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BATTERY CAPACITY OPTIMIZATION IN PV-BATTERY INTEGRATED ENERGY SYSTEM BASED ON MODIFIED MIN-MAX DISPATCH METHOD

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ABSTRACT

With increasing capacity of renewable energy power generation system, energy storage sizing problem raised with growing attention. Optimal energy storage capacity minimizes system cost while ensuring renewable energy meet grid codes. The modified min-max dispatch method has been proved to be one of the superior dispatching methods in wind power integration. In this paper, this dispatching method is applied to photovoltaic grid-connected system, and the corresponding optimal capacity of energy storage system is calculated. Moreover, state of charge (SOC) and depth of discharge (DOD) is considered in the determination of energy storage capacity. Using lifetime cost function as the optimization objective of energy storage capacity. The data of this study are derived from the measured data of the photovoltaic power generation experimental platform in Jinan, China.

Keywords: energy storage, sizing, optimization methods, state of charge control, PV–battery integrated energy system

1. INTRODUCTION

The increasing demand for energy and the concern about environmental stimulate the growth in renewable energy [1]. According to the IRENA's statistics [2], the world's total renewable energy capacity increased from 1,060,668 MW in 2008 to 2,179,426 MW in 2017. However, renewable energy is usually characterized by high uncertainty and large fluctuation (or intermittency) due to, e.g., natural and meteorological conditions [3]. With the increasing permeability of renewable energy in power grid, the high uncertainty and large fluctuation characteristics of renewable energy bring great challenges to the power system, such as grid interconnection, power quality and system reliability [4].

A battery energy storage system (BESS) and a PV cooperate to stably dispatch power to the grid. This system is referred to as a PV–battery integrated energy system, in which the dispatched power influences the BESS output power. As a result, to optimize the battery capacity, the dispatch power needs to be identified primarily. At present, the dispatching methods that have been applied include average power method [5], min-max method [6] and dispatching method using low-pass filter [7] or spectral analysis method [8] to assign the dispatch power. However, the average power method makes the ES charged and discharged frequently, which reduces the life of the ES. The last two methods do not consider the cooperation with the transmission system operator. And the original min-max method usually requires large storage capacity.

Therefore, in this paper, we introduce the modified min-max method developed by Nguyen et al. [9] into the research of PV grid-connected, and optimize the battery capacity in PV-battery integrated energy system. Section 2 introduces the configurations and power dispatching methods for PV. In Section 3, a linear search method is used to optimize the ES capacity with lifetime cost as the objective function. Case study is provided in Section 4. Section 5 demonstrates conclusions of this paper.

2. CONFIGURATION AND POWER DISPATCHING METHODS FOR PV

Fig 1 illustrates the common configuration of a PV-battery system. The PV and BESS are connected to the grid at a point of coupling (PCC) through power converter system (PCS), respectively. The BESS functions as an energy buffer for the PV: It absorbs and releases power to compensate for the intermittent solar power, allowing the integration of stable power into the grid.

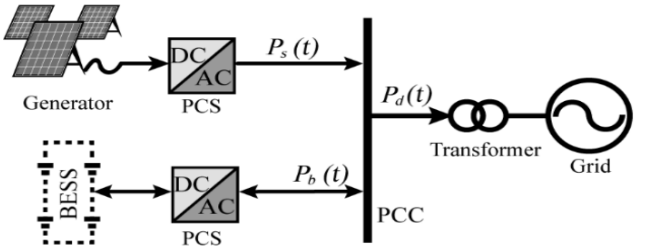

Fig 1 Configurations of hybrid BESS and PV system.

The required BESS capacity, which is normally specified in terms of energy rating E_b^{rat} and power rating P_b^{rat}, is defined based on the BESS power flow. As shown in Fig 1, $P_s(t)$ is the PV power and $P_d(t)$ is the power that the IES dispatches to the grid. If the power loss in the system is neglected, the power output of the BESS, $P_b(t)$, can be expressed as:

$$P_b(t) = P_d(t) - P_s(t). \quad (1)$$

For a system operating over time period T, the BESS power rating required is

$$P_b^{rat} = \max_{0\le t\le T} |P_b(t)| = \max_{0\le t\le T} |P_d(t) - P_s(t)|. \quad (2)$$

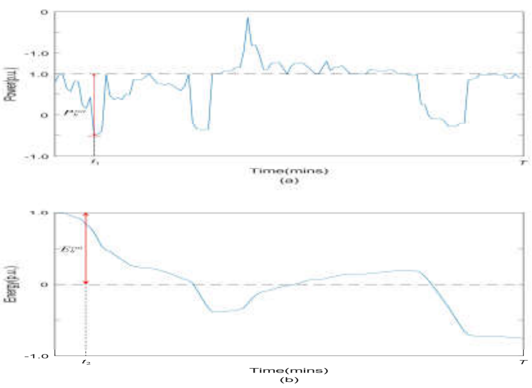

Fig 2 Definition of the required BESS capacity. (a) BESS power flow. (b) BESS energy response.

Fig 2(a) shows the $P_b(t)$ response when $P_d(t)$ and $P_s(t)$ are known. Because the BESS power is maximal at instant t_1, this value is defined as the BESS power rating. The net energy injected into or drawn from the battery up to time t can be calculated as follows:

$$E_b(t) = \int_0^t P_b(\tau)d\tau = \int_0^t [P_d(\tau) - P_s(\tau)]d\tau. \quad (3)$$

Similar to the power rating, the energy rating is the maximum volume defined as

$$E_b^{rat} = \max_{0\le t\le T} [E_b(t)]. \quad (4)$$

The BESS energy response, in which the energy rating is designated at instant t_2 when the BESS stores the largest amount of energy, is illustrated in Fig 2(b).

The modified min-max method proposed by Nguyen et al. has a good application effect in the wind power integration, but is never applied in the PV grid-connected. Fig 3 clearly illustrates the application of this dispatching method in PV grid-connected. The control strategy and other details of this method can be found in literature [9]. Essentially, this control method is a feedback control method based on SOC state.

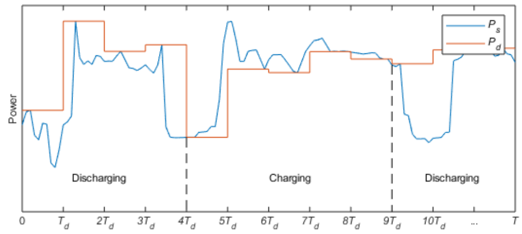

Fig 3 Modified min–max dispatching power strategy for PV.

3. OPTIMIZATION OF BESS CAPACITY

The basic capacity of the BESS needs to be determined before the battery capacity is optimized. Because the state of the battery during each dispatching time can only be charging or discharging, the maximum value of the absolute value of the charge and discharge power rating and energy rating in each dispatching time T_d need to be found first. At this point, the basic value of battery power rating can be obtained, and it is also the optimal value, that is

$$\begin{cases} P_b^{basic} = \max_{1\le i\le N} \{P_b^{rat}[i]\} \\ E_b^{basic\prime} = \max_{1\le i\le N} \{E_b^{rat}[i]\} \end{cases}. \quad (5)$$

Where, $P_b^{rat}[i]$ represents the larger value of the charge and discharge power rating and $E_b^{rat}[i]$ represents the larger value of the charge and discharge energy rating in the ith interval T_d, respectively. The PV-power profile during time period T is divided into N sets, i.e. $T = NT_d$. According to the characteristics of PV power generation, in order to ensure that the SOC of the battery is always within the appropriate range, the basic energy rating of the battery should be twice as much as $E_b^{basic\prime}$. Considering the DOD of the battery, E_b^{basic} is

$$E_b^{basic} = 2E_b^{basic\prime}/DOD. \quad (6)$$

The determined basic capacity guarantees that the battery can handle the charge and discharge requirements of the modified min-max dispatching strategy within the time period under study. However, it often does not ensure that the system gain the maximum profit, so it is necessary to find the optimal capacity. Based on the dispatching strategy of this paper, if it is assumed that the price of electricity sold by PV to the grid is fixed, then the profit of the system increases with the decrease of battery cost. Two factors should be taken into account in measuring battery cost, that is, battery investment cost and battery lifetime. The function of battery lifetime cost (LTC) interprets this problem very well, and it is used as the objective function of battery capacity optimization in this paper. LTC is defined as

$$LTC = \frac{\alpha E_b^{cap}}{E_d} \cdot \frac{c}{C_r}. \tag{7}$$

Where, α is battery energy cost (in dollars/kilowatt-hour), E_b^{cap} is BESS capacity, their product is the total cost of BESS. E_d is the total energy that the renewable energy generation system delivers to the grid in time period T (i.e. $E_d = \sum_T P_d T_d$). c is the total number of battery charge-discharge cycles in time period T. C_r is the number of full-charge-discharge cycles, which the battery can perform in its entire lifetime. Once the battery capacity is provided, all components in (7) can be computed to define LTC. In this paper, a linear search method is used to find the optimal battery capacity, E_b^{opt}, in $[E_b^{basic}, +\infty]$. In the search process, the BESS capacity at each searching step is set as

$$E_b^{cap} = E_b^{basic} + k \times E_b^{basic\prime}. \tag{8}$$

Where, k is the normalized ratio of the $E_b^{basic\prime}$ and we set $k = 0$ at the first iterative step to compute LTC corresponding to the basic BESS capacity.

4. CASE STUDY

In order to illustrate the BESS capacity determination method for the hybrid PV-battery system, several numerical examples are made by using MATLAB software. The PV power profile from June 1, 2018 to July 15, 2018 is taken from a PV power generation experimental platform in Jinan, China, with a 1-min sampling time. In addition, the minimum dispatching time interval is assumed to be set to 15 min by the transmission system operator (i.e., $T_d = 15$ min). It is assumed that the system utilized a Li-Ion battery with the following price and cycle life: α = \$1,000/kWh and C_r = 2,500 cycles, respectively [10]. And the battery SOC is controlled within a safe range 10% to 90% (i.e. $DOD = 0.8$).

For ease of explaining the steps to decide the basic BESS capacity, we only consider the PV power between 05:00 and 19:30 of a day. During the discharge phase, the power dispatch was set to the maximum PV power for each T_d, as shown in Fig 4(a). The BESS discharge power and energy in each T_d interval were calculated and then plotted in Fig 4(b) and (c), respectively. The comparison of all the discharge power ratings in the considered window time revealed that the biggest rating was the basic BESS power rating during the discharge phase; it is P_{dis}^{rat} or 212.8 W at instant t_1. Similarly, the biggest BESS energy rating in the discharge stage is E_{dis}^{rat} or 28.79 Wh at instant t_2. Based on (6), the basic BESS energy rating E_b^{basic} is 71.975 Wh.

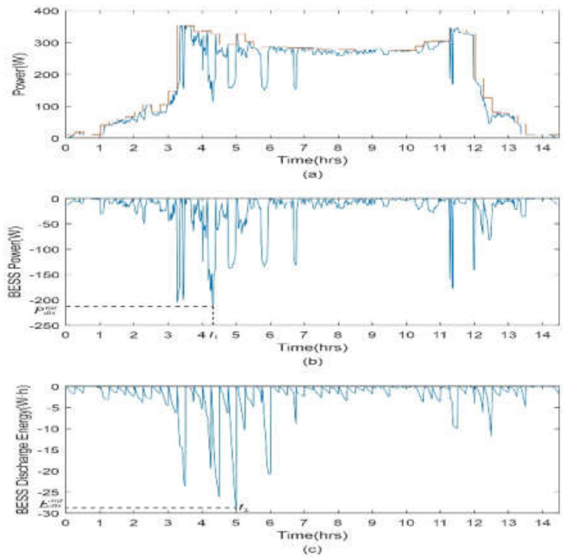

Fig 4 Discharge phase. (a) PV power and dispatched power. (b) BESS discharge power. (c) BESS discharge energy.

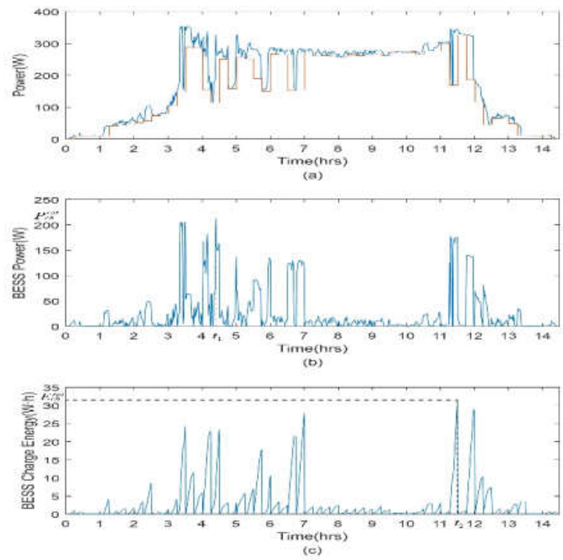

Fig 5 Charge phase. (a) PV power and dispatched power. (b) BESS charge power. (c) BESS charge energy.

Fig 5 shows the charge phase, the basic BESS power rating in the charge stage is P_{ch}^{rat} or 212.8 W at instant t_1 as shown in Fig 5(b) and the biggest BESS energy rating in the charge stage is E_{ch}^{rat} or 31.49 Wh at instant t_2 as shown in Fig 5(c). And the basic BESS energy rating E_b^{basic} is 78.725 Wh.

The basic BESS power rating and basic BESS energy rating in the considered 14.5 hours is the bigger one of the capacities in charge and discharge phases, respectively. Therefore, the basic BESS power rating is 212.8 W and basic BESS energy rating is 78.725 Wh. When considering PV power from June 1, 2018 to July 15, 2018, we obtain the basic BESS capacity as P_b^{basic} = 332.6850 W and E_b^{basic}=153.3225 Wh.

In order to investigate the general relationship or correlation between the system cost and the battery capacity, LTC, the total energy delivered into the grid E_d, and the total charge–discharge cycles c of the battery are shown in Table 1 at the given battery capacity. Five cases of k from 0 to 0.4 are considered.

Table 1

k	0	0.1	0.2	0.3	0.4
$E_b^{cap}(Wh)$	153.3 225	159.3 554	165.3 883	171.4 212	177.4 541
$E_d(kWh)$	90.23 62	90.24 52	90.25 07	90.29 60	90.19 69
$c(cycles)$	71	66	62	60	59
$LTC(\$/kW$	0.047 6	0.046 6	0.045 5	0.045 6	0.046 5

In Table 1, it is clear that there exists an optimal battery capacity that minimizes the cost because LTC approaches a certain minimal value corresponding to k. When the accuracy of k considered in this paper is 0.1, the optimal BESS capacity is 165.3883 Wh, and the smallest LTC value is 0.0455 \$/kWh. In addition, using the optimal capacity, the system is also evaluated and the SOC of battery is managed and kept successfully in a safe range of 0.1-0.9 as illustrated in Fig 6. However, the situation that when the battery charge and discharge state transition, the SOC of the battery does not reach the maximum or minimum value has occurred many times, which makes the battery capacity wasted at these moments. Therefore, if we can make full use of these wasted capacity, then LTC will be further reduced.

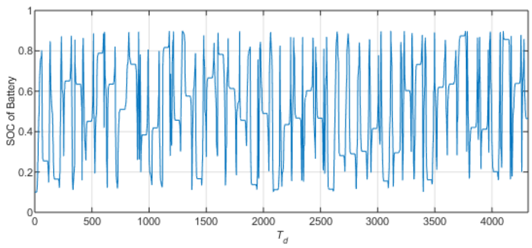

Fig. 6 SOC of BESS with its optimal capacity.

5. CONCLUSIONS

In this paper, the modified min-max dispatch method is applied to PV grid-connected system and the corresponding optimal capacity of BESS is determined by using a lifetime cost function. Through the case study, we find that the existing modified min-max dispatch method is not superior in PV grid-connected, which is due to the high fluctuation of PV power generation at sunrise and sunset. Therefore, the scheduling method used in PV grid-connected in the future needs to take into account the characteristics of PV power generation and prolong the lifespan of ES system as much as possible.

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REFERENCE

[1]. Wennersten, R., Q. Sun and H. Li, The future potential for Carbon Capture and Storage in climate change mitigation – an overview from perspectives of technology, economy and risk. Journal of Cleaner Production, 2015. 103: p. 724-736.

[2]. IRENA, Renewable Energy Statistics 2018. The International Renewable Energy Agency, Abu Dhabi.

[3]. Liu, L., et al., Prediction of short-term PV power output and uncertainty analysis. Applied Energy, 2018. 228: p. 700-711.

[4]. Sun, Q., et al., A Comprehensive Review of Smart Energy Meters in Intelligent Energy Networks. IEEE Internet of Things Journal, 2016. 3(4): p. 464-479.

[5]. Gholami, M., et al., A new strategy based on hybrid battery – wind power system for wind power dispatching. IET Generation, Transmission & Distribution, 2018. 12(1): p. 160-169.

[6]. Fathima, A.H., N. Prabaharan and K. Palanisamy. Sizing of a VRB battery based on max-min method of power dispatch in a wind-PV hybrid system. in 2015 IEEE Conference on Energy Conversion (CENCON). 2015: IEEE.

[7]. Jiang, Q. and H. Wang, Two-Time-Scale Coordination Control for a Battery Energy Storage System to Mitigate Wind Power Fluctuations. IEEE Transactions on Energy Conversion, 2013. 28(1): p. 52-61.

[8]. Ding, M. and J. Wu, A Novel Control Strategy of Hybrid Energy Storage System for Wind Power Smoothing. Electric Power Components and Systems, 2017. 45(12): p. 1265-1274.

[9]. Nguyen, C., H. Lee and T. Chun, Cost Optimized Battery Capacity and Short-Term Power Dispatch Control for Wind Farm. IEEE Transactions on Industry Applications, 2015. 51(1): p. 595-606.

[10]. IRENA, Electricity Storage and RE for Island Power-A Guide for Decision Makers. The International Renewable Energy Agency, Abu Dhabi.