The Power Output and Capacity Configuration Method of Hybrid Energy Storage Systems Considering the Confidence Level of PV Fluctuation

Jin Zong, Kai Bai, Bo Yuan, and Zhi Li

Abstract—**The fluctuation of Photovoltaic (PV) generation brings significant impact on power systems. To reduce such impact, this paper proposed a power and capacity configuration method for hybrid energy storage systems (EES) considering the confidence level of PV output fluctuation. The spectral analysis and lowpass filtering (LPF) methods are combined, and according to the spectral analysis results of PV output, the optimized second-order LPF time constant is determined by considering the confidence level of fluctuation rate, integrated power fluctuation constraints, charging and discharging power balance constraints, charging-discharging efficiency of energy storage equipment and the state of charge. Then the output of hybrid PV-ESS and the charging and discharging power and capacity of each components of the hybrid energy storage system that satisfies the power fluctuation demand can be calculated. Simulation is carried out using Matlab to validate the effectiveness of the algorithm on smoothing PV output fluctuation.**

Index Terms—**Hybrid energy storage, fluctuation rate, spectral analysis, lowpass filtering, charging and discharging power balance.**

I. Introduction

With ever increasing PV penetration, the intermittent and random characteristic of Photovoltaic (PV) has brought significant impact on the stable and reliable operation of power systems [1]. Due to the rapid adjustment ability of power electronic devices, energy storage system (EES) has become an effective way to deal with the random fluctuation of PV power [2]. The hybrid EES consists of super capacitor and storage battery. It can make full use of the two kinds of accumulators and improve the operating condition of storage battery, therefore to extend its lifespan [3]-[5].

Currently, the main EES capacity configuration method to smooth new energy generation output is to establish a quantitative model with the objective of minimal energy storage device capacity or minimal cost [6]. Then according to certain constraints, configuration model and algorithm to solve the model and achieve the optimal capacity of EES. However, there has been few such model that can be used in actual project. In [7], filter is deployed to dispatch of power output of EES. The high-frequency component is compensated by power type energy storage, and the low-frequency component is compensated by energy type energy storage. Then the charging and discharging instructions of the hybrid EES can be obtained. However, the method to determine filtering constant and capacity optimization method is not given. In [8], the rain-flow calculation method is used to calculate the battery discharge depth, and the battery life quantification model is built by equivalent life circle curve; it has proved that replacing single-type battery energy storage system with hybrid energy storage system can greatly reduce operation cost. But the control strategy doesn’t involve the real time operation status and charging-discharging balance. In [9], to minimize the initial construction cost of energy storage system is considered, and fuzzy control strategy is used to modify reference power value, and the capacity and output of Li-battery and supercapacitor is decided. But the SOC variation range of Li-battery is limited to be very small in this method, and the Li-battery capacity is relatively large, which can extend its life span, but may reduce economy.

Although there are a lot of research on hybrid EES currently, but most of them focused on capacity optimization. Such as in [10], a multi-objective optimization model is built from three aspects: peak shaving, voltage quality and active power adjustment. It has deployed particle swarm optimization (PSO) algorithm to solve the model. But the PSO cannot simulate the real operation status of the hybrid EES.

This paper proposed a capacity and output configuration method for hybrid EES considering the confidence level of PV output fluctuation rate. The spectral analysis and lowpass filtering (LPF) methods are combined, and according to the spectral analysis results of PV output, the optimized second-order LPF time constant is determined by considering the confidence level of fluctuation rate, integrated power fluctuation constraints, charging and discharging power balance constraints, charging-discharging efficiency of energy storage equipment and the state of charge. Then the output of hybrid PV-ESS and the charging and discharging power and capacity of each components of the hybrid energy storage system that satisfies the power fluctuation demand can be calculated.

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II. PV Output Characteristic

A. Selection of PV Data Sample

The charge and discharge cycle of the supercapacitor of the hybrid EES is relatively short, approximately 10-30 seconds. According to sampling theorem and considering the current monitoring system, the sampling interval is set to be 5-15 seconds. As to the choosing of PV data sample, according to the output curve of different season and weather, the EES is used to smooth PV output fluctuation. The sample period is set to be one day.

B. Statistics of PV Output Fluctuation Rate

The national standard of grid-integrated PV output fluctuation rate in China is “the variation speed of PV real power should be less than 10% of the installed capacity per minutes” [11]. There is no such standard for distributed PV currently. The fluctuation rate limitation of PV output and its confidence level can be determined according to the operation characteristic of local distribution network and load characteristic. The fluctuation rate of PV output can be calculated by:

$$F_t = \frac{\Delta P_t}{P_n} = \frac{P_{t\max} - P_{t\min}}{P_n} \times 100\% \quad (1)$$

where P_n is the PV rated power; P_t is the max power change during time period t; $P_{\max}$ and $P_{\min}$ is the maximum and minimum output during time period t.

The confidence level of PV output fluctuation rate is determined according to statistical results. It is the percentage P% of the time period that can meet the fluctuation rate demand after adding EES to the total time period.

$$P\% = t_1 / t_{\text{total}} \quad (2)$$

where t_1 is the sample point when the sample can meet the fluctuation rate demand; t_{total} is the number of all the sampling points.

C. Spectral Analysis of PV Output

Applying discrete Fourier transform to the sample data of PV output:

$$P(k) = \sum_{n=0}^{N-1} P(n) \cdot e^{-j\frac{2\pi}{N}kn}, \quad k = 0,1,\ldots,N-1 \quad (3)$$

By analyzing it amplitude-frequency characteristic, we can get the major frequency range, where ω_L and ω_H are the upper limit and lower limit of fluctuation rate range. Then the filtering time constant $[T_L, T_H]$ can be calculated.

III. Math

Appling second-order low-pass filtering (LPF) to PV output (see Fig. 1).

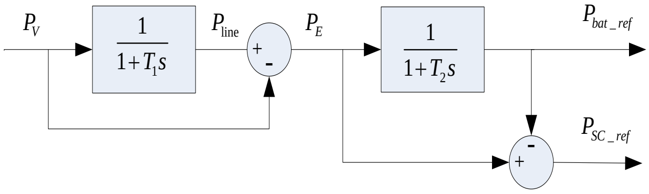

Fig. 1. Schematic diagram of second-order lowpass filtering.

$$P_{\text{line}} = \frac{1}{1+T_1 s} P_V \quad (4)$$

$$P_E = -\frac{1}{1+T_1 s} P_V \quad (5)$$

$$P_{bat\_ref} = \frac{1}{1+T_2 s} P_E \quad (6)$$

$$P_{SC\_ref} = \frac{T_2 s}{1+T_2 s} P_E \quad (7)$$

where P_V is the output of PV; P_{line} is the grid tie line power; P_E is the power of energy storage compensation; P_{bat_ref} is the reference output power of Li-battery; P_{SC_ref} is the reference output power of supercapacitor; T_1 is the first-order filtering time constant; T_2 is the second-order filtering time constant.

Choose a filtering time constant from small to large from $[T_L, T_H]$, and calculate the fluctuation rate and confidence level of the output of the PV-energy storage generation system until the desirable confidence level is achieved. This constant is the first-order filtering time constant. The second-order lowpass filtering is then carried out in the same way. The second-order filtering time constant is usually set to be 10-30 seconds when Li-battery and supercapacitor are used in hybrid ESS. The reference output value of Li-battery and supercapacitor is then obtained.

IV. Calculation of the Rated Power of Hybrid Energy Storage

The reference output value that need to be compensated should ensure the stable operation and consider the energy loss during the charging and discharging process of the hybrid ESS. The time period for Li-battery capacity calculation is usually set to be one day. The charging time of super capacitor is relatively short, therefore its calculation time period is usually set to be 1-5 minutes.

The adjustment is carried out as follows:

Step 1) Translation the power instructions of the super capacitor during each T_{SC} until the sum of them is zero;

Step 2) Translation the power instructions of the Li-battery in opposite direction, and let the total power instructions of the hybrid ESS stay unchanged;

Step 3) Re-modify the modified power instructions of the Li-battery during T_{bat}, and let the sum be 0. This could ensure the energy balance of the hybrid ESS. T_{SC}, T_{bat} are the charging and discharging cycle of the super capacitor and the battery.

$$\begin{aligned} &\Delta P_{SC} = \frac{1}{N}\sum_{1}^{N} P_{SC\_ref}[n],\ n = 1,2,...N \\ &N = T_{SC} / T_S \end{aligned} \tag{8}$$

$$\begin{aligned} &P_{SC}^{'}[n] = P_{SC}[n] - \Delta P_{SC},\ n = 1,2,...N \\ &N = T_{SC} / T_S \end{aligned} \tag{9}$$

$$\begin{aligned} &P_{\mathrm{batx}}[n] = P_{\mathrm{bat\_ref}}[n] + \Delta P_{SC},\ n = 1,2,...N \\ &N = T_{bat} / T_S \end{aligned} \tag{10}$$

$$\begin{aligned} &\Delta P_{bat} = \frac{1}{N}\sum_{1}^{N} P_{batx}[n],\quad n = 1,2,...N \\ &N = T_{bat} / T_S \end{aligned} \tag{11}$$

$$\begin{aligned} &P_{bat}^{'}[n] = P_{batx}[n] - \Delta P_{bat},\quad n = 1,2,...N \\ &N = T_{bat} / T_S \end{aligned} \tag{12}$$

$$\begin{aligned} &P_{line}^{'}[n] = P_{line}[n] - \Delta P_{bat},\ n = 1,2,...N \\ &N = T_{bat} / T_S \end{aligned} \tag{13}$$

where ΔP_{SC} and ΔP_{bat} are the translation, $P_{SC}[n]$, $P_{bat}[n]$ and $P_{\mathrm{line}}[n]$ are the power output of the super capacitor, Li-battery and connecting line after translation. T_S is the sampling period.

During the whole period, the maximum value of the compensation power of each components of the hybrid ESS is the maximum charging and discharging power of each components, i.e. the rated power.

$$P_N = \max\left\{\left|P^{'}[n]\right|\right\} \tag{14}$$

V. Calculation of ESS Rated Capacity

The calculation methods of Li-batter and super capacitor rated capacity are much the same. Take Li-battery as an example.

A. Charging and Discharging Electric Quantity Calculation

After we obtain the output curve of the Li-battery, its charging and discharging electric quantity can be calculated as:

$$E[n] = \sum_{1}^{n} P_{bat}^{'}[i]\frac{T_s}{3600},\quad n = 1,2...N \tag{15}$$

B. Rated Capacity Calculation

The real-time state of charge (SOC) of the ESS is:

$$E[n] = \sum_{1}^{n} P_{bat}^{'}[i]\frac{T_s}{3600},\quad n = 1,2...N \tag{16}$$

$$SOC = SOC_0 - \frac{E[n]}{E_N} \tag{17}$$

$$\begin{cases} SOC_0 - SOC_{low} \geq \dfrac{\max\{E[n]\}}{E_N} \\ SOC_{up} - SOC_0 \leq \dfrac{\min\{E[n]\}}{E_N} \end{cases} \tag{18}$$

Then we have

$$E_N = \frac{\max\{E[n]\} + \left|\min\{E[n]\}\right|}{SOC_{up} - SOC_{low}} \tag{19}$$

where SOC_0 is the initial SOC, E_N is the rated power of Li-battery; SOC_{up} and SOC_{low} are the maximum and minimum value of SOC.

VI. Case Study

The test system is a 10kV distribution network with distributed PV integrated. The output and capacity of the hybrid ESS that can meet the demand of the fluctuation rate confidence level are calculated. The sampling time period is from 6am to 6pm, and the sampling step is 6 seconds. The maximum and minimum output of PV is 466.25kW and 1.25kW. The fluctuation rate demand is less than 10% per minute.

The sample output curve is shown is Fig. 2.

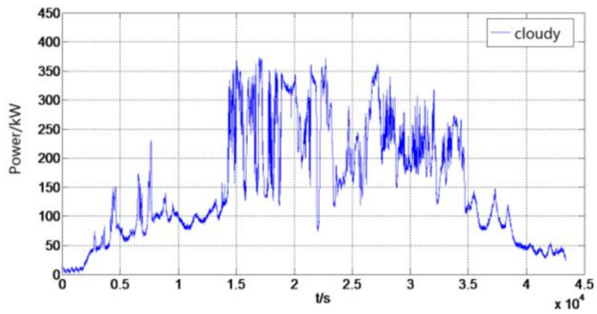

Fig. 2. PV output curve.

Apply spectral analysis, we can have the frequency domain curve as shown in Fig. 3.

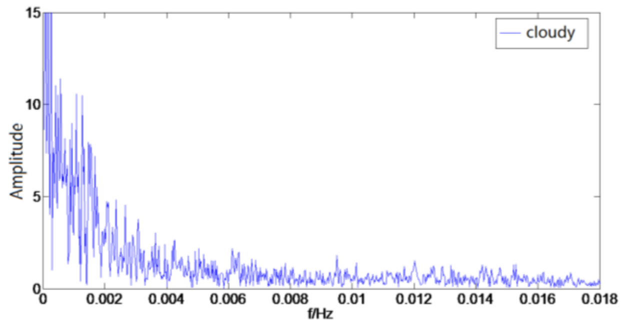

Fig. 3. PV output spectrogram.

From Fig. 3 we can see that, the high frequency fluctuation of PV output located between 6×10−5~18×10−3Hz, the corresponding filtering time constant is 1min-277min.

From frequency-trying method, the fluctuation rate corresponding to different filer time constants are shown in Table I.

TABLE I: FLUCTUATING RATE CORRESPONDING TO DIFFERENT FILTER TIME CONSTANT

T_1(min)	1	1.5	2	2.5	3	3.5	4
F_{tmax} (%)	28.7	25.3	22.4	18.6	15.7	12.1	10
P%	95.3	96.2	97.4	98.1	98.9	99.5	100

It can be seen that, when the confidence level are 100% and 95%, the corresponding first-order filtering time constant T_1 are 4min and 1min. From the charging and discharging characteristics of super capacitor, and considering the sampling cycle of PV, we choose 12s, 20s and 30s as the second-order filtering time constants. Simulation results are shown in Table II.

TABLE II: OUTPUT AND CAPACITY CONFIGURATION AND OF HYBRID ENERGY STORAGE SYSTEM CORRESPONDING TO DIFFERENT FILTER TIME CONSTANT

T_1 (min)	P_{EN} (kW)	E_N (kWh)	T_2 (s)	P_{batN} (kW)	E_{batN} (kWh)	P_{SCN} (kW)	E_{SCN} (kWh)
			12	186.1	12.5	178.8	1.37
1	217.6	11.96	20	184.1	12.6	181.4	1.67
			30	180.6	12.7	182.9	1.75
			12	251.3	41.1	172.8	1.41
4	253.1	40.6	20	248.8	41.3	173.8	1.71
			30	240.2	41.4	176.7	1.78

For lack of space, only some of the Matlab simulation results are shown below. (T_1=1min, T_2=20s; T_1=4min, T_2=12s).

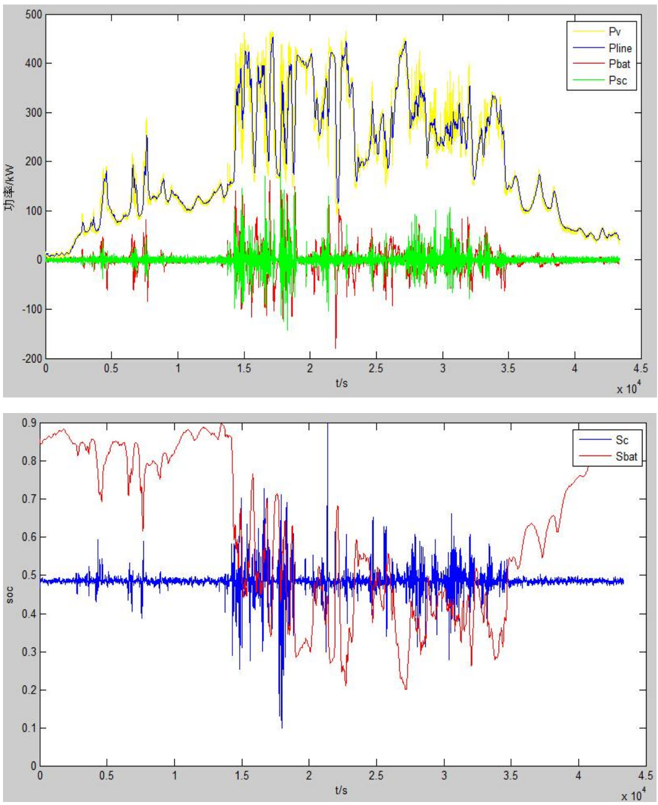

Fig. 4. Output of the hybrid generation system and the SOC operating curve of Li-battery, super capacitor.

The simulation curve has shown the real operating status of the hybrid ESS. The SOC of the battery varies from 0.9 to its initial state after a whole day of charging and discharging cycle. The SOC of the super capacitor is around 0.49 all the time, which is its initial state. From Table II, Fig. 4 and Fig. 5 we can see that, the larger the first-order filtering time constant is, the higher the confidence level is. Also the output curve of the hybrid ESS is more smooth, and the capacity of the ESS that need to installed is larger. If the first-order filtering time constant stays the same, the power of super capacitor increases slightly with the increase of the second-order filtering time constant. The output and capacity of the Li-battery doesn't change much, but the charging and discharging time become less. In real application, we can choose appropriate second-order filtering time constants according to the objective of the fluctuation rate and the performance of the battery.

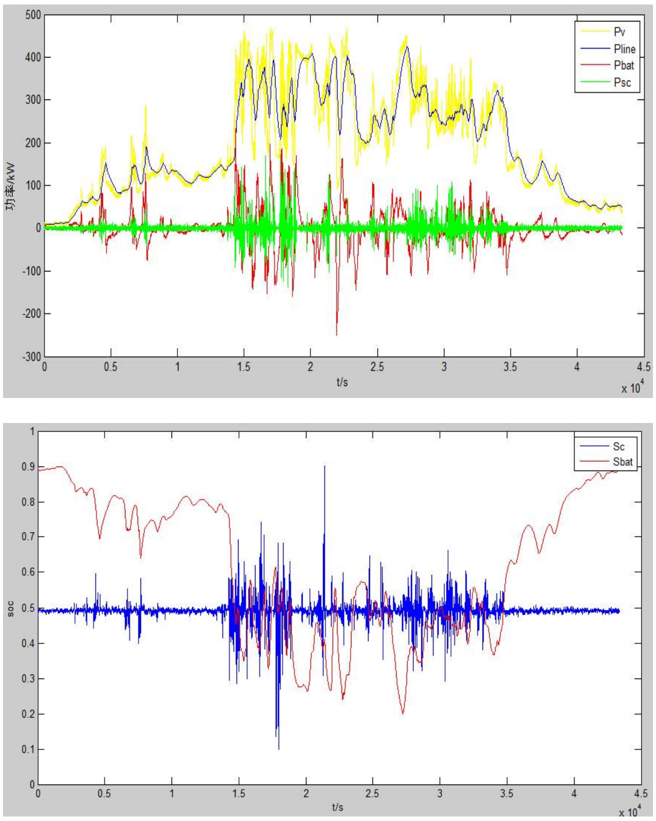

Fig. 5. Output of the hybrid generation system and the SOC operating curve of Li-battery, super capacitor.

In conclusion, the fluctuation rate of the power of the connecting line is restrained after adding hybrid ESS. The SOC curve of the Li-battery is smoother and went to its initial state after a period cycle. The super capacitor operated around its initial state, and its SOC curve is sharper. The rapid charging and discharging property of the super capacitor is fully used and the operating status of the Li-battery is optimized.

VII. CONCLUSION

This paper proposed a capacity and output configuration method for hybrid EES considering the confidence level of PV output fluctuation rate. The fluctuation rate confidence level, power fluctuation rate constraint, energy balance constraint, charging and discharging efficiency of ESS and SOC is considered to get the output of the hybrid ESS that can meet the fluctuation rate demand. The output and capacity of the components of the hybrid ESS are also obtained. Simulation is performed in a 10kV distribution network system. The rated power and capacity of the Li-battery and super capacitor considering different fluctuation rate confidence level are obtained. The proposed method has a guiding significance for the application of distributed power source in distribution network.

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