Coordinated control strategy of hybrid energy storage to improve accommodating ability of PV

Delong Zhang, Jianbo Guo, Jianlin Li

China Electric Power Research Institute, Haidian District, Beijing 100192, People’s Republic of China
E-mail: zdl5496@163.com

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Abstract: The energy storage system of PV power plant can improve the accommodating ability of photovoltaic (PV) generation. The coordinated control of hybrid energy storage system (HESS) becomes one of the urgent problems to be solved. This study proposes a coordinated control strategy of HESS with complementary features to improve the accommodating ability of PV. In the 1 min time scale, a time window selection method is proposed to control the super conductor to smooth the short-term fluctuation of the PV. In the 1 h time scale, the lithium-ion battery output model maximising the system economic benefit is established, and the particle swarm optimisation algorithm is used to solve the model. Based on the result of 1 h time scale, the objective function of reducing the fluctuation of electric power consumption is established and solved on the 15 min time scale. The effectiveness of the proposed control strategy is verified by simulation. The coordinated operation of HESS improves the utilisation rate of the PV power generation.

1 Introduction

In recent years, China’s photovoltaic (PV) generation transferring to the eastern and distributed has become a new trend. In 2016, national new installed capacity in the northwest region accounted for 28%, other regions accounted for 72%. Distributed PV installed capacity is 4.24 GW. With the advantages of distributed generation, distributed power generation, especially distributed PV, has attracted wide attention and rapid development [1–3].

On the one hand, the owners of PV would like to maximise their own income. On the one hand, PV must meet the power grid needs to achieve its safe and stable operation. The disordered control will have an influence on the power quality of traditional distribution network. Therefore, using hybrid energy storage system (HESS) in the PV plant to improve PV characteristics and economic operation becomes a hot spot [4–6].

In the view of control strategy, Wei et al. [7] proposed a control strategy to eliminate the impact of grid-connected power fluctuations on the grid by local control and global control. However, the control strategy is only applicable to the distribution network system with a large number of PV generations. Li et al. [8] used hysteresis comparison method to control the grid current, so that it can be stable to the power grid. It cannot achieve full use of light energy because of not using the energy storage system.

In [9], the double-moving average algorithm is used to stabilise the fluctuation of the PV output power and proves its superiority compared with the moving average algorithm and the moving median algorithm. Peng et al. [10] proposed a two-layer control model and established the expert information base. Using energy storage to stabilises a variety of fluctuations in the wind power and simplifying the control logic. In the literature [11], the first-order Butterworth low-pass filter is used to obtain the wind target power, the compensation power of the battery and the super capacitor. The working state of the energy storage in combination with the super capacitor terminal voltage control is optimised. This paper proposes a coordinated control strategy of HESS with complementary features to improve the accommodating ability of PV. In the different time scale, this paper establishes different objective functions to meet the fluctuation target and optimal operation. The effectiveness of the proposed control strategy is verified by simulation. The coordinated operation of HESS improves the utilisation rate of the PV power generation.

2 HESS and PV combined power generation system

Installing HESS at the PV plant, on the one hand, it can smooth the short-term fluctuations of PV power, so that PV power plants meet the grid standard. On the other hand, in a longer time scale, the use of HESS can achieve the purpose of economic operation.

The HESS is usually composed of power type and energy type energy storage system. The super capacitor (SC) has the advantages of fast response speed, high power density, low energy density, and can be used to smooth the short-term fluctuation of PV. The lithium-ion battery (LiB) energy density is higher than SC and is the more mature application in the tens of kilowatts of power plants and load scenarios. This paper uses LiB to achieve the joint optimisation operation of PV. The topology is shown in Fig. 1.

3 Coordinated control strategy of HESS

3.1 Selection of sliding average control time window

The sliding average method is a mathematical method of selecting a fixed-length window that takes all the values in the window as the arithmetic mean and the average as the centre of the window. Take the time window equaled to five for instance, the reference value of the centre point is

\[
X_{\text{ref}}(i) = \frac{1}{5} \left[ X(i-2) + X(i-1) + X(i) + X(i+1) + X(i+2) \right]
\]  

(1)

The average means that the weight of the points is the same. The sliding average calculation appears to be simple, but it is a very time-consuming calculation, especially the time window is too long. Moreover, for the sliding average control to smooth the PV
fluctuations, the calculation of next moment reference is based on the historical values, so it cannot use the centre of the window. It can be found that the new measured value is different from the previous measured value by two points. The earliest point is lost and the latest point is accumulated, so it can be improved. The improved sliding average filter is

\[ X_{\text{ref}}(i) = X(i-1) + \frac{1}{N}[X(i) - X(i-N)] \] (2)

According to this method, the smooth signal reference values can be obtained. As shown in (2), the time window length \( N \) is a very important parameter. If the time window length is too long, the PV power will be too smoothing, the capacity of SC will be too large. The smaller window will lead to the PV power cannot meet the grid power standard. Therefore, this paper presents a method for selecting time windows based on the smoothing target and economy of the SC.

According to the selection of different time window \( N \), we can get different power reference value. In this paper, the sum of squares of the difference between each two adjacent values is used as the fluctuation index

\[ \Delta P = \sum_{i=1}^{1439} (p_{\text{PV}}^{i+1} - p_{\text{PV}}^{i})^2 \] (3)

The output power of SC at each sampling point is

\[ P_{\text{SC}}^{i} = p_{\text{PV}}^{i} - P_{\text{ref}} \] (4)

The maximum output power of SC is

\[ P_{\text{SC}}^{\text{max}} = \max \{|P_{\text{SC}}^{i}|\} \] (5)

The energy of SC at each sampling point is

\[ E_{\text{SC}}^{i} = E_{\text{SC}}^{i-1} + \eta P_{\text{SC}}^{i}/60 \] (6)

The maximum energy of SC is

\[ E_{\text{SC}}^{\text{max}} = \max \{|E_{\text{SC}}^{i}|\} \] (7)

In the case of satisfying the smoothing effect, the objective function is

\[ f = f_1 + f_2 = \Delta P + (c_1 P_{\text{SC}}^{\text{max}} + c_2 E_{\text{SC}}^{\text{max}}) \] (8)

where \( P_{\text{PV}}^{i} \) is the PV power at time \( i \) (1 min), \( P_{\text{ref}} \) is the reference PV power. \( P_{\text{SC}}^{i} \) is the SC power at time \( i \). \( P_{\text{SC}}^{\text{max}} \) is the maximum SC power. \( E \) is the SC energy. The corresponding optimal time window \( N \) can be obtained by solving the objective function.

### 3.2 Control of LiB at long time scale

The goal of the joint operation control is to ensure the use of LiB to promote the consumption of PV and ensure the economy operation of ES and PV. In this paper, we consider the optimal operation control of the LiB energy storage system at 15 min and 1 h time scale. First, according to the day-ahead PV forecast data, the energy storage is optimised on the 1 h time scale to ensure the economic. Second, according to the ultra-short-term PV forecast data of 3 h, the optimal operation of LiB is achieved. At each sampling time, the short-term forecast data of 3 h is updated to achieve the effect of rolling optimisation.

The objective function of the hourly optimal control is

\[ F_1 = \sum_{i=1}^{24} (c_1 P_{\text{SC}}^{i} + c_2 E_{\text{SC}}^{i} + c_3 P_{\text{PV}}^{i}) \] (9)

The constraints are

\[ P_{\text{SC}}^{i} = p_{\text{PV}}^{i} - P_{\text{ref}} \] (10)
\[ P_{\text{PV}}^{i} = P_{\text{PV}}^{i-1} + + P_{\text{PV}}^{i-2} \] (11)
\[ |P_{\text{PV}}^{i}| \leq P_{\text{PV}}^{\text{max}} \] (12)
\[ \text{SOC}_{\text{ES}}^{\text{min}} \leq \text{SOC}_{\text{ES}}^{i} \leq \text{SOC}_{\text{ES}}^{\text{max}} \] (13)

\( P_{\text{SC}}^{i} \) is the electric power bought from the power grid at time \( i \) (1 h). \( P_{\text{PV}}^{i} \) is the load power at time \( i \). \( P_{\text{PV}}^{\text{max}} \) is the energy storage output power. \( P_{\text{PV}}^{\text{min}} \) is the PV power sell to grid. \( \text{SOC}_{\text{ES}}^{i} \) is the state of charge (SOC) of energy storage at \( i \).

The optimal operation of 15 min time scale is based on the result of \( F_1 \). For an optimisation period, the charge and discharge power of LiB is optimised, and the forward rolling is carried forward until the optimisation calculation of the whole day is completed. The objective function of the 15 min optimal control is

\[ F_2 = \frac{1}{M} \sum_{i=1}^{M} (P_{\text{PV}}^{i} - \text{FPP})^2 \] (14)

where \( M \) is the sampling number in a price period. \( \text{FPP} \) is the average of a period. \( \tau \) is the sample time 15 min.

The purpose of this objective function is to reduce the fluctuation of the purchase power from the grid. Constraints are same with the 1 h constraints. In addition, the 1 h SOC results should be the references of the time of the price change, that is \( \text{SOC}_{\text{ES}}^{15\text{min}} = \text{SOC}_{\text{ES}}^{16} \). where \( t \) is the time point of the electric power price change.

### 4 Solution method

In this paper, the particle swarm algorithm [12] is used to solve the objective function, the solution steps are as follows:

**Step 1:** Enter the predicted power of the PV, the power of each load and the time-of-use electricity price.

**Step 2:** Set the particle number dimension \( D \) that is the number of variables in the objective function, the maximum number of iterations \( M \), and the calculation precision \( A \).

**Step 3:** Initialise the position and velocity of the particle population and calculate the particle fitness value based on the fitness function.

**Step 4:** Compare each particle fitness value to its individual extremes, and if appropriate, update the current individual extremes.
Comparing each particle fitness value with the global value, if appropriate, update the current global extreme.

Step 5: According to (15) and (16), update the location and velocity of each particle, and check whether the updated particle satisfies the constraint condition, if not satisfied, regenerate the particle velocity, update the position until the constraint condition is satisfied

\[ v^{i+1} = w v^i + c_1 r_1 (p^i - x^i) + c_2 r_2 (g^i - x^i) \]  
\[ x^{i+1} = x^i + v^i \]

where \( c_1 \) and \( c_2 \) are particle weighting factors, \( w \) is inertia weight, \( r_1 \) and \( r_2 \) are the evenly distributed random number in (0,1). \( x^i \) and \( v^i \) are the position and velocity of \( i \)th particle, respectively. \( p \) and \( g \) are the individual extreme and global extreme, respectively.

Step 6: Repeat Steps 4 and 5.

Step 7: Determine whether the current number of iterations and the error value meets the requirements. If the current value is not satisfied, return to Step 7. Otherwise, the particle optimisation calculation is terminated and the calculation result is output.

5 Simulation analysis

In this paper, the data of a day of PV power plant is used for simulation analysis. The installed capacity of PV power plants 30 kW, the maximum load is 20 kW. The PV power generation and load curve are shown in Fig. 2. The solid line is the PV power curve; the dotted line is the load curve.

5.1 Selection result of time window \( N \)

The different time window \( N \) is selected to calculate the objective function \( f \), where \( \lambda \) is the weight of the smoothing index. The selection of the different weights, the optimal solution of the objective function is different. Thus, in the simulation, we use the exhaustive method to calculate the relationship between the objective function and the time window under different weights. The simulation result is shown in Fig. 3.

Fig. 3 illustrates the relationship between the objective function and the time window \( N \) with \( \lambda \) equaling 0.1, 0.2, and 0.3. The other \( \lambda \) values are not shown in the graph. It can be seen that when the time window \( N = 8 \), the objective function is minimal.

As shown in Fig. 4, it is the calculated result of the smoothing index and the SC cost. The vertical axis is the smoothing index of (3). The horizontal axis is the SC costs. The points from the right to the left in the order are the results of time window is 2–21. When the corresponding calculation results \( N = 8 \), the smoothing effect of short-term fluctuations is the best, and the cost is relatively low.

When the time window \( N \) is 8, the reference value of PV power is calculated. The SC charge and discharge power and the SOC are as shown in Fig. 5.
5.2 Control of LiB at long time scale

At the 1 h time scale, the economic operation of combined system is based on the day-ahead prediction of the PV. In this case, the rate power of LiB energy storage is 10 kW and the rate energy is 37.5 kWh. The SOC is between 0.1 and 0.9. Therefore, the LiB energy storage can charge or discharge 3 h continuously. The forecast data are shown in Fig. 6. The solid line is the PV power curve, the dotted line is the load curve. The time-of-use price is shown in Table 1. The sampling points are only 24 points. It can be found that there are different optimal solutions, one of the results is as shown in Fig. 7. PG is the curve of the power bought from the grid. PV is the curve of PV power sell to grid. PE is the curve of LiB power, positive value is charge power, negative value is discharge power. The optimised result is $F_1 = 7.4979$ curve.

In fact, this optimal operation is achieved by charging when the price is low and discharging when the price is high. The LiB output power has some optimal solutions under constrains. Take 1:00–8:00 for instance, the energy storage in LiB is 30 kWh. It can charge averagely with 3.75 kW for 8 h as shown in Fig. 7. Or it can charge with 10 kW for 3 h.

The operation results can be get by solve the objective function $F_2$. As shown in Fig. 8, PG is the curve of the power bought from the grid. PL is the curve of the load power. PE is the curve of LiB power, positive value is charge power, negative value is discharge power.

In Fig. 8, the curve of power bought from the grid is smooth in each price period. The charge and discharge of LiB energy storage is different from Fig. 7.

6 Conclusions

This paper proposes a coordinated control strategy of HESS with complementary features to improve the accommodating ability of PV. In the 1 min time scale, this paper chooses an optimal time window for sliding average method and gets good smoothing effect. In the 1 h time scale, the charge and discharge powers of LiB and the PV power sell to grid are obtained by solve the best economic result. Moreover, this paper gets the 15 min charge and discharge powers of LiB by smoothing the power in each price period.

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8 References

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