Smoothing Photovoltaic Power Fluctuations for Cascade Hydro-PV-Pumped Storage Generation System Based on a Fuzzy CEEMDAN

IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received October 24, 2019, accepted November 13, 2019, date of publication December 2, 2019, date of current version December 12, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2955569

Smoothing Photovoltaic Power Fluctuations for Cascade Hydro-PV-Pumped Storage Generation System Based on a Fuzzy CEEMDAN

LEI CHEN[1,2], JUN WANG[1,2], ZHANG SUN[1,2], TAO HUANG[3], (Member, IEEE), AND FAN WU[1,2]

[1]School of Electrical Engineering and Electronic Information, Xihua University, Chengdu 610039, China
[2]Key Laboratory of Fluid and Power Machinery, Ministry of Education, Xihua University, Chengdu 610039, China
[3]Department of Energy, Politecnico di Torino, 10129 Turino, Italy

Corresponding author: Jun Wang (wj.xhu@hotmail.com)

This work was supported in part by the Grant from National Key Research and Development Program of China under Grant 2018YFB0905200, and in part by the Innovation Fund of Postgraduate, Xihua University under Grant ycjj2019048 and Grant ycjj2019049.

ABSTRACT Due to strong volatility and intermittent characteristics, the fluctuations of the photovoltaic (PV) output is inevitable which cause negative impacts on power system operation. However, such an issue can be resolved in a combined cascade hydro-PV-pumped storage (CH-PV-PS) generation system through an appropriate control. Based on the optimal base power of variable-speed pumped storage station (VSPSS), a smoothing method of fuzzy complete ensemble empirical mode decomposition with adaptive noise (CEEMDAN) is proposed in this paper. To prevent smoothing insufficient and excessive, the fuzzy CEEMDAN algorithm is used to obtain the target power of the photovoltaic-pumped storage (PV-PS) generation system and the control signal of cascade hydro stations (CHSs) for eliminating large amplitude fluctuations of the PV output. Furthermore, in order to overcome the drawback that too frequent conversion of unit operating mode would reduce the service life and smoothing effect of the VSPSS unit, the optimization model of the base power of the VSPSS is established and solved by the grid adaptive direct search method (MADS) to obtain the control signal of the VSPSS for suppressing the short-term fluctuations of the PV output. Finally, the performance of the method is evaluated through using the PV station data in Xiaojin County, Sichuan province, China. The simulation results reveal that compared with the fixed base power smoothing method, this method can effectively suppress the PV power fluctuations and improve the smoothing effect and energy efficiency.

INDEX TERMS Cascade hydro stations, PV smoothing, power fluctuations, variable-speed pumped storage station.

I. INTRODUCTION

In order to build a sustainable energy system, solar energy as a low-carbon and friendly renewable energy form has attracted worldwide attention. However, output power of the PV systems, which is strong volatility and intermittent characteristics, due to frequent change solar radiation and temperature [1], [2], may induce voltage fluctuations, voltage flicker, grid side power fluctuations, and frequency fluctuations [3]. Therefore, PV energy sources cause grid power instability and poor power quality when large quantities of PV energy penetrate the power grid [4]. In order to increase the permeability of PV generation and reduce the impact of power fluctuations, the Puerto Rico Electric Power Authority (PREPA) and State Grid Corporation of China requires that the maximum power fluctuations range of a PV plant should be less than 10%/min of its installed capacity [5].

In some regions where water resources and solar energy are abundant, many small and medium-sized PV power stations and hydro stations have been built. Therefore, we should rationally combine these two energy sources to build a hydro-PV complementary generation system which can effectively suppress PV power fluctuations and fully improve the PV and hydro economic benefits [18]. It is well known that pumped storage is a kind of more mature and economically efficient storage technology, which can store high quantities of unpredictable energy for avoiding grid stability problems [6]. In recent years, due to the rapid development of

The associate editor coordinating the review of this manuscript and approving it for publication was Lorenzo Ciani.

control technology and the reduction of the power electronic devices price, the variable speed pumped storage technology has become an important developing trend for pumped storage station. Compared with traditional fixed-speed units, variable speed units have advantages including rapidity, high efficiency, flexibility, and reliability in operation and regulation. Therefore, using CHSs and VSPSS to reduce the impact of renewable energy fluctuations on the stable operation of utility grid has become increasingly trend [7], [8].

To reduce PV/wind power fluctuations, numerous methods have been proposed and developed in recent years. In [9], Ma Wei et al. present a coordinated control strategy of PV and ES for smoothing PV power fluctuations. The dynamic adjustment strategy is proposed based on maximum power tracking operation point of PV system and the charging and discharging control strategy of energy storage with adaptive Kalman filter algorithm. In [10] and [11], the PV/wind power signal is decomposed by using the advantage of wavelet packet decomposition to obtain more detailed information of the signal, and the amplitude-frequency characteristics of the PV/wind power signal are analyzed to obtain the smoothed PV/wind power. In [12], the low-pass filtering algorithm is used to calculate the target power of smoothing wind power for achieving smoothing effect. In [13], an exponential suppressing method for variable suppression parameters is proposed. As a result, the PV power fluctuations are suppressed by controlling the charge and discharge of energy storage. In [14], the topology of VSPSS with FSC is proposed. According to the situation of the Faroe Islands, the power of the VSPSS is controlled by load following method to suppress the fluctuations of wind power for limiting the influence of wind power operation on other parts of the utility grid. In [15], a control method based on net load of the system is presented for the pumped storage power station of the wind-PV-pumped storage complementary generation system to reduce the impact of renewable energy instability on the power grid stable operation. In [16], based on direct power control, a VSPSS is researched to reduce the impact of wind power fluctuations on utility grid stability. In [17], utilizing the controllability of variable speed pump, a move average PV power fluctuations smooth method based on fixed pump base power is proposed to suppress the PV power fluctuations.

In the above description, battery energy storage and supercapacitor are used to suppress PV power fluctuations in [9]–[13]. In [14]–[16], the influence of the operation mode conversion of VSPSS on the smoothing effect and the life of the unit has not been considered. In [17], a fixed base power is proposed to solve the problem of operation mode conversion. However, previous studies have several aspects to be improved. (1) Battery energy storage is the chemical energy storage that has potential hazards. Moreover, to build battery energy storage will increase the cost of smoothing photovoltaic fluctuations. (2) Because too frequent conversion of the VSPSS unit operating mode would reduce the unit service life and take a long time, it is difficult to smooth photovoltaic fluctuations. (3) Setting the base power can solve the problem that operating mode conversion. However, the base power will have a great impact on the smoothing effect. Taking the VSPSS working in the pumping mode operation as an example, if the base power is set too small, it is difficult to absorb the energy which exceeds the upper limit requirement of grid-connected. On the contrary, if the base power is set too large, it is difficult to compensate the energy which is not meet the deficit of the lower limit requirement of grid-connected. At the same time, if its value is too small, the energy waste be increased. So, it is necessary to on-line optimize the base power for improving the smooth effect and energy efficiency.

Therefore, in this paper, the fast regulation ability of VSPSS with full size converter (FSC) is used to effectively smooth the short-term fast fluctuations of PV power. After smoothing, the short-term fast fluctuations of PV power are eliminated, and traditional hydro can compensate it. In order to improve the schedulability of CH-PV-PS generation system and eliminate large amplitude fluctuations of the PV power output, CHSs are used to compensate the combined output of PV-PS. Furthermore, the combined output of CH-PV-PS generation system can meet the daily operation planning of PV power station. So, we focus on the control method of smoothing PV power fluctuations and only considers the daily operation planning of PV power station. In this paper, the main idea of the smoothing method is to use the low-frequency power signal of PV output as the target power of combined output of the PV-PS, and to use the high-frequency power signal of PV output as control signal of the VSPSS. How to separate the high and low frequency power signal of PV output reasonably will seriously affect the effect of smoothing PV power fluctuations. Here, the CEEMDAN algorithm has a strong ability to deal with non-stationary and non-linear signals. In the meantime, compared with the wavelet transform and low-pass filtering, the CEEMDAN algorithm is more adaptive and its parameters are easier to be determined [19], [20]. So, the CEEMDAN algorithm is used to decompose the PV generation power of real-time for obtaining several IMFs. Furthermore, to obtain the target power of combined output of the PV-PS and the control signal of CHSs for eliminating the large amplitude fluctuations of the PV power output, the fuzzy algorithm is employed to determine the orders of the IMFs which is used for the reconstruction of the IMF of the PV power.

However, the high frequency power signal of PV output extracted by the fuzzy CEEMDAN algorithm has random positive and negative transformations. So, it will make frequently change the operation mode of the VSPSS, which will cause service life of the unit is shorten. In the meantime, the PV fluctuations cannot be suppressed in the process of change operation mode, so that the smoothing effect will be affected. In this paper, to solve the problem mentioned above, the optimal base power of the VSPSS is introduced and obtained by the MADS algorithm, around which the control signal of the VSPSS for suppressing the short-term rapid fluctuations of PV output is set to avoid frequent changes of the VSPSS operation mode.

The main contributions of this work are summarized as follows:

1) A smoothing method of PV power fluctuations for CH-PV-PS generation system is proposed. The existing VSPSS with FSC and CHSs are used to suppress PV power fluctuations. So, the cost of smoothing PV power fluctuations is reduced.
2) The fuzzy CEEMDAN algorithm is presented to calculate the reference power of combined output of the PV-PS on-line adaptively in order to prevent smoothing excessive and insufficient.
3) How to set the base power P_j of VSPSS, and how to build a base power optimization model of VSPSS for the first time is presented in this paper. The optimization model of the base power is solved by using MADS algorithm, in order to adaptively adjust the base power which can improve the smooth effect and reduce the energy waste.
4) The efficiency of the proposed smoothing method is compared with the fixed base power smoothing method. As the result, the proposed smoothing method is more effective to suppress PV power fluctuations and reduce energy waste.

The rest of the paper is organized as follows. Section II introduces CH-PV-PS generation system. In Section III, the smoothing method is described and the PV power fluctuations is defined. In Section IV, the CEEMDAN algorithm is used to decompose the actual PV power, and the order number of reconfigurations is calculated by the fuzzy control algorithm to obtain the reference power of combined output of the PV-PS. In Section V, the optimization model of base power of VSPSS is established and MADS algorithm is used to obtain optimal base power. Simulations are carried out in Section VI and conclusions are given in Section VII.

II. SYSTEM DESCRIPTION

Fig. 1 shows the system structure of the CH-PV-PS generation system in Xiao Jing County, Sichuan Province China, which including a PV power station, three CHSs and a VSPSS with FSC. All the stations are connected to a 220 kV AC bus, and then to a 500 kV bus connecting the transmission grid through a boost transformer. The energy management system (EMS) calibrates power generation set-points of the VSPSS and the CHSs through the measured real-time output power P_{PV} of the PV power station and the ultra-short-term predicted power P_{Pred}. Thus, the smoothed output power of the entire CH-PV-PS generation system to the transmission grid can be denoted as P_{smooth}.

III. THE SMOOTHING STRATEGY AND DEFINITION OF PV POWER FLUCTUATIONS

A. THE SMOOTHING STRATEGY OF PV POWER FLUCTUATIONS

Fig. 2 shows the schematic diagram of the control strategy for smoothing PV fluctuations in the CH-PV-PS generation system. Here, P_j is the optimal base power of VSPSS, and P_m is the target power of combined output of the PV-PS. The actual power signal of PV is decomposed and reconstructed by fuzzy CEEMDAN to determine the target power P_m of combined output of the PV-PS at the next time. The optimization model of base power of VSPSS is solved by using MADS algorithm in order to obtain the P_j. The ideal power P_{dFSC} of VSPSS is calculated as follows:

$$P_{dFSC} = P_m - P_{PV} + P_j \tag{1}$$

Then, the actual power P_{FSC} of VSPSS is obtained by utilizing power limiter which principle is shown in Fig. 3. Here, $P_{l.low}$ is the lower limit of VSPSS power variation and $P_{l.up}$ is the upper limit of VSPSS power variation. The power instruction of CHSs is calculated as follows:

$$P_c = P_{plan} - P_m - P_j \tag{2}$$

The smoothed output power of CH-PV-PS generation system is calculated as follows:

$$P_{smooth} = P_{PV} + P_c + P_{FSC} \tag{3}$$

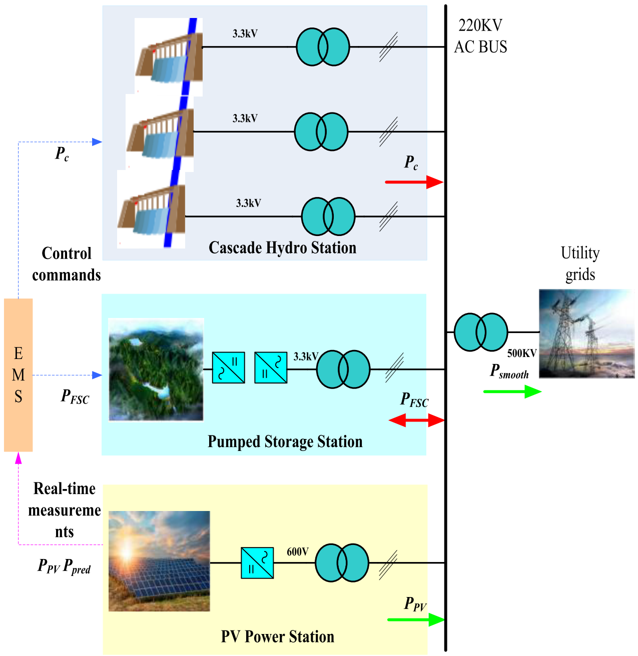

FIGURE 1. The system structure of the CH-PV-PS generation system in Xiao Jing County.

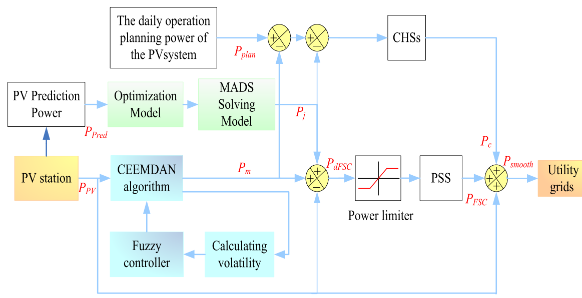

FIGURE 2. The schematic diagram of the control strategy for smoothing PV fluctuation.

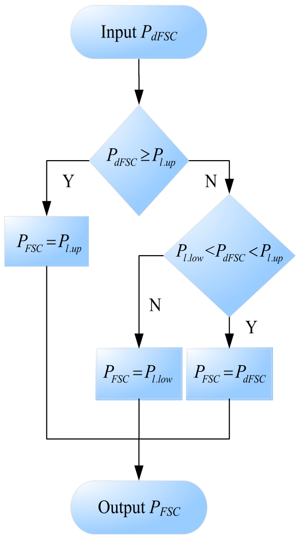

FIGURE 3. The schematic diagram of power limiter.

B. DEFINITION OF PV POWER FLUCTUATIONS

In this paper, we mainly discuss the power fluctuation of PV in one minute. The power fluctuations can be defined as the difference between the minimum value and the maximum value of the measured power in a period divided by the period. The period is 1 min. Here, $P_{PV}(t)$ denotes the power value of PV power station at time t, and $P_{smooth}(t)$ denotes smoothed output power of the CH-PV-PS generation system at time t. The power fluctuations of PV before and after the smoothing are defined as $\Delta P_{PV}(t)$ and $\Delta P_{smooth}(t)$, respectively. According to the data of P_{Pv} and P_{smooth}, $\Delta P_{PV}(t)$ and $\Delta P_{smooth}(t)$ can be calculated as follows, respectively.

$$\begin{cases} \Delta P_{PV}(t) = \left(\alpha P_{max,PV} + \beta P_{min,PV}\right)/1min \\ \begin{cases} \alpha = 1, \beta = -1, & t_{max} \geq t_{min} \\ \alpha = -1, \beta = 1, & t_{max} < t_{min} \end{cases} \\ \left[P_{max,PV},\ t_{max}\right] = max\left(\overline{P}_{PV}\right) \\ \left[P_{min,PV},\ t_{min}\right] = min\left(\overline{P}_{PV}\right) \\ \overline{P}_{PV} = [P_{PV}(t-60+\Delta t), \ldots P_{PV}(t-\Delta t), P_{PV}(t)] \end{cases} \tag{4}$$

$$\begin{cases} \Delta P_{smooth}(t) = \left(\alpha P_{max,smooth} + \beta P_{min,smooth}\right)/1min \\ \begin{cases} \alpha = 1, \beta = -1, & t_{max} \geq t_{min} \\ \alpha = -1, \beta = 1, & t_{max} < t_{min} \end{cases} \\ \left[P_{max,smooth},\ t_{max}\right] = max\left(\overline{P}_{smooth}\right) \\ \left[P_{min,smooth},\ t_{min}\right] = min\left(\overline{P}_{smooth}\right) \\ \overline{P}_{smooth} = [P_{smooth}(t-60+\Delta t), \ldots P_{smooth}(t-\Delta t), \\ \qquad P_{smooth}(t)] \end{cases} \tag{5}$$

where $P_{max,PV}(t)$ and $P_{min,PV}(t)$ are the maximum and minimum values of the power before smoothing, respectively; $P_{max,smooth}(t)$ and $P_{min,smooth}(t)$ are the maximum and minimum values of the power after smoothing, respectively; t_{max} and t_{min} represent the time points of the maximum and minimum values of the power, respectively; $[x, y] = max(.)$ is the function of returns the maximum element; $[x, y] = min(.)$ returns the function of the minimum element; x and y represent the corresponding values and time points of returns the element, respectively; $\overline{P}_{PV}$ and $\overline{P}_{smooth}$ are the power sets of 1 minute before and after smoothing, respectively; Δt is the sampling interval and $\Delta t = 5$s.

C. CEEMDAN

CEEMDAN is an improved algorithm of empirical mode decomposition (EMD). It weakens the mode aliasing problem by adding adaptive Gauss white noise at each stage of decomposition, and the decomposition process has integrity and almost no reconstruction error [21]. The algorithm can be described as follows:

1) The noise component $\varepsilon_0 w_j(t)$, $(j = 1, 2, \ldots, J)$ is added to the actual PV power signal $x(t)$. J is the number times added white Gaussian noise. Definition: $imf_{j1}(t)$ is the first-order PV IMF decomposed by EMD after adding noise for the j times. Then the first-order IMF of CEEMDAN is expressed as follows:

$$imf_{j1}(t) = E_1\left(x(t) + e_0 w_j(t)\right) \tag{6}$$

$$imf_1'(t) = \frac{1}{J}\sum_{j=1}^{J} imf_{j1}(t) \tag{7}$$

2) Calculating the first residue signal $r_1(t)$ of CEEMDAN decomposition as follows:

$$r_1(t) = x(t) - imf_1'(t) \tag{8}$$

3) Adding the adaptive noise component $\varepsilon_1 E_1(w_j(t))$ to the first residue signal $r_1(t)$ and then solving the second-order IMF by EMD decomposition, as shown in the following:

$$imf_2'(t) = \frac{1}{J}\sum_{j=1}^{J} E_1\left(r_1(t) + \varepsilon_1 E_1\left(w_j(t)\right)\right) \tag{9}$$

4) Repeating steps (2) and (3) to obtain the i-orders residue signal and the $(i+1)$ orders IMFs, as follows:

$$r_i(t) = r_{i-1}(t) - imf_i'(t) \tag{10}$$

$$imf_{i+1}'(t) = \frac{1}{J}\sum_{j=1}^{J} E_1\left(r_i(t) + \varepsilon_i E_i\left(w_j(t)\right)\right) \tag{11}$$

5) The termination condition of CEEMDAN decomposition is that the residual signal must be a non-oscillatory monotone function or a constant less than a predetermined value. The actual PV power signal is eventually decomposed into n IMFs and one residual signal $r_n(t)$, which can be described as follows:

$$x(t) = \sum_{i=1}^{n} imf_i(t) + r_n(t) \tag{12}$$

where $E_i(.)$ is i-orders EMD decomposition operator; $w_j(t)$ is the white noise of j-th added; t is the time variable and $imf_i'(t)$ is the i-orders IMF of CEEMDAN decomposition.

D. USING CEEMDAN TO DECOMPOSE PV POWER SIGNAL

The PV power generation with intermittent and random fluctuations, resulting in non-stationary and non-linear power signal. CEEMDAN can handle this type of signal very well. Fig. 4 shows the actual operation data of a PV power station in Xiao Jing County, Sichuan Province China, on typical day, with a sampling interval of 1 min. The actual PV signal is decomposed by CEEMDAN algorithm to obtain all orders IMF. Here, $\varepsilon_i = 0.4$ and $J = 50$. Fig. 5 shows all IMFs of PV power signals.

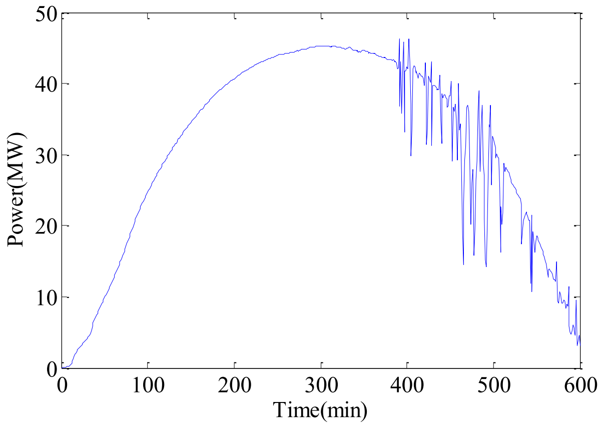

FIGURE 4. Actual PV power signal curve.

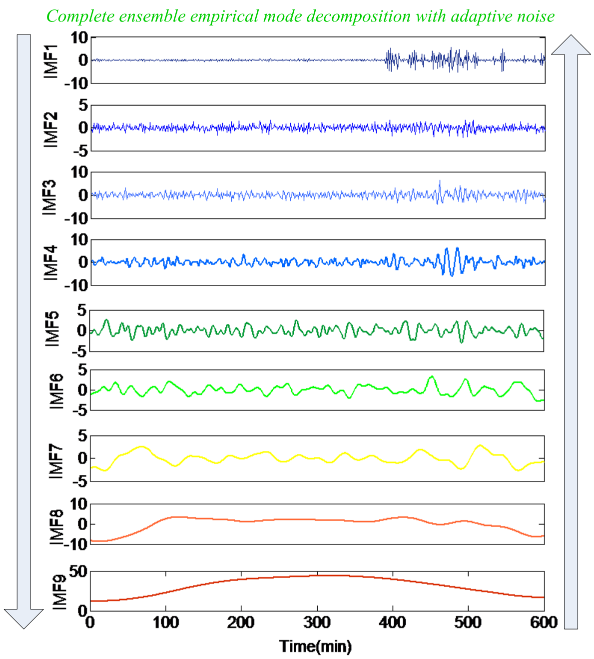

FIGURE 5. The IMFs, from high frequency to low frequency, of PV power signals.

E. CALCULATING RECONSTRUCTION ORDER OF PV IMF

As can be seen from Fig. 5, the power fluctuations frequency of PV IMFs is successively decreased from lower order to higher order. Thus, the IMFs reconstruction with lower frequency is selected as the target power of combined output of the PV-PS. Here, the reconstruction order K of the PV IMFs will have great impact on the smoothing effect. If the value is too large, it will lead to excessive smoothing. On the contrary, if the value is too small, it will lead to insufficient smoothing. The fuzzy intelligent control algorithm does not need the precise mathematical model of the controlled object, and has simple structure, and good robustness. For this reason, this paper proposes that the volatility of PV power after reconstruction can be taken as a constraint and the order K which can be adjusted adaptively by the fuzzy control algorithm to achieve better smoothing effect [19].

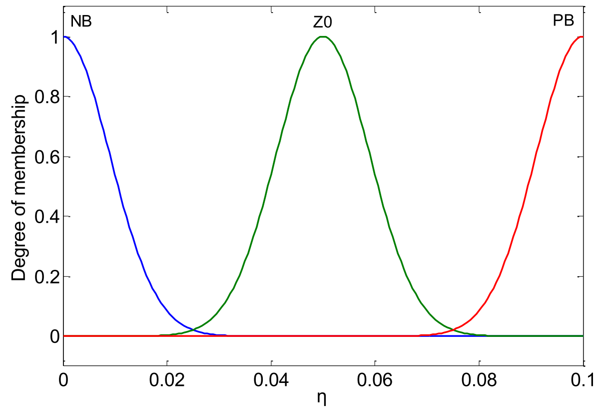

FIGURE 6. Membership function of PV volatility.

In order to reconstruct the IMFs of PV power using the fuzzy control algorithm, a single-input and single-output fuzzy controller is designed with the volatility of PV power after reconstructed as a constraint. A fuzzy subset of the volatility of reconstructed power is {NB, ZO, PB}, which indicates that volatility of the current reconstructed power is {low, moderate, high}. In order to meet the technical requirements of PV grid-connected, its volatility does not exceed 0.1 installed capacity/min. Therefore, the universe is set to [0-0.1], and the membership function is Gauss function, as shown in Fig. 6. A fuzzy subset of the reconstruction order is {NB, ZO, PB}, which indicates that the current reconstruction order is {low, moderate, high} respectively. The membership function of reconstructed order uses triangular function, as shown in Fig. 7. The rounding value of reconstruction order $K_{i-1} + l$ as the newest order number K_i of reconstruction. Here, K_{i-1} is the order of the previous reconstruction, and l is the output of the fuzzy controller.

The fuzzy control rules are as follows: when the fluctuations of the PV power are large, in order to improve the participation of VSPSS for suppressing PV power fluctuations, the order of reconstructing the PV IMFs will be increased to obtain a smoother reference power. When the fluctuations of the PV power are small, the participation of pumped storage should be reduced to improve energy efficiency. So, the order of reconstructing PV IMFs will be decreased. Fuzzy rules as shown in Table 1. Fig. 8 shows the reference power of combined output of the PV-PS is obtained by the Fuzzy CEEMDAN algorithm.

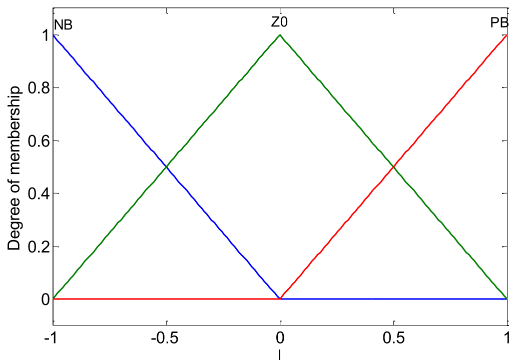

FIGURE 7. Membership function of reconstructed order.

TABLE 1. Fuzzy rule table.

IF (volatility)	NB	Z0	PB
THEN (order)	NB	Z0	PB

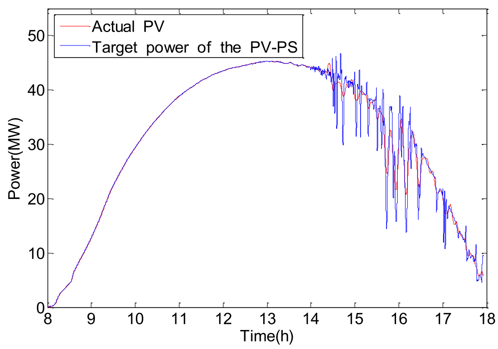

FIGURE 8. The target power of the PV-PS power system and the actual PV power.

IV. ROLLING OPTIMIZATION FOR BASE POWER OF VSPSS

In this section, the base power P_j of VSPSS is set in order to equate the VSPSS under single mode operation to battery energy storage which has two-layer capacity. Charging layer capacity and discharging layer capacity of battery energy storage with double layer capacities is calculated as follows:

$$P_{disc} = (1-\delta)\left(P_{Pump.low} - P_j\right) + \delta\left(P_j - P_{gene.low}\right) \quad (13)$$

$$P_{char} = (1-\delta)\left(P_j - P_{Pump.up}\right) + \delta\left(P_{gene.up} - P_j\right) \quad (14)$$

$$\delta = \begin{cases} 0, & \textit{if} \text{ Pumping status} \\ 1, & \textit{if} \text{ generation status} \end{cases} \quad (15)$$

where P_{disc} is the discharge layer capacity of equivalent battery energy storage; P_{char} is the charge layer capacity of equivalent battery energy storage; $P_{Pump.low}$ is lower limit of VSPSS pumping water power variation; $P_{Pump.up}$ is upper limit of VSPSS pumping water power variation; $P_{gene.low}$ is lower limit of VSPSS generation power variation; $P_{gene.up}$ is upper limit of VSPSS generation power variation. Here, $P_{Pump.up}/P_{Pump.low} = -8/0$ (MW), and $P_{gene.up}/P_{gene.low} = 8/0$ (MW).

The basic power determines the ability of the VSPSS to compensate and absorb PV fluctuations power. Taking VSPSS working in pump mode operation as an example, if the value is too small/large, the VSPSS is difficult to absorb/compensate the energy of beyond fluctuations requirements, thus reducing the suppression effect. At the same time, if the value is too small, it will lead to energy waste. In order to improve the smoothing effect and energy utilization efficiency, a base power optimization model of VSPSS for the first time is proposed in this paper.

A. OBJECTIVE FUNCTION

In order to improve the smoothing effect and energy efficiency, the smoothing effect index of VSPSS primary smoothing PV power fluctuations and energy waste index are used to describe the objective function in the optimization model. The smoothing effect index is the cumulative error between the combined output of PV- pumped storage and the PV target power of PV- pumped storage, as follows:

$$P_{dev}(P_j, t) = P(P_j, t) - P_m(t) \quad (16)$$

The base power of VSPSS is used as the index of energy waste. So, the objective function is given as follows:

$$P_{min} = \sum_{t=1}^{T} P_{dev}(P_j, t) - P_j \quad (17)$$

Constraint:

$$P_{l.low} < P_j < P_{l.up} \quad (18)$$

where P_{min} is the objective function; $P_{dev}(P_j, t)$ is the smoothing effect function of VSPSS primary smoothing PV power fluctuations; $P(P_j, t)$ is the combined output of PV-Pumped storage at time t; $P_m(t)$ is the target power at time t; P_j is the base power of VSPSS and T is the optimal period.

B. SOLVING METHOD OF OPTIMIZATION MODE

At present, mathematical programming, heuristic algorithm and direct search method are used to solve the optimal problem [22]–[24]. In this optimization model, because the smoothing effect index is obtained by simulation in which the smoothing strategy and PV-pumped storage model is used. So, the optimization model is difficult to give its analytic expression, which is defined as black box functions. In the meantime, because of its strong non-linearity and no derivative information available, it cannot be solved by mathematical programming method, while heuristic algorithms, such as particle swarm optimization, have the shortcoming of insufficient local search ability [23]. So, for these non-derivative black box functions, mesh adaptive direct search (MADS) algorithm is used in this paper. With the same global convergence properties as line search algorithm and trust region algorithm, the algorithm is easy to expand and is still effective when no-derivative and finite difference is unreliable. In addition, its convergence speed is faster and more likely to find the global optimal solution [24].

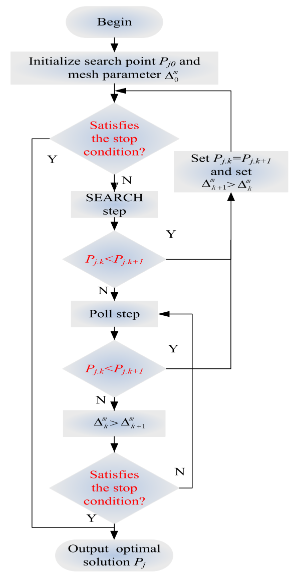

FIGURE 9. The MADS searching process.

MADS algorithm is an alternate iteration process of global and local search, where the black box functions are evaluated at some trial points called the mesh which is located on a discretization of the space of variables. The coarseness of this mesh, at iteration k of the algorithm, is named as the mesh size parameter Δ_k^m [25]. Each iteration is composed of three steps: the POLL, the SEARCH and updates. Fig. 9 shows the MADS search process. Firstly, we need to determine the initial trial point P_{j0} as well as the mesh size parameters Δ_0^m, and the size of the framework of POLL step. Then the optimization search is carried out. If the optimal value is found in the SEARCH step, the mesh size parameter will be increased, and continue to be optimized at the SEARCH step. Otherwise, the optimization will continue in the POLL step. If the optimal value is found, the updated mesh size parameters will be increased and returned to the SEARCH step. Otherwise, the mesh size parameters will be reduced. Optimization process is stopped when stopping condition is satisfied or global optimal is found.

Fig. 10 shows the framework of solving optimization model. Firstly, the smoothed method operation parameters and PV prediction data are determined, and then the MADS search process is carried out. Each step of optimization iteration needs to use the smoothing strategy to control the PV pumped storage generation model. Furthermore, $P(P_j, t)$ and $P_{dev}(P_j, t)$ are calculated. Finally, the optimal base power of VSPSS is obtained.

The optimal base power of all-day is obtained by using PV data of a typical day and the optimization model of base power. The simulation result is shown in Fig. 11. The validity of optimization model of the base power can be proved by Fig. 12, Fig. 13 and Table 2. It should be noted that the time interval between subsequent points in Fig.12 and Fig.13 is 1 min. From Fig.12, the PV power becomes very smooth after being processed by the fuzzy CEEMDAN algorithm.

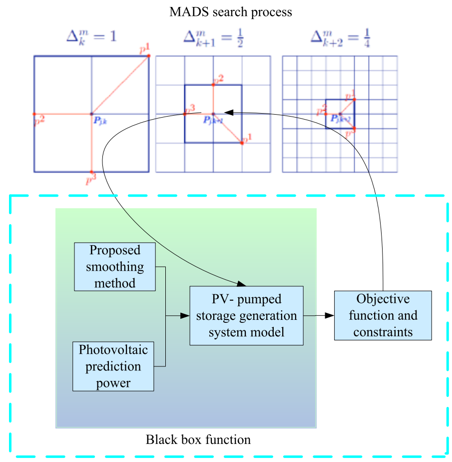

FIGURE 10. The framework of solving optimization model.

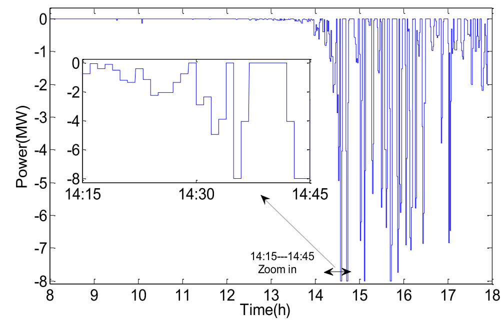

FIGURE 11. The optimal base power of all-day.

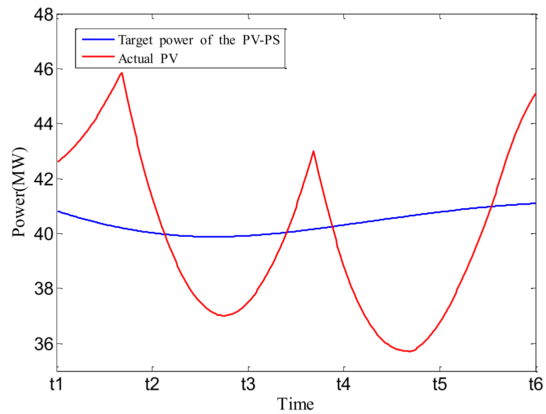

FIGURE 12. The target power of the PV-PS power system and the actual PV power in a certain period.

The maximum compensation power $P_{c.max}$ and the maximum absorption power $P_{ab.max}$ which are required in each period to suppress the actual PV power are obtained by using the data in the Fig.12. At the same time, the capacity ratio of charge and discharge of equivalent battery energy storage is calculated by using the base power of each period and Eq. (13) to Eq. (15). Finally, the compensation error $P_{c.er}$ and the absorption error $P_{ab.er}$ are calculated as follows:

$$P_{c.er} = \begin{cases} 0, & if\ P_{disc} - P_{c.max} \geq 0 \\ \left|P_{disc} - P_{c.max}\right|, & if\ P_{disc} - P_{c.max} < 0 \end{cases} \tag{19}$$

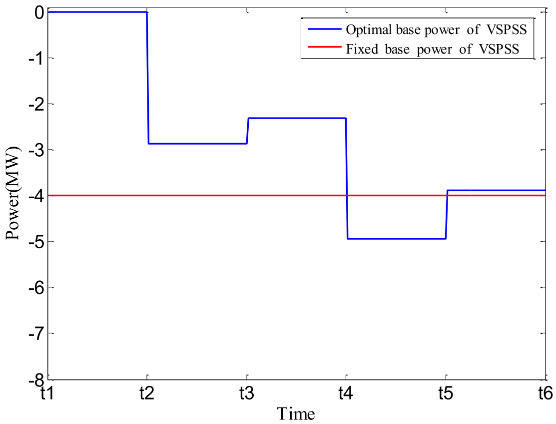

FIGURE 13. The optimal base power in a certain period.

TABLE 2. Statistical table of base power and compensation/absorption error.

Time Period	P_j(MW)	$P_{c.er}$(MW)	$P_{ab.er}$(MW)
t1-t2	0/-4	0/0	0/1.6330
t2-t3	-2.8717/-4	0.04/0	0/0
t3-t4	-2.3178/-4	0.04/0	0/0
t4-t5	-4.9327/-4	0.01/0.95	0/0
t5-t6	-3.8933/-4	0.03/0	0/0.02

$$P_{ab.er} = \begin{cases} 0, & \text{if } P_{char} - P_{ab.max} \geq 0 \\ |P_{char} - P_{ab.max}|, & \text{if } P_{char} - P_{ab.max} < 0 \end{cases} \quad (20)$$

When the error is smaller, the smoothing effect is better. The pumping energy of VSPSS is larger under the situation of small base power. The analysis in Table 2 shows that the compensation error is 1.6330 MW in t1-t2 and the absorption error is 0.95 MW in t4-t5 when the base power of VSPSS is fixed to 4MW. However, when the optimal base power of VSPSS is adopted, the compensation error and absorption error in each period are less than 0.04 MW. It means that the smoothing effect of optimal base power method is better. At the same time, the pumping energy of fixed base power is 1.4 times as much as the pumping energy of optimal base power in t1-t6 period, so this proposed method can reduce the energy waste.

V. EXPERIMENTS AND RESULTS

The simulation platform of CH-PV-PS generation system in the section II is built to verify the effectiveness and rationality of the PV power fluctuations smoothing method proposed in this paper. In this simulation platform, the rated capacity of the VSPSS with FSC is 8 MW, and the capacity of the PV power station is 50 MW, and the total capacity of the CHSs is 150 MW.

The PV data of a typical day are selected for simulation, in addition, CHSs have set a base power of 20 MW and the day-ahead prediction power is taken as the daily operation plan of photovoltaic power station. The actual PV power and the PV power after smoothing are shown in Fig. 14. As can be seen, the proposed method can effectively suppress the

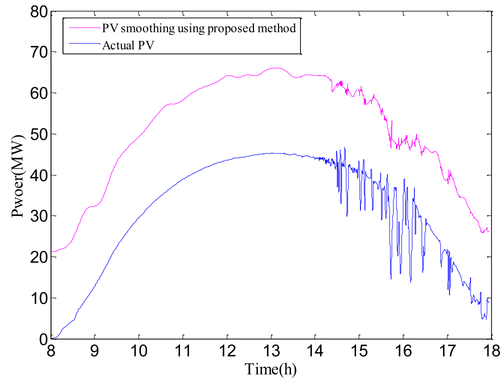

FIGURE 14. Comparison of the power profiles of PV before and after smoothing.

PV power fluctuations. In order to further demonstrate the smooth effect, Fig.15 shows the power fluctuations of PV before and after smoothing. It can be seen that the actual PV power fluctuations greatly, and the PV power fluctuations violation event is 8.7% of all-day. After smoothing, the fluctuations of PV power output are greatly reduced, which is all within the allowable power fluctuations range.

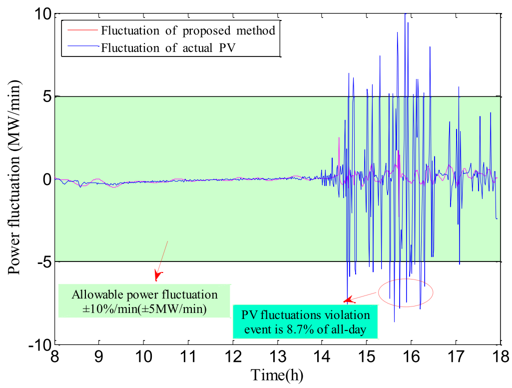

FIGURE 15. Comparison of the power fluctuations profiles of PV before and after smoothing.

In order to further verify the effectiveness of the proposed method, the experiments are carried out compared with the fixed base power smoothing method, and the fixed base power is 4MW. For comparing the smoothing effect, Fig. 16 is a comparison of the power after smoothing between optimal base power method and the fixed base power smoothing method. It can be seen that when the base power is fixed, the fluctuations of the power after smoothing is decreased, but the effect of smooth is not ideal.

Fig. 17 shows that the PV power fluctuations violation event is 1.6% of all-day when using fixed base power smoothing method. So, it is much less effective than the optimal base power method. In order to compare energy efficiency, Fig. 18 shows that the pumping power of VSPSS for suppressing PV power fluctuations. It can be seen that the pumping power of the fixed base power smoothing method is more than 4 MW at most of the time and the pumping power of optimal base power method is less than 4 MW at most of the time. At the same time, the pumping power of all-day of the fixed base

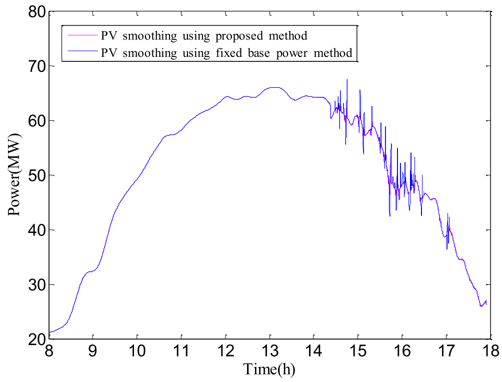

FIGURE 16. Comparison of the power of PV after smoothing using optimal base power smoothing method and fixed base power smoothing method.

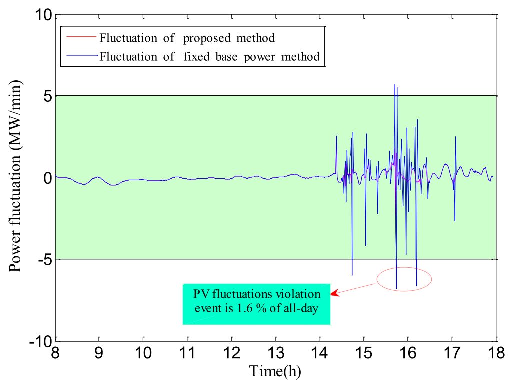

FIGURE 17. Comparison of the power fluctuations profiles of PV after smoothing using optimal base power smoothing method and fixed base power smoothing method.

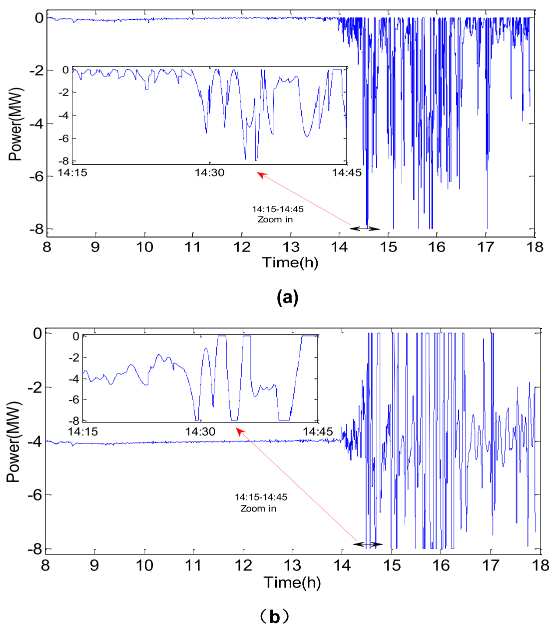

FIGURE 18. Pumping power of VSPSS: (a) Pumping power of optimal base power smoothing method and (b) Pumping power of the fixed base power smoothing method.

power smoothing method is 6.8 times as much as the optimal basic power method. So, the energy waste is reduced when using optimal basic power method.

VI. CONCLUSION

The method of smoothing PV power fluctuations for CH-PV-PS generation system is proposed. The existing VSPSS and CHSs are used to suppress PV power fluctuations and reduce the cost of smoothing. The CEEMDAN algorithm is used to calculate the target power of combined output of the PV-PS on-line adaptively in order to prevent smoothing excessive and insufficient. The optimization model of base power of VSPSS is proposed, and the optimal base power is obtained by using MADS algorithm to solve the optimization model in order to improve smoothing effect and the energy efficiency. Finally, the experiment is designed to prove the effectiveness of the proposed smoothing method. The results show that the proposed method has better smoothing effect than the fixed power base method, and the power fluctuations can be controlled within 10%/min of its installed capacity, and the energy waste is reduced.

REFERENCES

[1] M. Lei, Z. Yang, and Y. Wang, "An MPC-based ESS control method for PV power smoothing applications," *IEEE Trans. Power Electron.*, vol. 33, no. 3, pp. 2136–2144, Mar. 2018.

[2] W. Ma, W. Wang, X. Wu, R. Hu, F. Tang, and W. Zhang, "Control strategy of a hybrid energy storage system to smooth photovoltaic power fluctuations considering photovoltaic output power curtailment," *Sustainability*, vol. 11, no. 5, p. 1324, 2019.

[3] D. A. Elvira-Ortiz, D. Morinigo-Sotelo, O. Duque-Perez, A. Y. Jaen-Cuellar, R. A. Osornio-Rios, and R. D. J. Romero-Troncoso, "Methodology for flicker estimation and its correlation to environmental factors in photovoltaic generation," *IEEE Access*, vol. 6, pp. 24035–24047, 2018.

[4] P. Li, C. Zhang, X. Fu, G. Song, C. Wang, and J. Wu, "Determination of local voltage control strategy of distributed generators in active distribution networks based on Kriging metamodel," *IEEE Access*, vol. 7, pp. 34438–34450, 2019.

[5] M. Anvari, B. Werther, G. Lohmann, M. Wächter, J. Peinke, and H.-P. Beck, "Suppressing power output fluctuations of photovoltaic power plants," *Solar Energy*, vol. 157, pp. 735–743, Nov. 2017.

[6] A. Busca-Forcos and C. Marinescu, "Pumped storage system for wind energy in variable operating conditions," presented at the Int. Symp. Fundamentals Electr. Eng. (ISFEE), Nov. 2014, doi: 10.1109/ISFEE.2014.7050574.

[7] W. Yang and J. Yang, "Advantage of variable-speed pumped storage plants for mitigating wind power variations: Integrated modelling and performance assessment," *Appl. Energy*, vol. 237, pp. 720–732, Mar. 2019.

[8] T. Li, W. Hu, X. Xu, Q. Huang, G. Chen, X. Han, and Z. Chen, "Optimized operation of hybrid system integrated with MHP, PV and PHS considering generation/load similarity," *IEEE Access*, vol. 7, pp. 107793–107804, 2019.

[9] W. Ma, W. Wang, X. Wu, R. Hu, F. Tang, W. Zhang, X. Han, and L. Ding, "Optimal allocation of hybrid energy storage systems for smoothing photovoltaic power fluctuations considering the active power curtailment of photovoltaic," *IEEE Access*, vol. 7, pp. 74787–74799, 2019.

[10] Z. Wu, X. Jiang, S. Ma, and H. Ma, "Wavelet packet-fuzzy control of hybrid energy storage systems for PV power smoothing," *Chin. J. Electr. Eng.*, vol. 34, no. 3, pp. 317–324, Jan. 2014.

[11] X. Han, Y. Chen, H. Zhang, and F. Chen, "Application of hybrid energy storage technology based on wavelet packet decomposition in smoothing the fluctuations of wind power," *Chin. J. Electr. Eng.*, vol. 34, no. 19, pp. 8–13, Jul. 2013.

[12] Q. Jiang and H. Wang, "Two-time-scale coordination control for a battery energy storage system to mitigate wind power fluctuations," *IEEE Trans. Energy Convers.*, vol. 28, no. 1, pp. 52–61, Mar. 2013.

[13] S. Sukumar, H. Mokhlis, S. Mekhilef, M. Karimi, and S. Raza, "Ramp-rate control approach based on dynamic smoothing parameter to mitigate solar PV output fluctuations," *Int. J. Elect. Power Energy Syst.*, vol. 96, pp. 296–305, 2018.

[14] J. A. Suul, K. Uhlen, and T. Undeland, "Wind power integration in isolated grids enabled by variable speed pumped storage hydropower plant," presented at the IEEE Int. Conf. Sustain. Energy Technol., 2009, doi: 10.1109/ICSET.2008.4747040.

[15] Y. Ren, Y. Zheng, B. Zhou, and Q. Guo, "Model and operation strategy of pumped-storage in hybrid power system," *J. Drainage Irrigation Machinery Eng.*, vol. 31, no. 2, pp. 137–141, Feb. 2013.

[16] B. G. Teshager, M. Han, S. Patrobers, L. K. Tuan, F. M. Shah, and Z. W. Khan, "Direct power control strategy based variable speed pumped storage system for the reduction of the wind power fluctuation impact on the grid stability," presented at the IEEE Int. Conf. Compat., Power Electron. Power Eng. (CPE-POWERENG), Apr. 2018.

[17] M. Imanaka, H. Sasamoto, J. Baba, N. Higa, and M. Shimabuku, "Compensation for photovoltaic generation fluctuation by use of pump system with consideration for water demand," *J. Electr. Eng. Technol.*, vol. 10, no. 3, pp. 1304–1310, 2015.

[18] Y. An, W. Fang, and Q. Huang, "Preliminary research of theory and method of hydro/solar complementary operation," *Acta Energiae Solaris Sinica*, vol. 37, no. 8, pp. 1985–1992, Aug. 2016.

[19] X. Y. Yang, C. Cao, J. Ren, and F. Gao, "Control method of smoothing PV power output with battery energy storage system based on fuzzy ensemble empirical mode decomposition," *High Voltage Eng.*, vol. 42, no. 7, pp. 2127–2133, Jul. 2016.

[20] Q. Han, Q. Sun, X. Wang, B, Li, and Q. Gao, "Application of CEEMDAN in Raman spectroscopy denoising," *Laser Optoelectron. Progr.*, vol. 52, no. 7, 2015, Art. no. 113003.

[21] M. A. Colominas, G. Schlotthauer, and M. E. Torres, "Improved complete ensemble EMD: A suitable tool for biomedical signal processing," *Biomed. Signal Process. Control*, vol. 14, pp. 19–29, Nov. 2014.

[22] L. Pi, Y. Pan, and L. Shi, "Hybrid nested partitions and mathematical programming approach and its applications," *IEEE Trans. Autom. Sci. Eng.*, vol. 5, no. 4, pp. 573–586, Oct. 2008.

[23] Z. Shen, W. Pei, W. Deng, H. Xiao, Z. Zhao, and Z. Qi, "Storage capacity optimization for wind farm considering the impact of battery lifetime and control strategy," *High Voltage Eng.*, vol. 7, no. 41, pp. 2236–2244, Jul. 2015.

[24] C. Audet and J. E. Dennis, Jr., "Mesh adaptive direct search algorithms for constrained optimization," *SIAM J. Optim.*, vol. 17, no. 1, pp. 188–217, 2006.

[25] H. Xue, Y. Wang, and S. Zhao, "Optimization for serial supply chain's control strategy based on mesh adaptive direct search and simulation," *Comput. Integr. Manuf. Syst.*, vol. 5, no. 22, pp. 1339–1346, May 2016.

LEI CHEN is currently pursuing the M.S. degree in electrical engineering with Xihua University, Chengdu, China. His current research interests include photovoltaic (PV) systems, new energy conversion technology, and power electronic energy saving technology.

JUN WANG received the Ph.D. degree in electrical engineering from Southwest Jiaotong University, China, in 2006. She was a Lecturer with the Sichuan College of Science and Technology, China, from 1991 to 2003; and an Associate Professor with Xihua University, China, from 1998 to 2003. She has been a Professor with the School of Electrical and Information Engineering, Xihua University, China, since 2004. Her research interests include electrical automation, intelligent control, and membrane computing.

ZHANG SUN received the M.S. degree from Xihua University, Chengdu, China, in 2013. He is currently pursuing the Ph.D. degree in electrical engineering with Southwest Jiaotong University, Chengdu. He has been a Lecturer with Xihua University. His current research interests include power system protection, power converter, dc microgrid, and hybrid energy storage technology.

TAO HUANG (M'18) received the Ph.D. degree from the Politecnico di Torino, Italy, in 2011. He is currently a Researcher and a Professor with the Department of Energy, Politecnico di Torino and the School of Electrical Engineering and Electronic Information, Xihua University, China, respectively. His research interests include critical infrastructure protection, power system modelling and analysis, electricity markets, and smart grids.

FAN WU received the B.S. degree from Shanghai Dianji University, China, in 2018. He is currently pursuing the M.S. degree with Xihua University, Chengdu, China. His current research interests include power converter and dc micro-grid.