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Energy storage configuration for smoothing the output volatility of PV power generation

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Abstract. The volatility of photovoltaic (PV) power generation affects its schedulability and friendly grid connection. Energy storage as a highly flexible and controllable regulation resource is regarded as a key technical means to smooth PV power output. This paper proposes a BESS power and capacity determination method based on the definition of maximum PV power volatility and gives an empirical formula for determining the energy storage capacity under different levels of PV output volatility. Furthermore, the determination of BESS under different maximum power volatility constraints and installed capacity of PV plants is also studied. It provides a reference for the actual energy storage planning with different renewable energy penetration levels, which is conducive to the friendly grid connection and dispatch of renewable energy power generation.

1. Introduction

The diurnal characteristics, volatility, and randomness of photovoltaic (PV) power generation lead to short utilization hours of PV power generation, poor schedulability and unfavorable for its friendly grid connection [1]. Due to the limited active power adjustment capability of large-scale PV power plants, the output of PV power plants fluctuates even to 70%/min~90%/min under extreme scenarios [2,3]. The national standard specification for power ramp rate change does not exceed 10% installed capacity in one minute [4]. At present, it is difficult for PV power plants to meet the grid-connected conditions, which results in the consequence that many power plants choose to abandon PV power to meet the grid standards. Some additional control measures have been taken to smooth the PV output. With the advancement of energy storage technology, its large-scale application has become possible, which is an effective measure to improve the volatility of PV output. In order to meet this condition, large-scale PV power plants are generally equipped with certain energy storage devices to stabilize the power fluctuations of the PV power station.

Research on energy storage capacity configuration currently focus on analyzing the important applications of energy storage in large power grids or single PV power plants. Usually, these methods are based on the detailed description of the battery energy storage and its flexible operation and control strategies to stabilize the volatility of PV systems[5-8]. For example, when ESS is used in large power grids, it is mainly used for hour-level load following, climbing control of conventional units of the 1min~1h level, transient stability and frequency control of seconds to minutes. When used in a single PV power plant, it is mainly used for the smoothing of the output power of the PV power station [9,10]. Unfortunately, current research requires a detailed model and corresponding optimization algorithm for calculating the energy storage configuration. Therefore, it is necessary to propose a practical model that is simple, quantifiable and easy to be implemented.



Therefore, the main contribution of this paper is to reveal the law of energy storage capacity configuration under different PV volatility and penetration levels and provide practical references for energy storage planning in a power system with a high-density PV integration.

2. Model construction based on maximum power fluctuation rate constraint

2.1. Definition of maximum PV power fluctuation

In order to determine the minimum BESS capacity to achieve PV grid-connected power fluctuations within a reasonable range, it is first necessary to define the volatility of the PV output power. Given a PV output power sequence $P_{PV}(t)$ and set Δt to be a sampling time window, the PV power fluctuation $\Delta P_{\Delta t}(t)$ at time t is defined as the percentage of the PV output power difference and the rated power of the inverter P^* at two adjacent sampling time intervals [2], indicating as follows:

$$\Delta P_{\Delta t}(t) = \frac{|P_{PV}(t) - P_{PV}(t - \Delta t)|}{P^*} \times 100 (\%) \quad (1)$$

By setting the fluctuation threshold r , the frequency distribution of the PV output power time series exceeding the threshold (i.e. $\Delta P_{\Delta t}(t) > r$) can be counted, and different thresholds can be selected to obtain the distribution of different fluctuation levels in the sequence. For example, when $r = 1\%/min$, $P^* = 550$ kW, there will be 40% of the time power fluctuations in the statistical period exceeding the threshold. When the threshold value r is kept constant, when the PV power plant capacity is increased to $P^* = 38.5$ MW, the time for the power fluctuation within the statistical period is only 23%. When $r = 30\%/min$, the power fluctuation time is only 3% for the $P^* = 550$ kW system. To characterize the maximum power volatility of a PV plant at the sampling interval Δt , define the following:

$$r_{MAX} = \max \{ \Delta P_{\Delta t}(1), \Delta P_{\Delta t}(2), \dots, \Delta P_{\Delta t}(k), \dots, \Delta P_{\Delta t}(n) | k = 1, 2, \dots, n \} \quad (2)$$

After the BESS is added to the PV power generation system, the real-time power of the PV+BESS hybrid system fed into the grid can be expressed as follows.

$$P_g(t) = P_{PV}(t) + P_{bat_sys}(t) \quad (3)$$

where $P_{PV}(t)$ and $P_{bat_sys}(t)$ indicate the real-time output power of the PV power generation and BESS. In order to stabilize the fluctuation of PV output, the maximum power fluctuation $\Delta P_{G,max}(t)$ of this PV+BESS system should not exceed the power volatility limit of the grid r_{MAX} (%/min). When the real-time power volatility of the PV+BESS system exceeds the limit, the following formula is satisfied. At the time, the energy storage is triggered to charge and discharge to meet the power shortage portion.

$$\Delta P_{G,max}(t) = \max(|P_g(t) - P_g(t - \Delta t)|) > r_{MAX} \quad (4)$$

At that time $\Delta P_{G,max}(t) > r_{MAX}$, then $P_{bat_sys}(t) > 0$, the excess PV power is charged to the stored energy to suppress excessive power fluctuation; if $\Delta P_{G,max}(t) < -r_{MAX}$, then $P_{bat_sys}(t) < 0$, the energy storage discharge meets the power shortage caused by the insufficient power. The rate power and capacity of BESS can be calculated according to the fluctuation amplitude and duration of $\Delta P_{G,max}(t)$.

2.2. Determination of BESS power and capacity

In order to completely stabilize the volatility of PV output, it is necessary to consider the maximum fluctuation of PV output (maximum fluctuation should consider both power and energy) and determine the maximum power fluctuation range to determine the power and capacity of BESS. In practice, the fluctuation of PV output mainly comes from the shading of the cloud shading. The literature [2] suggested that the fluctuation of a PV power generation due to cloud passage can be modeled as an exponential function. Figure 1 shows the output of a 100MW PV power plant on a

certain day. The blue exponential form curve in figure 1 is the PV output $P_{PV(t)}$, and the red oblique solid line is the power $P_{g(t)}$ at the grid connection point of the PV+energy storage described in equation (3), and the black solid line is $P_{g(t)}$. The solid black line is the difference between $P_{g(t)}$ and $P_{PV(t)}$, which is the charge and discharge power of the BESS. The maximum value of the difference corresponds to the maximum power $P_{BAT,MAX}$ required by BESS. The area enclosed by the time axis is the charge and discharge capacity of the BESS, that is, the capacity of the BESS.

$$P_{bat_sys}(t) = \frac{P^*}{100} \left[90(1 - \exp(-t/\tau)) - t \times r_{MAX} \right] \quad (5)$$

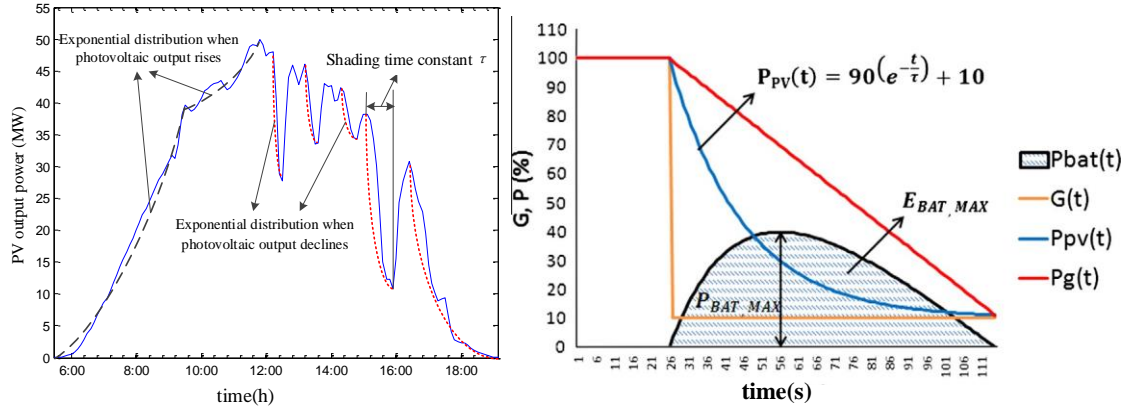


Figure 1. The exponential distribution of PV output power fluctuation

Where P^* is the rated power of the inverter; it should be noted that the actual rated DC power P_N of the PV power station and P^* satisfy the relationship of $P^* = 0.85P_N$. The time constant τ in the above equation is mainly affected by the PV power plant area. Since PV power plants generally have regular polygonal geometry, their maximum power volatility is related to the shortest path through which the clouds pass. The empirical formula is as follows:

$$\tau = a \times l + b \quad (6)$$

Where l is the shortest distance of the PV power plant in the direction of the cloud path, and $a = 0.042$ (s/m), $b = -0.5$ s. Since different PV power plants have different geometric parameters, the time constants are different, generally ranging from several seconds to several tens of seconds. Therefore, the larger the footprint of the PV power station, the smoother the output power. Deriving equation (5) to get the maximum value when $t = \tau \times \ln(90 / (\tau \times r_{MAX}))$, and the rated power of the required BESS can be obtained as follows:

$$P_{bat_sys,MAX} = \frac{P^*}{100} \left[90 - \tau \times r_{MAX} \left(1 + \ln \frac{90}{\tau \times r_{MAX}} \right) \right] \quad (7)$$

As can be seen from figure 1, the PV output can be expressed as (8) from the rated power P^* to $0.1P^*$, which is also the residence time of the cloud shading in the PV power plant.

$$T_R = \frac{90}{r_{MAX}} \quad (8)$$

At the same time, the storage capacity $E_{BAT,MAX}$ is:

$$E_{BAT,MAX} = \int_0^{T_R} P_{bat_sys}(t) dt = \frac{0.9P^*}{3600} \left[\frac{90}{2r_{MAX}} - \tau \left(1 - \exp\left(-\frac{90}{\tau r_{MAX}}\right) \right) \right] \approx \frac{0.9P^*}{3600} \left[\frac{90}{2r_{MAX}} - \tau \right] \quad (9)$$

Since the initial direction of PV output power fluctuation is unknown, in order to ensure that the battery can completely suppress power fluctuations, twice the maximum energy storage and discharge capacity are needed to balance the power fluctuations that may be upward or downward, that is, the energy storage capacity is:

$$S_{Ah} = 2E_{BAT,MAX} = \frac{1.8P^*}{3600} \left[\frac{90}{2r_{MAX}} - \tau \right] \quad (10)$$

At this point, formula (7) and (10) can quickly determine the power rating and capacity value of the BESS that an actual PV system needs to be installed.

3. Case Study

3.1. Parameter settings and model validation

For a PV power plant with a maximum AC inverter power of about $P^*=100$ MW, the DC power density of the PV power plant is 65 dc-W/m², and the DC power is $100/0.85=117.65$ MW. The area is $A_{PV}=117.65 \times 10^6/65=1.81 \times 10^6$ (m²). In order to calculate the shape parameters l of the PV power plant, simplified here that the PV power plant is a square layout, so $l = \sqrt{A_{PV}} = 1345$ (m). Substituting (8) can obtain the corresponding fluctuation time under the maximum power fluctuation rate, which is $\tau = 0.042 \times 1345 + (-0.5) = 56$ (s). Under the maximum power fluctuation rate constraint $r_{MAX}=10\%/min$, the rated charge and discharge power of BESS $P_{bat,sys,MAX}=0.5952P^*=59.52$ (MW) can be obtained from (9), and the maximum battery capacity is $S_{Ah}=P^* \times 0.1070h=10.70$ (MWh).

3.2. Sensitivity analysis

As can be seen from the left image in figure 2, as the capacity of the PV power plant increases and the r_{MAX} decreases, the power of the required BESS will increase rapidly. It is easy to know that as the capacity of the PV power plant gradually increases, the power fluctuation range is smaller. At 10MW, the maximum power fluctuation reaches $r_{MAX}=45\%/min$; when the PV capacity increases to 100MW and 1000MW, the maximum power fluctuation is reduced to about 30% and 15%, respectively. It can be seen that the PV power fluctuation is difficult to meet the 10%/min fluctuation constraint specified by the grid without taking any control measures. According to statistical analysis, when the PV capacity is 10MW, 100MW, 500MW and 1000MW, the corresponding PV power fluctuation rate exceeds the threshold by 10% is 6.3484%, 2.4636%, 0.5516%, and 0.1411%. If the power threshold is exceeded, a certain capacity of BESS needs to be installed to stabilize the fluctuation. The right one in figure 2 shows the variation of the capacity of BESS under different PV installation capacity and different maximum PV power fluctuation rates. It can be seen from figure 2 that as the maximum power volatility increases, the rated power of the BESS will decrease exponentially. The figure shows the BESS power required for 10MW, 100MW, 500MW, and 1000MW PV power generation systems at the maximum power fluctuation rate $r_{MAX}=10\%/min$ is 7.80 MW, 59.52 MW, 204.68 MW and 300.46 MW.

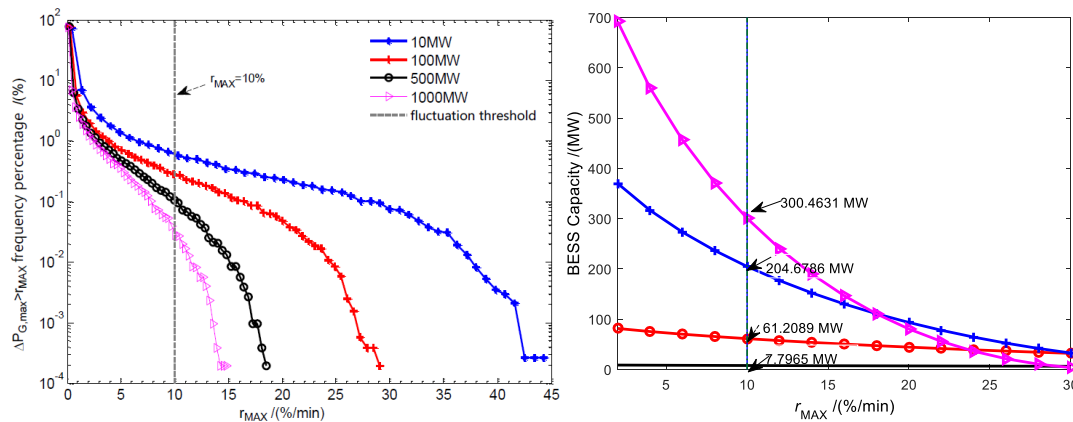


Figure 2. The BESS power under varying r_{MAX} and PV plant capacity

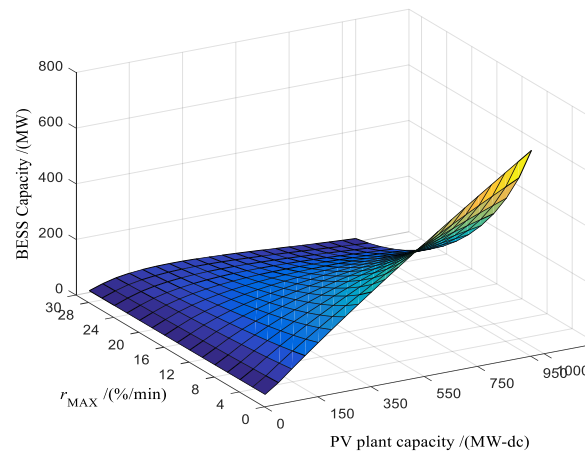


Figure 3. BESS capacity distribution varies with r_{MAX} and PV capacity

Table 1 shows that as the installed capacity of PVs increases, although the required energy storage capacity also increases gradually, its percentage of PV installation capacity P^* will gradually decrease because as the PV installation capacity increases, its floor space increases. The PV output power will have a smoothing effect so that its power volatility will decrease.

Table 1. BESS power and its ratio to P^* at different PV mounting capacities.

PV Capacity (MW)	BESS Capacity (MW)	Storage capacity as a percentage of P^* capacity
10	7.80	78.00%
100	59.52	59.52%
500	204.68	40.94%
1000	300.46	30.05%

4. Conclusions

With the development of battery energy storage technology in power systems, how to properly evaluate the system's capacity requirements for battery energy storage is extremely important. In this paper, a simple and practical model to determine the power and capacity of BESS is proposed. The model is based on the definition of maximum output volatility. Furthermore, the determination of BESS under different maximum power volatility constraints and installed capacity of PV plants is also studied.

It is worth noting that the empirical model constructed in this paper is based on the statistical analysis. Although it eliminates the complicated optimization and determination process and is convenient for practical application, it ignores the sequential charging and discharging process of BESS. Therefore, it is necessary to consider the state of charge of the BESS under the fluctuation of the PV output time series of the study time period (usually in days or years) to determine the capacity of the BESS.

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