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OPTIMIZATION OF CHARGING/DISCHARGING STRATEGY OF DISTRIBUTED BATTERY STORAGE SYSTEM IN BUILDINGS USING DYNAMIC PROGRAMMING

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ABSTRACT

This paper developed a new control strategy of distributed battery storage in response to price signal as an effective way of demand side management, using dynamic programming algorism to calculate the hourly power use from grid. An office building in Shenzhen, China was studied, verifying the feasibility of the control strategy. The result turned out that the total electricity cost can be saved by 28.1% comparing with a system without distributed battery storage, and by 8.1% comparing with a system where the distributed battery storage operates in the strategy of constant grid power taking.

Furthermore, the relationship of electricity cost with battery size and maximum charging/discharging power was studied. Based on the model, capacity and maximum charging/discharging power of battery fit well with a segmented linear model, in the range of practical application. The maximum charging/discharging power of battery storage system and minimum electricity fee could be fitted into a quadratic polynomial model. These findings could provide information and give reference for battery storage system design and operation.

Keywords: energy storage system, demand side management, dynamic programming, control strategy, price signal

1. INTRODUCTION

Due to the ever-increasing electricity consumption worldwide and the raising environmental concerns, energy efficiency has gained much more attention in recent decades. Many approaches have been adopted in order to improve utilization efficiency of electric energy and diminish carbon emission. Since the late 1970s, demand side management (DSM) methods and technologies emerged, techniques of which include peak clipping, valley filling, load shifting, strategic conservation, strategic load growth and flexible load shape. [2][3] It has been proved to be an effective strategy in improving energy efficiency in operating system and reliability of composite system, alleviating transmission congestion, and stabilizing market prices. [1]

In this regard, energy storage system in the demand side is commonly used to improve energy efficiency without lowering down the indoor comfort. [4][5] By charging in off-peak hours and discharging at in peak hours, energy storage system can achieve the effects of DSM, without a prominent change in occupant behaviors and energy consumption pattern from the occupants' side.

Distributed energy storage system could be applied in both AC/DC building to balance the mismatching of loads and energy generating and transmitting system, and to improve energy efficiency on a larger scale. However, in DC buildings that are usually equipped with low-cost, renewable energy systems, energy storage system is attached with even more significance. With use of DC power sources or end-user equipment such as PV panels, small wind generation, and LEDs lighting, storage systems coordinate the integration of distributed energy sources, diminish conversion losses of DC-to-AC inverters, and ensure high energy efficiency. [9] [10]

Different strategies and optimal allocation of energy storage system have been carried out. [12][13] Nevertheless, most control strategies start out from the grid point of view, lacking consideration of occupants' interest and a precise control strategy for distributed batteries in building corresponding to the time-of-use tariff has not yet studied deeply enough.

Price signal is often used to conduct a desired demand response which would be beneficial to the grid system. Considering that energy price would impact energy consumption pattern of occupant, governments would employ different pricing mechanisms based on historical data to reach a certain target on the market. [11] Researches on different pricing mechanisms have been done to evaluate their performance and to help

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setting an effective one. [5]-[7] It is generally recognized that the commercial efficiency would reinforce the system efficiency. While the participating customers try to lower their cost of electricity, they would enhance the reliability and efficiency of the system by balancing the energy supply and consumption. [1] Thus, this paper aims at an implementation of a control strategy of electric energy storage system based on price signal, to maximize commercial efficiency, minimize the total daily cost of electricity consumption, and reinforce system efficiency and reliability. The characteristics of batteries and their influences to electricity costs is also studied in the paper, providing important information for reference in practical engineering design.

The remainder of this paper is organized as follows. In section 2, a detailed model of control strategy of distributed battery storage in response to price signal is build based on dynamic programming algorism. Section 3 deals with a specific case, verifying the feasibility of the algorism. Section 4 discusses the effectiveness of the strategy in different energy storage system, where the capacity and maximum charging/discharging power of battery varies, in the light of referencing in engineering design. Finally, section 5 concludes the findings.

2. SYSTEM MODELLING AND METHODOLOGY

2.1 Dynamic Programming

Dynamic Programming (DP) is one of the most powerful solution approaches used in optimal control problems. In many cases when analytical solutions are not feasible, numerical approaches are used in reaching an optimal solution. DP excels many numerical approaches by processing a variety of characteristics. It solves optimal control problem at an acceptable computational cost; deals with constrains easily; provides a global minimum; and also offers closed-loop solutions. [14] These advantages make DP suitable for case handling in multiple situations, including control strategy design for distributed battery storage in building, where the charging power is to be determined in order to reach a most economic operating cost.

DP usually converts an optimal control problem into a sequential decision-making one by quantizing constant variables such us state and/or time into discrete values. An admissible control made up of a sequential of decisions is to be determined, and the system would follow an admissible trajectory on the sequential discrete time period.

In this case, the periodical time of control strategy is a day, which was quantized into 24 hours. For each time unit of an hour, the battery reserve was treated as state, and the charge quantity the decision to be made.

2.2 Problem Statement

This paper aims at minimize the total daily cost of electricity consumption of building by developing a control strategy of electricity storage with a known battery storage system under different pricing mechanisms.

Such a problem can be described as the minimization of the cost function in following form

$$f=\left(\sum_{t=1}^{12}P_{grid}(t)\times F_{elec}(t)\times\vartriangle t\right)_{\min} \tag{1}$$

where $P_{grid}(t)$ is the quantity of electricity took from grid during the time period of $t-1\sim t; F_{elec}(t)$ is the electricity price during the same period of time; $\vartriangle t$ is the length of the period, an hour in this case. $P_{grid}(t)$ could be determined by the equation below,

$$P_{grid}(t)\cdot\vartriangle t=\left(P_{load}(t)-P_{bat}(t)\right)\vartriangle t \tag{2}$$

where $P_{bat}(t)$ is the average charging power of the battery, and $P_{load}(t)$ the electricity load in the building.

From $P_{bat}(t)$ the total charging load in the time interval, of which $S_{up}(t)$ is used as representation, can be determined as follow,

$$P_{bat}(t)\cdot\vartriangle t=-S_{up}(t) \tag{3}$$

$S(t)$ describes the battery reserve after this time interval, viewing as 'state' at the end of each period of time. The state equation is

$$S(t)=(1-\sigma)S(t-1)+S_{up}(t) \tag{4}$$

where σ is self-discharge rate of the battery.

24 states of $S(t)$, as well as 24 decisions of $S_{up}(t)$ determine the whole control strategy of the electricity storage system.

2.3 Constraints

In order to prevent over-charging/over-discharging, the maximum/minimum battery reserve in each time interval is constrained between 5% to 95% of the total capacity S_r. In that $S_{\min}=0.05S_r, S_{\max}=0.95S_r$, $S(t)$ fulfills

$$S_{\min}<S(t)<S_{\max} \tag{5}$$

Total charging load in each time interval is confined by the maximum charging/discharging capacity and battery residual capacity/reserve:

$$\begin{cases} S_{up}(t) < \min\{S_{\max} - (1-\sigma)S(t-1), P\eta\triangle t\} \\ S_{up}(t) > -\min\{(1-\sigma)S(t-1) - S_{\min}, P\eta\triangle t\} \end{cases} \quad (6)$$

where P, η is the power rating and efficiency of charging/discharging.

Consider that the strategy design is based on a typical daily load curve, state meets requirement of periodical variation from $S(0)$, which is the battery reserve in the beginning of the day, to $S(24)$, which is the battery reserve in the end of the day. Thus,

$$S(0) = S(24) \quad (7)$$

Both $S(0)$ and $S(24)$ are set as 0 in this case, considering that all the lowest price of electricity only occurs after midnight.

3. RESULTS

3.1 Case Description

The case building is located in Shenzhen, China, with a total space of 4374 m^2. The building is designed with DC power system, a 375V high voltage power bud to deliver power across different floors. The structure of the building is modeled in DeST, and the electric load is simulated based on actual building envelope, weather condition of building location, and several official design standards. [15]-[17]

3.2 Daily Load Extraction

K-means cluster analysis is used to extract daily load based on seasonal feature. The following analysis is based on the category mainly occurred in summer-business-day. The following two figure shows all the days that fulfill this category and the typical daily load curve.

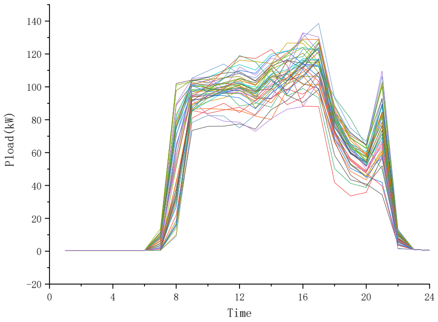

Figure 1 Days belong to the studied category

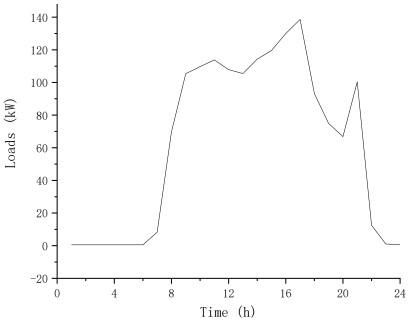

Figure 2 A typical daily load curve of the studied category

3.3 Optimization Results

The energy storage system uses a Pb-C battery group to store electricity, which has a total capacity of $600kW \cdot h$, and power rating of $75kW$ when charging/discharging. The capacity is initially design to fulfill the requirement of constant power extraction from the grid, calculated by the daily load curve.

The algorism is written in python and operated on a personal computer. The result of control strategy design is shown in the following figure.

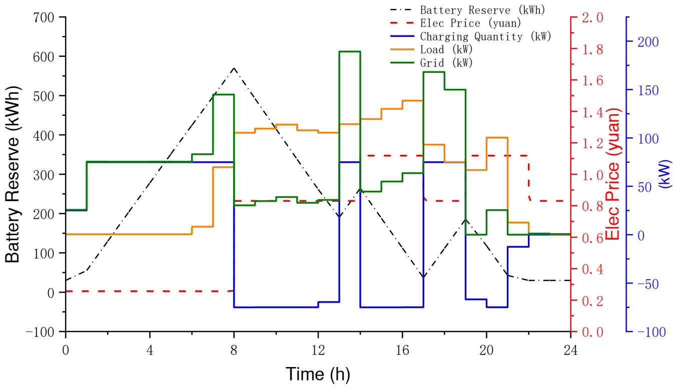

Figure 3 Control strategy of storage system in response of price signal

As can be seen in the figure, the charging or discharging of the battery is influenced by electricity price of the grid, the typical load curve, as well as the previous battery reserve. During peak hours the need of electricity is fulfilled by both the storage system and the grid, which would alleviate the pressure of the city grid. Charging mainly happens during the night and the normal hours, making the system operation economically satisfying.

The total cost of electricity was reduced by 28.13%, from originally 1341.94 yuan per day to 964.42 yuan per day. Obviously, with an additional energy storage system the total cost of electricity can decline. However, comparing with the constant grid power strategy, where the charging/discharging state of distributed batteries is controlled in order to ensure a constant grid power taking, the optimal strategy can save the cost by 8.1% with the same battery capacity. The strategy of constant grid power taking is shown in the Figure 4.

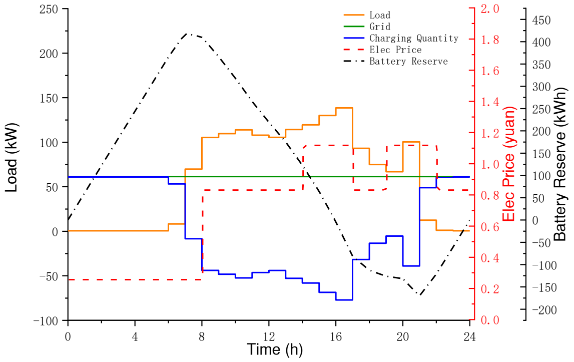

Figure 4 Control result of constant grid power strategy.

The results show that the optimal control strategy can be economical, which makes it feasible in actual application.

3.4 *Relevant Battery Characteristics*

In order to understand the characteristics of the proposed strategy, and to give reference in designing in the first place, further analysis should be made. Battery storage system with various capacity and maximum charging/discharging power was studied in this section.

3.4.1 Battery capacity

With maximum charging/discharging power fixed in a reasonable level of $75kW$, system of various capacity was analyzed. The relationship between capacity and total electricity fee is illustrated in figure 4. Capacity of battery storage system and minimum electricity price could be fit in to a linear model when capacity is in a certain range. This range also fits the common capacity range suitable for the building, considering that in practical application, a battery capacity too large or too small is meaningless. Thus, with the initial cost of system in different scale taken into consideration, the economic benefits of battery storage system could be calculated.

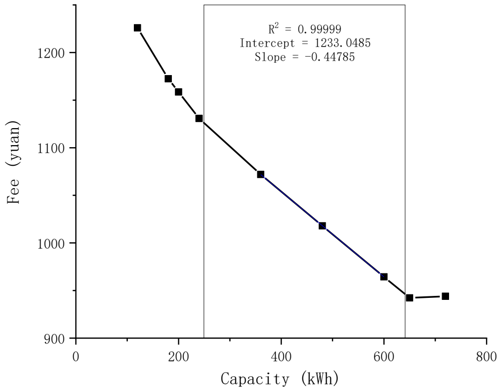

Figure 5 Relationship of capacity of battery storage system and minimum electricity fee

3.4.2 Maximum Charging/Discharging Power

With fixed battery capacity, systems of various maximum charging/discharging power were analyzed. Impropriate charging/discharging power could greatly influence the longevity of battery life. Relationship of maximum charging/discharging power of battery storage system and minimum electricity price could be shown in Figure 5.

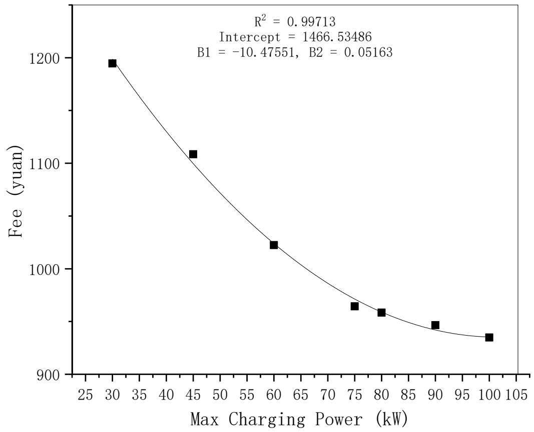

Figure 6 Relationship of maximum charging/discharging power of storage system and minimum electricity fee

As can be shown in the figure, maximum charging/discharging power of battery storage system and minimum electricity fee fits well with a quadratic polynomial model, indicating that increasing of maximum charging/discharging power could only cut the electricity fee to a certain degree. In this case, choosing a maximum charging/discharging power of $75kW$ is plausible, in that the absolute slope of the curve in Figure 5 declined greatly after $75kW$, which means that increasing of maximum charging/discharging power could receive little benefits. Same rules could be applied to other cases and shed light on designing and choosing of the battery storage system.

4. DISCUSSION

Batteries in building can balance the mismatch between the supply side and the consumption side. This imbalance exists in multiple conditions and thus could have wide applications. Especially for the zero-carbon building with renewable energy systems, the distributed battery storage system becomes more critical in order to balance the power mismatch, making this control strategy proposed by this paper promising in the further development of energy efficient building.

5. CONCLUSION

A control strategy of charging/discharging of distributed battery storage system in response to price signal is developed and optimized using Dynamic Programming algorism, which proved to be an effective way of demand side management. In dealing with a specific case of an office building in Shenzhen, China, the total cost of electricity was reduced by 28.13%, and by 8.1% comparing to the same distributed batteries operating in constant grid taking strategy. Distributed battery storage systems with various capacity and maximum charging/discharging power was also studied. The study shows a linear relationship between battery storage system's capacity and maximum charging/discharging power within a range fitting for practical application. It also founds that the maximum charging/discharging power of battery storage system and minimum electricity fee fits well with a quadratic polynomial model. The finding sheds light on future application in designing and operating of distributed battery storage system.

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