charging/discharging power (kW) were also accessed from the InfluxDB database. The proposed hybrid approach with the SSA and BPM was used to solve the optimal charging/discharging schedule and contracted capacity and finally to obtain the minimum annual electricity bill of the campus microgrid, which is the microgrid of the National Changhua University of Education (the NCUE microgrid).

Based on the time-of-use rate for the 11.4 kV high-voltage customers of Taipower, the minimum electricity bill of the NCUE microgrid is described in Figure 2. The contracted capacity dominates the annual electricity bill. The higher the signed contracted capacity is, the less likely it is to exceed the contract. However, the demand charge to be paid is higher. In the case of excess of the contracted capacity, it will result in an extra charge for the rate of contracted capacity. However, the minimum annual electricity bill can be obtained if an appropriate contracted capacity can be determined.

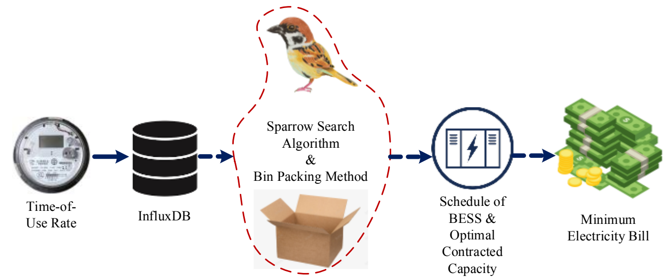

Fig. 1. An illustration of the proposed approach

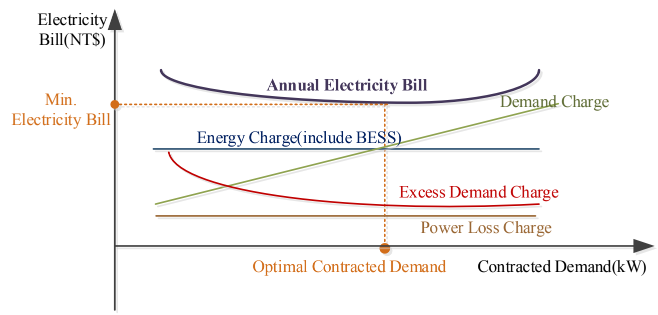

Fig. 2. A schematic diagram of the relationship between electricity bill and contracted capacity

Referring to TABLE I, the monthly demand charge, including basic contracted capacity and excess contracted capacity, can be formulated in (1), where P_{DeChg} is the contracted capacity; λ_{season} is the summer/non-summer demand charge per kW; and P_{EnChg}^{1hr} is the average load demand. In addition, the daily energy charge can be expressed as (2), where λ_{Peak} and $\lambda_{OffPeak}$ is the energy charge per kWh during the peak and off-peak period from Monday to Friday as well as Sunday and off-peak days, respectively; and $\lambda_{SatPeak}$ is the energy charge per kWh during the partial peak period on Saturdays.

$$EBill_{monthly}^{DeChg}=\begin{cases} P_{DeChg}\cdot\lambda_{season},\ P_{EnChg}^{1hr}\le P_{DeChg} \\ P_{DeChg}\cdot\lambda_{season}+\left(P_{EnChg}^{1hr}-P_{DeChg}\right)\cdot\lambda_{season},\ P_{DeChg}<P_{EnChg}^{1hr}\le 1.05P_{DeChg} \\ 1.05P_{DeChg}\cdot\lambda_{season}+\left(P_{EnChg}^{1hr}-1.05P_{DeChg}\right)\cdot 2\lambda_{season},\ 1.05P_{DeChg}<P_{EnChg}^{1hr}\le 1.1P_{DeChg} \\ 1.15P_{DeChg}\cdot\lambda_{season}+\left(P_{EnChg}^{1hr}-1.1P_{DeChg}\right)\cdot 3\lambda_{season},\ P_{EnChg}^{1hr}>1.1P_{DeChg} \end{cases} \quad (1)$$

$$EBill_{Daily}^{EnChg}=\begin{cases}\sum_{i=1}^{15}P_{EnChg}^{1hr}\cdot\lambda_{Peak}+\sum_{i=1}^{9}P_{EnChg}^{1hr}\cdot\lambda_{OffPeak},\ Weekday\\ \sum_{i=1}^{15}P_{EnChg}^{1hr}\cdot\lambda_{SatPeak}+\sum_{i=1}^{9}P_{EnChg}^{1hr}\cdot\lambda_{OffPeak},\ Saturaday\\ \sum_{i=1}^{24}P_{EnChg}^{1hr}\cdot\lambda_{OffPeak},\ Sunday\ \&\ Off-Peak\ Day\end{cases}\tag{2}$$

B. Hybrid Optimal Algorithm

The proposed hybrid optimal algorithm is composed of the SSA and BPM. The details are explained as follows.

Sparrow Search Algorithm: The SSA simulates the foraging and predation behavior of sparrows and has the advantages of good search ability and fast convergence characteristics[9]. This algorithm simulated the charging and discharging schedule of the 1MW/1.26 MWh BESS in the NCUE microgrid. The charging and discharging efficiency per round were set at 85%, and the SoC range was 90%-10%; the SoC could be used in the range of 80%. Referring to Figure 3, the overall charging capacity is 1185 kWh, and the overall discharging capacity is 856.8 kWh. In this algorithm, the best individual in the group would get food first during the foraging process. The search range of the finder was larger than that of the joiner. During each iteration, the position update formula of the finder could be expressed in (3)-(5).

$$X_{i,j}^{t+1}=\begin{cases}X_{i,j}^{t}\cdot\exp\left(\dfrac{-i}{\alpha\cdot T}\right) & if\ R_2<ST\\ X_{i,j}^{t}+Q\cdot L & if\ R_2\geq ST\end{cases}\tag{3}$$

$$X_{i,j}^{t+1}=\begin{cases}Q\cdot\exp\left(\dfrac{X_{i,j}^{t}-X_{worst}^{t}}{i^2}\right) & if\ i>\dfrac{n}{2}\\ X_{P}^{t+1}+\left|X_{i,j}^{t}-X_{P}^{t+1}\right|\cdot A^{+}\cdot L & otherwise\end{cases}\tag{4}$$

$$X_{i,j}^{t+1}=\begin{cases}X_{best}^{t}+\beta\cdot\left|X_{i,j}^{t}-X_{best}^{t}\right| & if\ f_i<f_g\\ X_{i,j}^{t}+K\cdot\left(\dfrac{\left|X_{i,j}^{t}-X_{worst}^{t}\right|}{(f_i-f_w)+\varepsilon}\right) & if\ f_i=f_g\end{cases}\tag{5}$$

In the above equations, t indicates the current iteration; and $X_{i,j}^{t}$ with a dimension of 1 × d represents the matrix of the j[th] dimension of the i[th] sparrow in iteration t. T is the number of iterations; is a random number; and $R_2\in[0,1]$ and $ST\in[0.5,1]$ represents the alarm value and safety threshold, respectively. Q is a random number that obeys normal distribution; and L shows a matrix of 1 × d for which each element inside is 1. Further, X_P is the optimal position occupied by the producer and X_{worst} denotes the current global worst location. A represents a matrix of 1 × d for which each element inside is randomly assigned 1 or −1, and $A^{+}=A^{T}(AA^{T})^{-1}$. When $i>n/2$, the i[th] scrounger with the worst fitness value is most likely to starve. Moreover, X_{best} is the current global optimal location. β, as the step size control parameter, is a normal distribution of random numbers with a mean value of 0 and a variance of 1. $K\in$[-1, 1] is a random number. Here, f_i is the fitness value of the present sparrow. f_g and f_w are the current global best and worst fitness values, respectively. ε is the smallest constant to avoid zero-division-error. The three behaviors of the sparrow, responsible for global searching, local searching and preventing poor solutions, make the algorithm converge quickly in a problem of large dimensions by small populations and iterations. Thus, the optimal contracted capacity and minimum annual electricity bill could be adequately solved by SSA to train the BPM parameters.

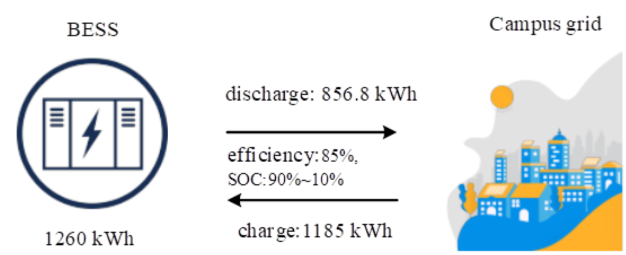

Fig. 3. The BESS parameters

Bin Packing Method: The SSA was used to train the parameters of the standard deviation σ and the normal distribution μ in (6) for BPM[10] to solve the charging and discharging schedule of the BESS, as shown in Figure 4. The objective function was based on the minimum annual electricity bill in (7). The constraint was set to the maximum net load demand to prevent over 835 kW of contracted capacity.

$$f(x)=\frac{1}{\sigma\sqrt{2\pi}}e^{-\frac{(x-\mu)^2}{2\sigma^2}}\tag{6}$$

$$\text{EBill}_{Annual}=\sum_{month=1}^{12}\sum_{day=1}^{Days}EBill_{Day}^{month}\tag{7}$$

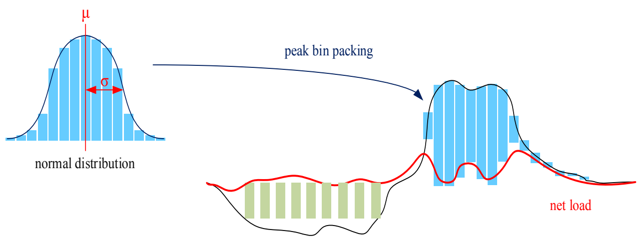

Fig. 4. An illustration of the schedule of BESS by BPM

III. Numerical Results and Discussions

The simple single-line diagram of the NCUE microgrid is shown in Figure 5; the yearly net peak and off-peak loads in 2020 are 1130 kW and 144 kW, respectively. The total installed capacity of photovoltaics is 582 kW. The BESS rating is 1 MW/1.26 MWh. The net load analysis and the optimal results are explained as follows.

A. Net Load Analysis

Figure 6 illustrates the net load distribution and duration of the NCUE microgrid in 2020. The annual net load demand is between 200-500 kW, accounting for more than 80% of the net yearly load. In addition, the annual net load is distinguished by the color depth and compared with a scale. Figure 6 shows that the horizontal axis is in units of days, and the vertical axis is in hours. It is evident from the figure that in the areas with a higher net load demand segment, the area's color is closer to red, and the segments with relatively low net load demand are closer to navy blue and turquoise. The net peak load is between 10:00-12:00 and 13:00-15:00; the net off-peak load is between 00:00 and 05:00, and the electricity consumption is relatively small.

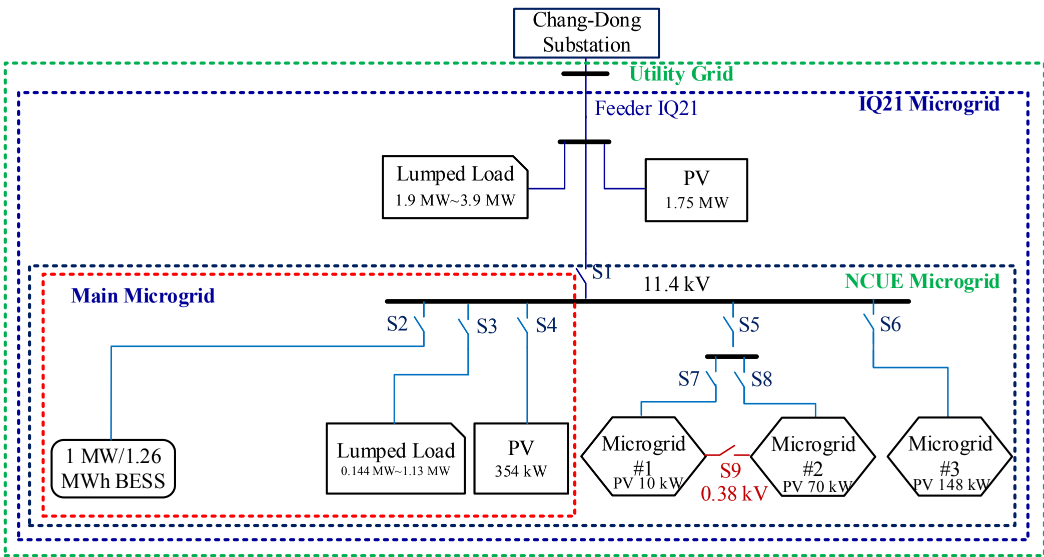

Fig. 5. A simple single line diagiam of the NCUE microgrid

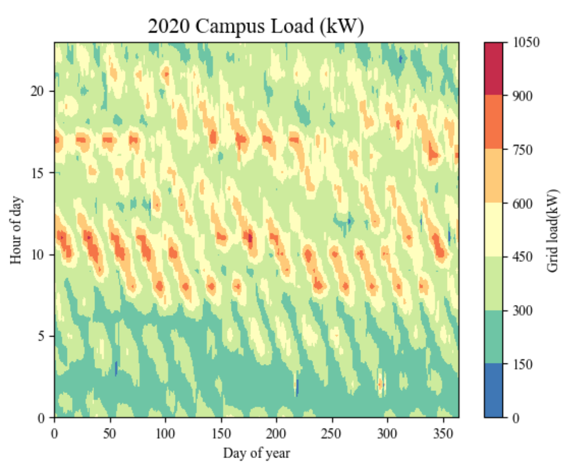

Fig. 6. Net load distribution and duration of the NCUE microgrid in 2020

B. Optimal Results

There are two scenarios in this study; one is the net load without the schedule of BESS, and the other is the net load with BESS. The numerical results are explained below.

Scenario #1: Figure 7 shows the net load curve in 2020; without considering the schedule of BESS, the optimal contracted capacity and the corresponding annual minimum electricity bill were derived by the proposed hybrid optimal approach with the SSA and BPM based on Figure 7. The optimal contracted capacity is 800 kW, and the annual minimum electricity bill is NTD 10,356,170 (342,279 USD), as shown in Figure 8. The minimum yearly electricity bill can be divided into three parts, i.e., the annual demand charge is NTD 1,783,680 (58,952 USD), the annual energy charge is NTD 8,333,312 (275,422 USD), and the extra cost for exceeding the contracted capacity is NTD 239,177 (7,905 USD). The months that exceed the optimal contracted capacity are May, June, September, and October, as shown in Figure 9. However, the annual electricity bill is still the lowest.

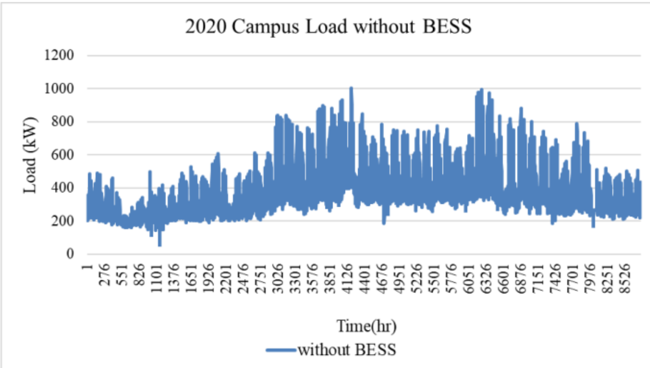

Fig. 7. Net load curve without scheduling of the BESS of the NCUE microgrid in 2020

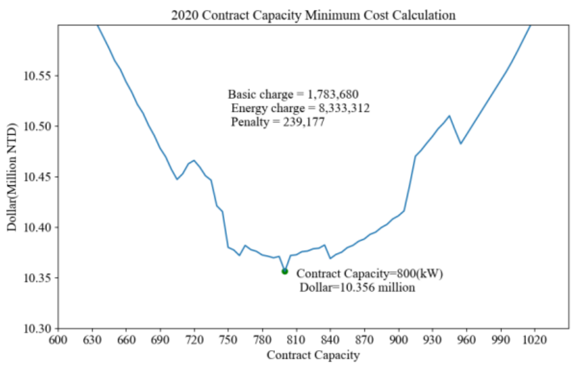

Fig. 8. Minimum electricity bill and optimal contracted capacity without scheduling of the BESS of the NCUE microgrid in 2020

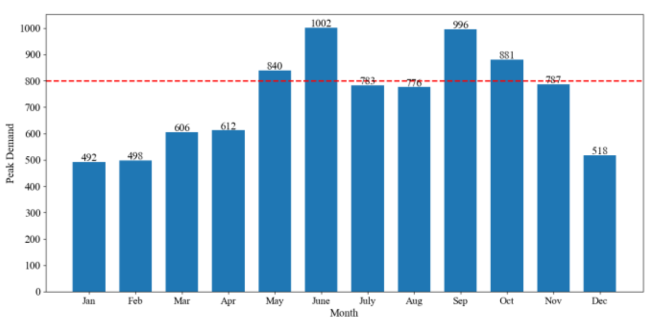

Fig. 9. Monthly net peak load and optimal contracted capacity without scheduling of the BESS of the NCUE microgrid in 2020

Scenario #2: Figure 10 shows the net load curves in 2020; the blue curve is the net load without the scheduling of BESS; the red curve is the net load with the optimal scheduling of BESS. The proposed hybrid optimal approach with the SSA and BPM obtained the optimal contracted capacity and the corresponding annual minimum electricity bill. The optimal contracted capacity is 745 kW, and the annual minimum electricity bill is NTD 9,933,487 (328,309 USD), as shown in Figure 11. The annual minimum electricity bill can be divided into three parts, i.e., the annual demand charge is NTD 1,661,052 (54,899 USD), the annual energy charge is NTD 8,072,307 (266,796 USD), and the extra cost for exceeding the contracted capacity is NTD 200,127 (6,614 USD). Similarly, the months that exceed the optimal contracted capacity are May, June, September, and October, as shown in Figure 12. However, the annual electricity bill is still the lowest.

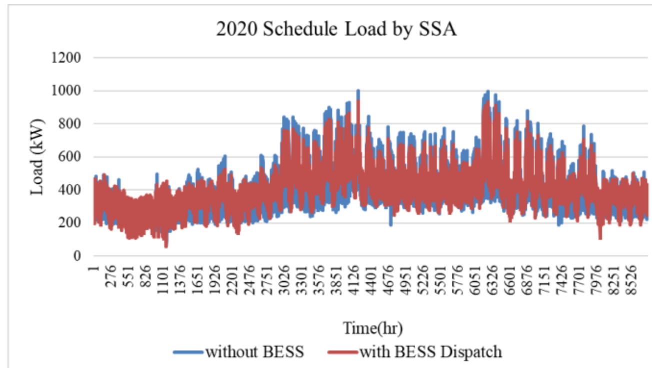

Fig. 10. Net load curve with scheduling of the BESS of the NCUE microgrid in 2020

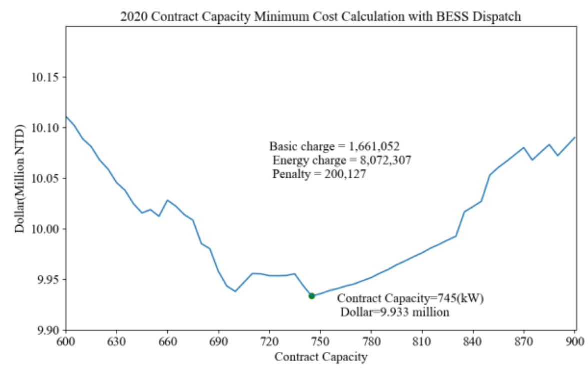

Fig. 11. Minimum electricity bill and optimal contracted capacity with scheduling of the BESS of the NCUE microgrid in 2020

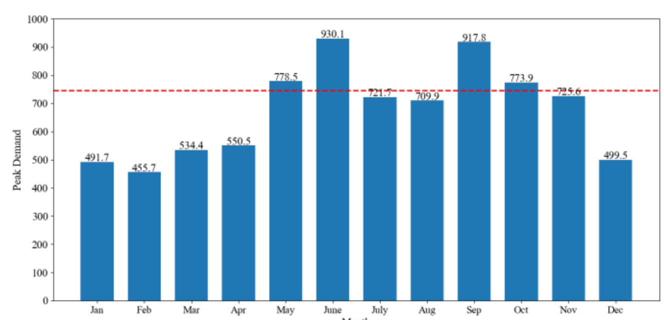

Fig. 12. Monthly net peak load and optimal contracted capacity with scheduling of the BESS of the NCUE microgrid in 2020

IV. CONCLUSION

A hybrid optimal approach using the SSA and BPM is proposed in this paper to solve for the optimal contracted capacity and its corresponding minimum annual electricity bill in a campus microgrid. The 8,760-load data with the unit of kW/hour were employed as the yearly load for this study. The numerical results demonstrate that the proposed approach could search for optimal solutions in two scenarios. Particularly with BESS's charging and discharging schedule, the optimal contracted capacity could be reduced to 6.875% compared with the net load without the scheduling of BESS; further, the minimum annual electricity bill could also decline to 4.08% compared with the net load without the scheduling of BESS. The proposed hybrid approach has rapid and effective characteristics for solving the minimum cost of microgrids.

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