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Optimized Operation of Hybrid System Integrated With MHP, PV and PHS Considering Generation/Load Similarity

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ABSTRACT Renewable energy is widely used as a clean energy in the world, yet the intermittent of the power generation from renewable energy power plants, resulting in poor quality of power supply. However, the hybrid energy system and some energy storage devices can be installed to mitigate the power fluctuation, to achieve power smoothing and maximize the profit, a double-objective optimization model of hybrid system integrated with micro-hydro power (MHP), photovoltaic (PV), and pumped hydro storage (PHS) is established in this study. The day-ahead optimized operation strategy of the PHS based-on hour-level data of seven days is obtained, which aims to maximize the similarity value (SIM) between the power generation curve and load profile, and the economic revenue (ER) of the PHS. Optimized schedule is obtained by means of chance-constrained programming (CCP) and modified multi-objective particle swarm optimization (MOPSO). The performance of the model is evaluated by using the meteorological, the historical MHP power generation and the load data obtained in Xiaojin County, Sichuan province, China. The simulation results reveal that the best trade-off value between SIM and ER can be obtained on the Pareto front with comprehensive consideration of the system operation strategy and target. Furthermore, the generation/load similarity can be increased 7.89% under the participating of the PHS.

INDEX TERMS Micro-hydro power, pump-hydro storage, chance-constrained programming, Pareto front.

I. INTRODUCTION

Electricity supply plays an increasingly important role with the development of economy. Fossil fuels such as coal, oil and natural gas are the main primary energy sources that is used to generate electricity. Since fossil fuels are non-renewable and violate the concept of green development, renewable energy is widely used as an emerging clean energy globally. Alternative energy sources such as hydropower (HP), photovoltaic (PV) and wind power (WP) are currently the most widely used renewable energy. Micro-hydro power (MHP) built on a run-of-river may be very beneficial for rural electrification [1]. Renewable energy can not only mitigate the consumption of non-renewable energy but also effectively reduce the economic cost for extending traditional power grids to remote areas. In addition, it can promote the economic development in remote areas [2].

However, the power generation of a standalone renewable energy power plant depends on many environmental factors. The HP is flexible in power system operation and can quickly meet the demand of the peak-frequency regulation. The PV output is mainly affected by solar radiation, ambient temperature and wind speed. The WP output is affected by wind speed and wind direction. The MHP output is related to the amount of water flow in the upstream of the run-of-river, and it generates a large amount of electricity in summer and autumn, less in winter and spring in China. Renewable energy, such as PV,

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WP and MHP, are characterized by intermittent, volatility and randomness.

Hybrid renewable energy system (HRES) may be a promising way to solve the problems mentioned above, such as wind-photovoltaic hybrid system (WP-PV) [3], [4] can complement each other on a spatial scale to compensate for the instantaneous fluctuation of wind speed and solar radiation. This HRES has higher superiority than independent renewable energy power plants, however, the fluctuating wind speed and the intermittent solar radiation are difficult to fully compensate each other, WP-PV will also pose a certain degree of intermittent output. The HP is flexible in power system operation and can quickly meet the demand of the peak-frequency regulation [5]. Hydropower-photovoltaic hybrid system (HP-PV) can make up for the randomness and volatility of PV output, improve the efficiency of photovoltaic resource utilization, the quality of power supply and stability of the power system, and optimize the structure of power grid [6], [8], the superiority of the HP-PV is self-evident.

Energy storage system (ESS) can store excess electricity and discharge to meet the demand of load, which can smooth the output curve of the HRES [9]. ESS is commonly used in power system including battery energy storage (BES) [10], flywheel energy storage (FES) [11], superconducting magnetic energy storage (SMES) [12], [13], compressed air energy storage (CAES) [14], pumped hydro storage (PHS) [15]. Among them, PHS has been widely used in HRES due to its mature technology, environmental friendliness and large throughput capacity [16]. A mixed integer linear programming algorithm (MILP) is used to achieve the maximum profit of the WP-PHS [17]. A techno-economic model of the WP-PV- PHS is to optimize the system design based on genetic algorithm (GA) in [18]. The optimal sizing of the WP-PHS is investigated considering PHS operation in an island system is proposed in [19]. A PV-PHS model for minimizing the operation cost of hybrid system and the energy reduction of PV is proposed and validated based on the IEEE-RTS 96 system [20].

Furthermore, for the off-grid operation mode of the hybrid energy system, the home energy management system with renewable energy is researched recently. In Ref. [21], the stochastic optimal battery storage sizing and scheduling in home energy management systems equipped with PV is proposed to manage the charging-discharging regime, capacity, and power of BES system, and the optimal operation strategy and sizing of BES system is solved by the stochastic mixed integer nonlinear programming with Monte-Carlo Simulation method. In Ref. [22], under the different price mechanisms, a bi-level model is investigated to size the capacity allocation strategy of the PV and BES in a smart household, and the installation capacity of PV is discussed under the different subsidies. In addition, it is difficult to control the power generation of renewable energy, so, the congestion on transmission line is occurred frequently; from this viewpoint, a reasonable planning and scheduling on energy storage system for congestion management is necessary; and this problem has mentioned in Ref. [23] based on the WP-PV-ESS to find the optimal capacity and charging-discharging regime of ESS, that is, the energy storage unit is optimally charged or discharged to tackle the uncertainty of the renewable energy as well as relief congestion in the transmission lines. Meanwhile, in order to ensure the economy and stability of the renewable energy system, some optimal reactive power dispatch strategies are proposed in Ref. [24], [25]. That is, the reactive power references of each renewable energy generator are selected as the strategy variables to minimize the power loss, hence, the economical revenue can be improved by the reactive optimization method.

There are plenty of researches on WP-PHS and PV-PHS hybrid system for rural electrification or home energy management, the results show that it can effectively improve energy utilization efficiency and the reliability and stability of power supply system. However, few researchers focus on the optimal operation of MHP-PV-PHS hybrid system and consider the similarity of the generation/load and the economy of the energy storage devices simultaneously.

In this paper, a novel concept for optimizing operation of MHP-PV-PHS hybrid system is proposed by considering both the similarity of generation/load and the economy of PHS under the uncertainty of MHP and PV. Based on the generation/load similarity of the MHP-PV-PHS hybrid system and the economic revenue of the PHS, a double-objective optimization model is established. The aims of the model are to maximize the similarity between the MHP-PV-PHS hybrid system power generation curve and the load profile, and the economic revenue of PHS. The day-ahead operation strategy of the PHS at different time in seven days is obtained, the uncertainty output of the MHP and PV is considered and can be define as the sum of the determined forecast value and the forecast error value. Then the model is addressed using chance-constrained programming (CCP) and modified multi-objective particle swarm optimization (MOPSO). The hour-level data of seven days is chosen to verify the performance of the proposed optimization model.

The contributions of this paper are:

(1) The concept of considering both the similarity of generation/load and the economy of energy storage system in MHP-PV-PHS hybrid off-grid system is proposed in this paper. (2) The MHP-PV-PHS hybrid system is investigated by using MOPSO based on similarity and economy from the perspective of single-objective and double-objective. (3) Sensitivity analysis of SIM and ER is carried out.

This paper is organized as follows. Section II introduces the components of the hybrid system and the mathematical model of PV and PHS. Section III introduces optimization model consists of objective function and constraint condition. Section IV states the optimization methods and flowchart diagram. The case study and the sensitivity analysis are carried out in section V. Finally, conclusions are drawn in section VI.

II. SYSTEM DESCRIPTION AND MODELING

In this section system schematic are described, and the mathematical model of PV and PHS are formulated by considering all important system parameters.

A. SYSTEM DESCRIPTION

Fig. 1 shows the physical system schematic of the MHP-PV-PHS hybrid system in Xiaojin County, Sichuan, China, which contains a run-of-river MHP, a PV power plant and a PHS. All the components in the hybrid system are connected to the same AC bus, the residential load demand power mainly supplied by the MHP-PV-PHS hybrid system. The optimized operation of PHS is investigated under the off-grid condition in this work.

B. METHEMATICAL MODELS

1) THE PV POWER GENERATION MODEL

The power generation of PV array is mainly affected by solar radiation, environmental temperature and wind speed, which can be formulated as follow [26]:

$$P_{PV}(t) = P_{STC}\frac{G_c(t)}{G_{STC}}\left[1 + k\left(T_c(t) - T_{STC}\right)\right] \tag{1}$$

where P_{PV} is the power generation with the solar radiation G_c and surface temperature T_c on the PV array. P_{STC} is the rate power generation of PV array under the standard condition, this parameter can be given by the manufacturer, and k is temperature coefficient, $G_{STC} = 1$ kW/m^2, T_{STC} is reference temperature 25°C. The surface temperature on PV array can be formulated:

$$T_c(t) = T_a(t) + \mu G_c(t) \tag{2}$$

where T_a is the environmental temperature, the coefficient μ is related to wind speed. For power generation of PV plant can be obtained by Eq. (1) with the solar radiation and environmental temperature data. The historical MHP power data is used in the case study, so the model of MHP is not given in this work.

2) THE PUMPED-HYDRO SYSTEM MODEL

The basic principle of the PHS utilize the alternative work of pump and hydro-turbine to achieve charge and discharge energy. During the off-peak hours of power consumption, the PHS works in pump/motor mode to store excess energy by pumping water from the lower reservoir to the upper, it converts electrical energy into the gravitational potential energy. During the load power shortage, the PHS works in hydro-turbine/generator mode to generate adequate power to meet load demand by converting the gravitational potential energy into electricity. The PHS can be used to generate power with a roundtrip efficiency of 70–80% [27]. In the hybrid system, the efficiencies of the pump and hydro-turbine are 83% and 86% [28], respectively. The energy storage state of the PHS is formulated as follows.

1) Pump/motor mode: The water quantity from lower reservoir by pumping can be expressed in Eq. (3) [29].

$$q_{Pump}(t) = 3600 \cdot \frac{\eta_{Pump} \cdot 1000 \cdot P_{PHS}^{Pump}(t)}{gH} \tag{3}$$

where q_{Pump} is the water volumetric flow rate from the lower reservoir into the pump (m^3/h), η_{Pump} is the overall efficiency of the pumps, P_{PHS}^{Pump} is the charge power (MW), g is the gravity acceleration (9.81 m/s^2), and H is the elevation height (m).

2) Hydro-turbine/generator mode: The water in the upper reservoir is used to drive the hydro-turbine. The energy generated from the hydro-turbine/generator can be expressed in Eq. (4).

$$P_{PHS}^{Turbine}(t) = \frac{\eta_{Turbine} gHq_{Turbine}(t)}{3600 \times 1000} \tag{4}$$

where $P_{PHS}^{Turbine}$ is the power generation of hydro-turbine (MW), $\eta_{Turbine}$ is the overall efficiency of the hydro-turbine, $q_{Turbine}$ is the water volumetric flow rate flow from upper reservoir into the hydro-turbine (m^3/h).

3) Water volume model of upper reservoir: The total water quantity stored in the upper reservoir can be formulated as:

$$Q(t+1) = Q(t)(1-\phi) + \int_t^{t+1} q_{Pump}(t)\,dt - \int_t^{t+1} q_{Turbine}(t)\,dt \tag{5}$$

where Q (m^3) is the water quantity in the upper reservoir at time t, ϕ is the evaporation and leakage coefficient. Since there are no constraints for the water quantity in the lower reservoir in this work, it is assumed that there is sufficient storage capacity of the lower reservoir.

The change of water quantity in upper reservoir can be regard as the state of charge (SoC) like the battery. The SoC can be written as:

$$SoC(t) = \frac{Q(t)}{V_{\max}} \times 100\% \tag{6}$$

where $V_{\max}$ is the volume of upper reservoir.

III. OPTIMIZATION MODELS

In this section, according to the above introduced system structure and models of PV and PHS, the similarity and economic function of the MHP-PV-PHS hybrid system can be formulated. The similarity of generation and load suggests the reliability function, and the economic function mainly includes the generation revenue and the cost of operation and maintenance simultaneously.

A. OBJECTIVE FUNCTION

The first objective function is to make the actual output of the MHP-PV-PHS hybrid system match the expected output. The expected output is a load demand profile in the off-grid condition. Since the aim of this work is to realize day-ahead optimal dispatch, the actual output of the MHP-PV-PHS hybrid system and the expected output consist of two vectors containing 168 dimensions, the problem of matching degree between two curves can be transformed into curve similarity. Cosine similarity is introduced in this paper to evaluate the curve similarity, it is expressed as follows [30]:

$$SIM = \frac{\sum_{t=1}^{T}\left[P_{hybrid}(t)\cdot P_{load}(t)\right]}{\left[\sum_{t=1}^{T}P_{hybrid}(t)^2\cdot\sum_{t=1}^{T}P_{load}(t)^2\right]^{1/2}} \quad (7)$$

$$P_{hybrid}(t) = P_{MHP}(t) + P_{PV}(t) + P_{PHS}(t) \quad (8)$$

where P_{hybrid} and P_{load} (MW) are the power generation of the MHP-PV-PHS hybrid system and load profile at time t, respectively. T is the simulation period (T = 168h) in this paper. P_{MHP} is the historical power generation data, P_{PV} is obtained by the historical solar radiation and environmental temperature data with Eq. (1).

Since the power generated from MHP and PV can be approximately fully utilized under the participating complementary regulation of pumped-hydro plant in the MHP-PV-PHS hybrid system, there is no need to optimize its economic revenue. The operation status of PHS depends on the power generation of MHP, PV and load profile, so this study only considers the economic revenue of the PHS, it can be expressed as:

$$\begin{aligned} ER = &\sum_{t=1}^{T}\left[B_{PHS}^{Turbine}(t)\cdot\lambda_{PHS}^{Turbine}(t)\cdot P_{PHS}^{Turbine}(t)\right] \\ &-\sum_{t=1}^{T}\left[B_{PHS}^{Pump}(t)\cdot\lambda_{PHS}^{Pump}(t)\cdot\left|P_{PHS}^{Pump}(t)\right|\right] \\ &-OMC \end{aligned} \quad (9)$$

$$B_{PHS}^{Turbine}(t) + B_{PHS}^{Pump}(t) = 1 \quad (10)$$

where $B_{PHS}^{Turbine}$ and B_{PHS}^{Pump} are binary variables, which are used to restrain the working status of pump and hydro-turbine, $\lambda_{PHS}^{Turbine}$ and λ_{PHS}^{Pump} are the electricity prices at time t (\$/MWh), respectively. The OMC is the operation and maintenance cost which is in direct proportion to power generation and can be defined in Eq. (11).

$$\begin{aligned} OMC = &k_{omc-T}\sum_{t=1}^{T}\left[B_{PHS}^{Turbine}(t)\cdot P_{PHS}^{Turbine}(t)\right] \\ &+k_{omc-P}\sum_{t=1}^{T}\left[B_{PHS}^{Pump}(t)\cdot\left|P_{PHS}^{Pump}(t)\right|\right] \end{aligned} \quad (11)$$

where k_{omc-T} and k_{omc-P} are the coefficient of power generation under the hydro-turbine and pump mode (\$/MWh), respectively. These coefficients represent the cost per unit of electricity generated.

Based on the discussion mentioned above, the aim of the double-objective optimization model is to achieve the win-win effect of SIM and ER, that is, to relatively maximize both SIM and ER, which is defined as:

$$\max F = \{\text{SIM,ER}\} \quad (12)$$

B. CONSTRAINTS

The uncertainty of the MHP and PV output is considered, which is expressed as the sum of the estimated value and deviation value. The chance-constrained programming (CCP) is adopted in this paper, which can be written as [31]:

$$P_r\{f(t) \le \varphi\} \ge \alpha \quad (13)$$

where $P_r\{\bullet\}$ is the probability that the inequality constraint is true.

The chance constrained model in Eq. (13) suggests that under the allowable risk level of unbalance power φ, the unbalance power supply probability of MHP-PV-PHS hybrid system should be greater or equal to a constant confidence-level which is denoted by α.

$$f(t) = \left|\frac{P_{hybrid}(t) + \varepsilon_k(t) - P_{load}(t)}{P_{load}(t)}\right| \quad (14)$$

$$\varepsilon_k(t) \sim \mathcal{N}\left(0, \delta(t)^2\right) \quad (15)$$

where $f(t)$ is the relative deviation between $P_{hybrid}(t)$ and $P_{load}(t)$. The forecast error value $\varepsilon_k(t)$ obeys normal distribution with mean 0 and standard deviation $\delta(t)$, which is expressed by Eq. (16) $\delta(t)$ can be defined as [32], and

$$\delta(t) = \sqrt{\delta_{MHP}(t)^2 + \delta_{PV}(t)^2} \quad (16)$$

According to Ref. [33], the standard deviation of the MHP and PV forecast error is approximated by Eq. (17) and Eq. (18), where $\beta_i\,(i = 1, 2)$ is the weight coefficient of the MHP output P_{MHP} and the installed capacity P_{MHPN}, and $\gamma_i\,(i = 1, 2)$ is the weight coefficient of the PV output P_{PV} and the installed capacity P_{PVN}.

$$\delta_{MHP}(t) = \beta_1 P_{MHP}(t) + \beta_2 P_{MHPN} \quad (17)$$

$$\delta_{PV}(t) = \gamma_1 P_{PV}(t) + \gamma_2 P_{PVN} \quad (18)$$

The constraints of PHS are as follows:

$$\int_{t=1}^{t=T} P_{PHS}^{Turbine}(t)dt \le (Q_{initial} - Q_{\min})gH\eta_{Turbine} \quad (19)$$

$$\int_{t=1}^{t=T} P_{PS}^{Pump}(t)\eta_{Pump}dt \le (Q_{\max} - Q_{initial})gH \quad (20)$$

$$P_{Turbine}^{\min} \le P_{PHS}^{Turbine}(t) \le P_{Turbine}^{\max} \quad (21)$$

$$P_{Pump}^{\max} \le P_{PHS}^{Pump}(t) \le P_{Pump}^{\min} \quad (22)$$

where $Q_{\min}$, $Q_{initial}$ and $Q_{\max}$ are the minimum, initial and maximum available water quantity of upper reservoir (m^3), respectively. Eq. (19) and Eq. (20) describe the upper and lower energy limit of the PHS. Eq. (21) and Eq. (22) represent the minimum and maximum power limit of the hydro-turbine and pump, respectively. In addition, the water quantity limit of lower reservoir is not considered in this paper.

In order not to affect the operation of MHP-PV-PHS hybrid system the following days, the stored water quantity in upper reservoir should be restricted at the end of the operation period. The SoC of upper reservoir can be formulated in Eq. (23), the limit value $\text{SoC}_{\min}$ and $\text{SoC}_{\max}$ are used to ensure the continuous operation of PHS and to protect other functions of the reservoir, such as ecological balance.

$$SoC_{\min} \leq SoC(t) \leq SoC_{\max} \tag{23}$$

IV. OPTIMIZATION MTHODS

In this paper, modified multi-objective particle swarm optimization (MOPSO) combined with stochastic simulation method (SSM) is introduced to search for the non-inferior solutions over the Pareto front.

TABLE 1. Pseudo code of the SSM.

```
Initialize α = 0.7, ξ and n = 0, i = j = 1, the length of
ξ is N( N = 10000 );
Input the strategy variable X, the length is T;
Do {
Sample the stochastic variable ξ for each strategy
variable X_i;
 While ( n/N < α and j ≤ N ) {
 If ( g_j(x_i, ξ_j) ≤ 0 ) { n = n+1 ;}
  j = j+1 ;
  }
  If ( n/N ≥ α ) {
     i = i+1 ;
     current strategy variable X_i is valid;
     }
  Else {
     Re-update the strategy variable X;
     Re-sample the stochastic variable ξ ;
     }
 } While ( i ≤ T );
 Print X;
```

The pseudo code of the SSM is in Tab. 1 considering the general model for chance-constraint programming in Eq. (24). The basic principle of the SSM is law of large numbers.

$$P_r\left\{g_j(x,\xi) \leq 0, j = 1, 2 \ldots n\right\} \geq \alpha \tag{24}$$

where g_j is the *jth* inequality constraint.

The PSO algorithm was firstly proposed by Eberhart and Kennedy [34], which based on the swarm intelligence, that is, the optimization problem can be solved through cooperation and information sharing among each particle in the swarm. And the PSO algorithm has an excellent performance to solve the non-convex and non-continue problem, with a high probability of finding the optimal solution.

To improve the performance of classical PSO, a linearly time-varying acceleration constant is adopted [35],

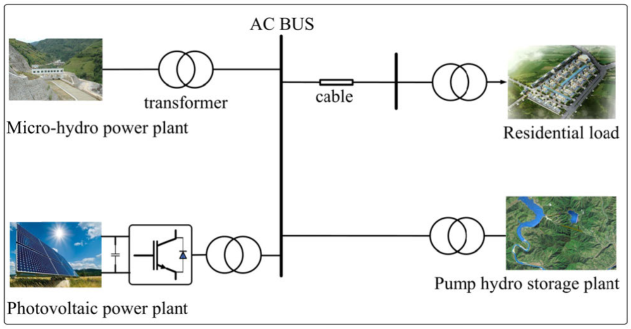

FIGURE 1. System schematic of the MHP-PV-PHS hybrid system.

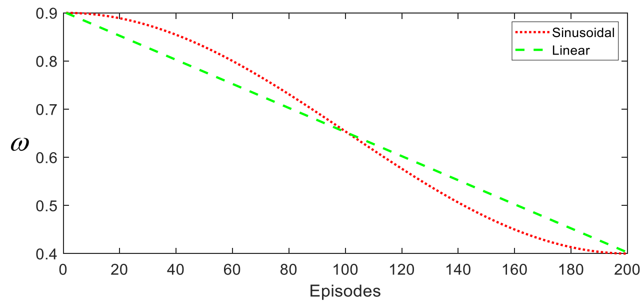

FIGURE 2. Comparison of linear and sinusoidal modulations of inertia weight.

which includes a high cognitive constraint (c1,max) and low social constant (c2,min) in initial status, c1 and c2 are constantly adjusted during the entire optimization process. Besides, a sinusoidal time-varying inertia weight (ω) is considered [36].

$$c_1(i) = c_{1,\max} + \left(c_{1,\min} - c_{1,\max}\right)\frac{i}{i_{\max}} \tag{25}$$

$$c_2(i) = c_{2,\min} + \left(c_{2,\max} - c_{2,\min}\right)\frac{i}{i_{\max}} \tag{26}$$

$$\omega(i) = \omega_{\min} + (\omega_{\max} - \omega_{\min})\cos^2\left(\frac{\theta}{2}\right) \tag{27}$$

$$\theta = \frac{i}{i_{max}}\pi \tag{28}$$

where i is the iteration times, and i_{max} is the maximum iterative episode. Eq. (25) and Eq. (26) describe the linear modulation of the acceleration, Eq. (27) present a truncated sinusoidal function modulation of the inertia weight. A linear modulation of the inertia weight is proposed in [37], a comparison of the conventional linear modulation and sinusoidal modulation for the inertia weight is given in Fig. 2. It can be observed that the inertia component of the velocity of particles is higher during the early half of the search, which is conducive to the global search and find a superior area, during the latter half of the search, a lower inertia value is conducive to local search under the superior area.

In order to better illustrate the application of the MOPSO in this research, a flowchart diagram is shown in Fig. 3. The main steps of the program are as follows:

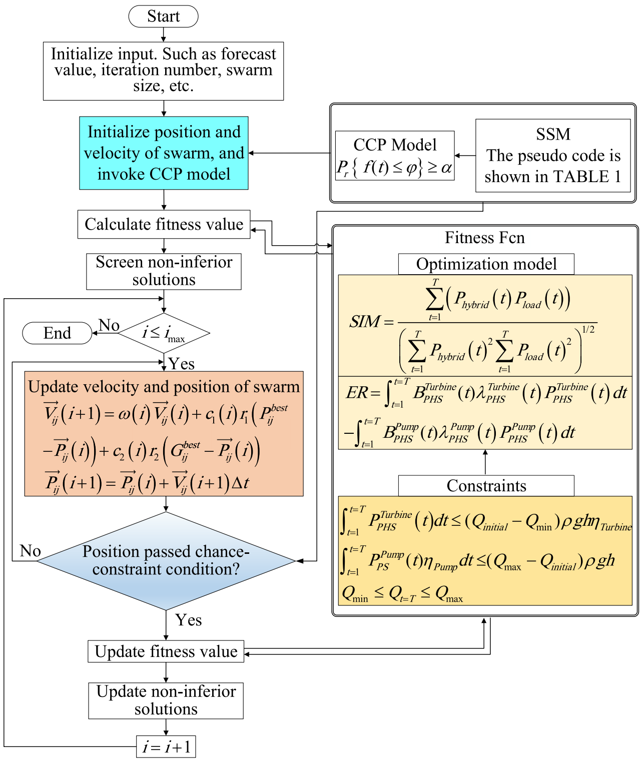

FIGURE 3. The flowchart diagram of the optimization model.

(1) Initialize the position of the particles based on chance-constraint model using the known generation/load data and SSM. The position of particles shows the energy storage or power generation of PHS in the optimizing operation period.
(2) Calculate the fitness value by integrating constraints and fitness functions. Because this problem is a maximization double-objective optimization, the fitness value are two components, similarity value and economic value, respectively.
(3) Screen non-inferior solution, that is, compare the fitness value of particle i_th with other particle j_th ($i \neq j$), if the fitness value of particle i_th is greater than the j_th in both dimensions, save the fitness value of particle i_th; another situation, if one component(similarity value or economic value) in the fitness value of particle i_th is greater than the particle j_th, the fitness value of particle i_th also should be saved; otherwise, particle j_th should be saved; and then the non-inferior solutions consist of the saved fitness value. The personal and global best position of particles are saved correspondingly to update the particle swarm.
(4) Update the velocity and position of the particle based on the personal and global best position.
(5) Perform chance-constraint condition on the particle position. If the condition can be achieved, go to step (6), otherwise, re-update the velocity and position and re-sample the stochastic variable.
(6) Update fitness value.

TABLE 2. The parameters of PHS.

Parameter	Value	Unit
H	100	m
η_{Pump}	83	%
$\eta_{Turbine}$	86	%
$P_{Turbine}^{max}$	5	MW
P_{Pump}^{max}	-5	MW
V_{max}	5×10^6	m^3
SoC_{max}	90	%
SoC_{min}	35	%
SoC_0	50	%

(7) Update the non-inferior solutions, that is, when the newly fitness value of particle i_th is both greater than other particle j_th and the particle in the non-inferior solutions, save the newly particle into the non-inferior.
(8) Repeat steps from (2) to (7) until the iterative calculation is completed.
(9) Print optimal results.

V. CASE STUDY AND SENSITIVITY ANALYSIS

In this section, according to the meteorological, the historical MHP power generation and the load data, this work stimulates the operation of PHS by using the established system model, constraints and proposed optimization method, and then the SIM and ER are analyzed by sensitivity analysis.

A. INTRODUCETION OF CASE DATA

The parameters of the PHS is listed in Tab. 2. The positive and negative power of PHS represent the state of hydro-turbine and pump, respectively. $P_{Turbine}^{max}$ and P_{Pump}^{max} are the maximum output power of hydro-turbine and pump, V_{max} is the maximum capacity of the upper reservoir, SoC_{max}, SoC_{min} and SoC_0 are the state of the maximum, minimum and initial water quantity in upper reservoir.

The focus of this paper is the operation way of PHS under the MHP-PV-PHS hybrid system, hence, the historical data of the energy produced by the renewable generators is used and the measurement error is considered. The data is obtained from Xiaojin County, Sichuan province, China. The hour-level data in the first week of January 2018 is selected in this case. Fig.4 shows the time series of power load and the sum of PV and MHP, it reveals that the overall load demand is usually lower during the midday hours while the sum of PV and MHP generation blows, and there is a peak load demands in the evening. However, there is only MHP can supply the power for load at the peak demand time. Compared with the load demand, the sum of PV and MHP generation is more unpredictable and intermittent. It shows that sometimes the sum of PV and MHP generation has a reverse trend to the load power demand, that is, the load demand peak and

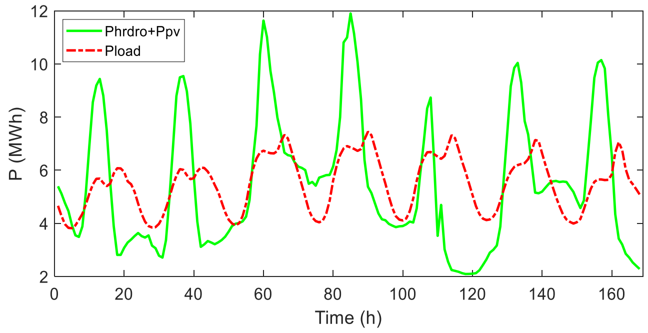

FIGURE 4. The fluctuation of generation and load data with low similarity.

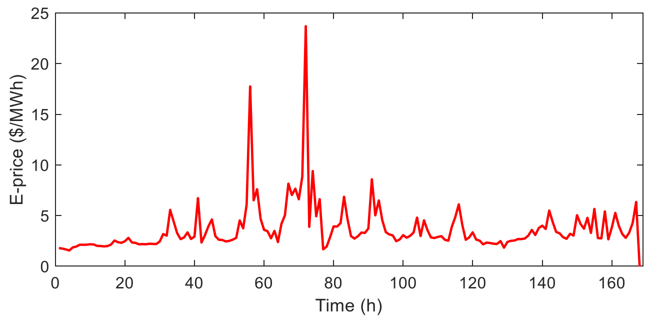

FIGURE 5. The real time electricity price for PHS.

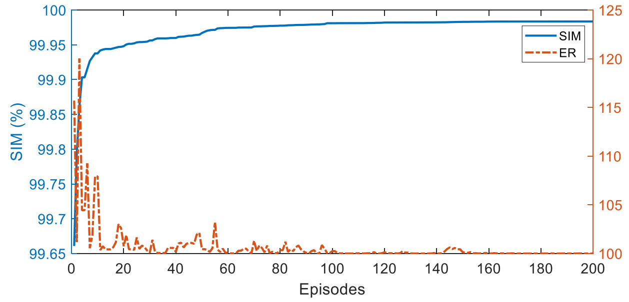

FIGURE 6. Contrasted analysis of SIM and ER considering optimal SIM.

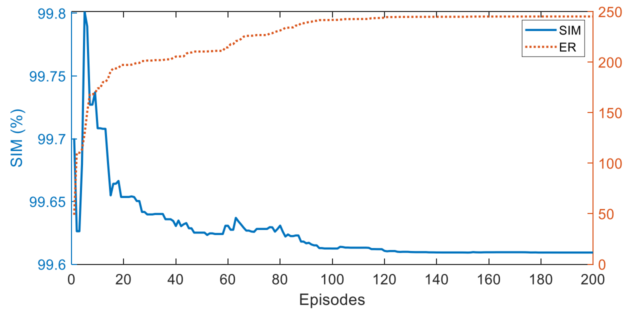

FIGURE 7. Contrasted analysis of ER and SIM considering optimal ER.

power source generation off-peak come together at the same time. Thus, energy storage device such as battery is required to provide peak regulation, while a largescale energy storage technology such as pump-hydro storage is increasingly needed to store the surplus the intermittent power source to accommodate the growing supplies of fluctuation renewable energy.

The economy of the pumped hydro storage is investigated in this paper. There is a lot of research about the power market, but there is no actual operation power market in China at present, hence, some assumption is introduced to assume that the pumped hydro storage is running under the real time electricity price. The price profile is obtained from the power market operator in Denmark in the first week of January 2017 and converted into a general monetary unit US dollar. For the sake of simplicity, the same price curve in Fig.5 is adopted for PHS under the pumped and hydro-turbine mode, and assuming that the operation of PHS cannot affect this price, that is, the economic revenue of PHS mainly depends on the difference between the income of its power generation and the expenditure of its power consumption.

B. VERIFICATION OF TRADE-OFF PROBLEM

To better explain the two optimization operation models established in this paper which can be classified into a trade-off issue (shown in Eq. (7) and (9)), two single-objective operation strategies are simulated in this paper, which is to find the maximum SIM without considering ER and obtain the maximum ER without considering SIM. The optimal results are shown in Fig. 6 and Fig. 7, respectively, it can be clearly seen that when the SIM is optimal, the ER of PHS is minimum, and vice versa. It can be observed from the Fig. 6 that SIM can quickly reach convergence and has a maximum value 99.984%, but the ER of PHS reaches the maximum value $120.034 at the 3th episode. Fig. 7 illustrates the variation trend of SIM is decreasing generally, and the maximum value of SIM is only 99.8% at 5th episode, compared with the Fig. 6, it is not optimal value, while the ER of PHS gradually converges and reaches the maximum value $245.225. Eventually, the two iterative curves become flat simultaneously.

The figures shown in Fig. 6 and Fig. 7 suggest that the SIM and ER of the MHP-PV-PHS hybrid system cannot achieve the optimal value simultaneously. Namely, when the power generated from the MHP-PV-PHS hybrid system can follow the load demand, the ER of the PHS is not the optimal value, and vice versa. Therefore, the trade-off option such as Pareto front is introduced to balance the contradiction between the SIM and ER.

C. DOUBLE-OBJECTIVE OPTIMIZATION OF TRADE-OFF PROBLEM

By comparing the characteristic of the SIM and ER established in this work. The multi-objective optimization method is necessarily required to find the Pareto front. The double-objective optimization algorithm based on MOPSO shown in Fig. 3, MATLAB is employed to realize the generation/load similarity and optimal operation strategy of PHS under the

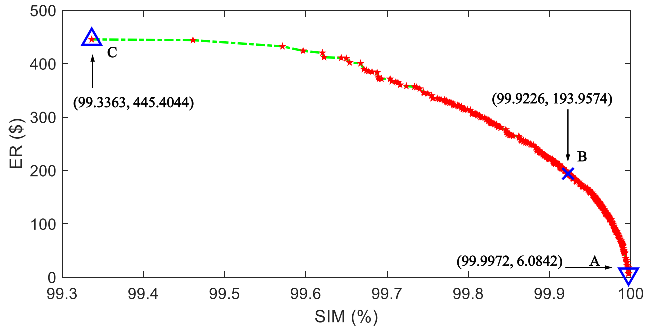

FIGURE 8. The pareto optimal front consist of SIM and ER.

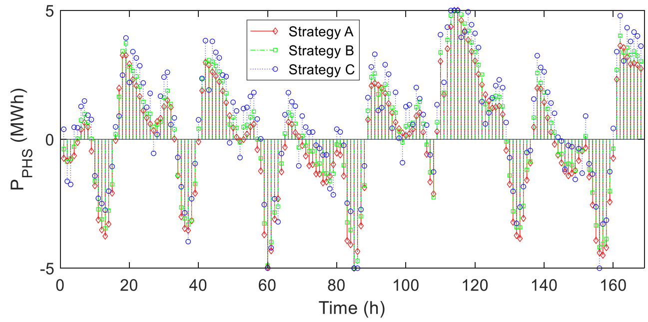

FIGURE 9. Hourly charge and discharge power distribution of PHS under strategy A, B and C.

constraints. The population size of PSO is 1680, and the maximum episode is 200.

The non-inferior solution set composed of SIM and ER, as shown in Fig. 8.

Firstly, it is clearly to see that there is a reverse function and non-linear relationship between the similarity and economy. At the initial stage, ER slowly decreases varying from \$445.4044 to \$193.9574 with the increase of SIM varying from 99.3363% to 99.923%, while ER sharply decreases varying from \$193.957 to \$6.084 with the further increase of SIM varying from 99.923% to 99.997% at the end stage. The variety intervals of the SIM and ER are 0.661% and \$439.32, respectively.

Secondly, when we need the power generation curve follows the load profile, the economy of the pumped hydro storage is close zero.

Thirdly, the economy cannot further increase with the similarity decrease. Somehow case A, B and C are selected from the Pareto front as the distinguished points, the non-inferior solution can be divided two intervals from case B; from the viewpoint of similarity, the interval from B to A is the reasonable range; otherwise, the interval from C to B is reasonable.

Since different decision-makers have different choices on operation risk level, from the perspective of the practical application, the operation strategy of the PHS can be selected in the non-inferior solution set to compromise the trade-off value of the MHP-PV-PHS hybrid system.

The above investigation indicates that the ER of PHS can be significantly increased by selecting an appropriate SIM between the generation and load. Thus, unnecessary economic loss can be avoided.

For further analysis, the minimum, medium and maximum SIM value are selected as the typical operation strategy (hourly charge and discharge power distribution) of PHS from the non-inferior solution sets in Fig. 8, which is shown the stem chart in Fig. 9, named as strategy A, B and C, respectively. The three strategies represent the best, moderate and worst solution on the Pareto front.

The ER of the PHS is mainly determined by the difference between its income and expenditure under the condition of PHS do not participate the market to affect the nodal price. Thus, from the perspective of PHS, the ER inverses with the growth of the power generation. Compared with strategy A and B, the charge power is usually lower while the discharge power is higher under the strategy C, which leads to higher ER of PHS.

At near the 120th hour, for strategy A, B and C, the generation power of PHS reaches its maximum power output 5 MW, the reason is that there is a large power shortage during this time shown in Fig. 4. Correspondingly, at near the 60th and 80th hour, there are two power surplus peaks, which leads to the pumped power of PHS is limited with the maximum value 5 MW for the three strategies.

The variation of the upper reservoir capacity within the given time horizon should be a constant value under any operation strategy. Therefore, compared with strategy B and A, strategy C has a large charge and discharge power under minimum and maximum output power constraint in Fig. 9. However, the increment of SIM from strategy B to strategy A is small in Fig. 8, since the charge and discharge power of strategy B and A are only slight difference in Fig. 9.

The graphical representation of the similarity of between the load demand profile and the power generation in the MHP-PV-PHS hybrid system under strategy A, B and C are illustrated in Fig. 10. As can be seen, from strategy B to C with the increasing of the ER, the generation/load similarity decreases significantly.

Furthermore, the number of Pareto solution from strategy A to B equals to from strategy B to C, but the difference of graphical representation results in Fig. 10 is very significant, the reason is that there are more solutions concentrated between the interval A and B, and the ratio of the variation of SIM to ER from strategy B to A is greater than from strategy C to B in Fig. 8.

Fig. 11 shows the generation/load deviation that is defined as the difference between the total power generation and the total power demand in the hybrid system. It should be mentioned that the uncertainty of PV and MHP are taken into consideration. It can be observed that there are maximum power surplus 1.5144 MW at 83th hour and power shortage 1.1804 MW at 79th hour respectively under strategy C. Correspondingly, the power deviation is relatively small that

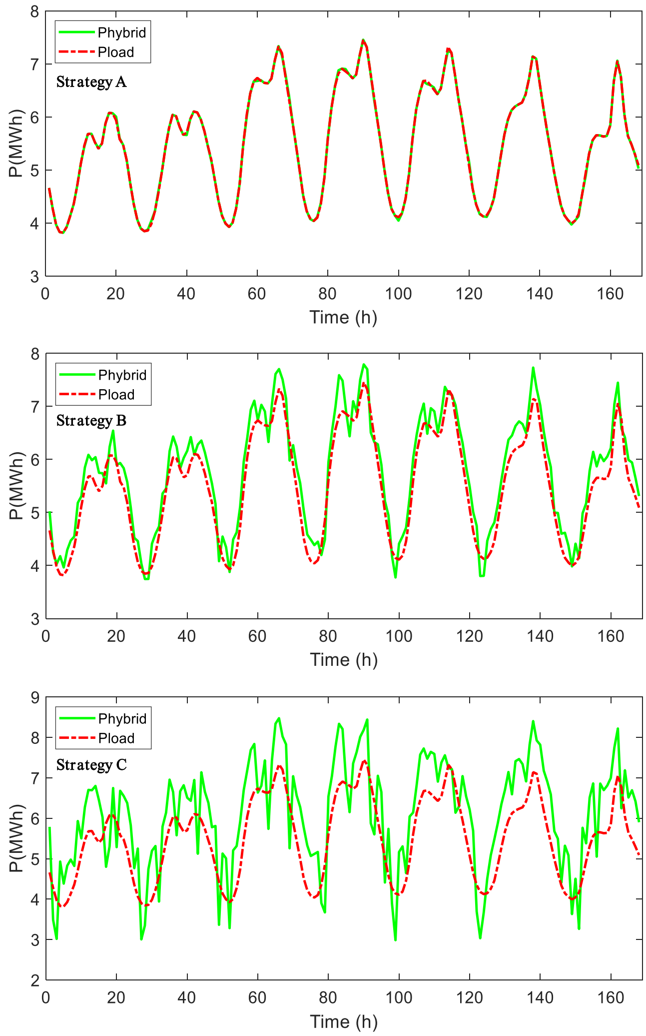

FIGURE 10. The graphical representation of generation/load similarity under strategy A, B and C.

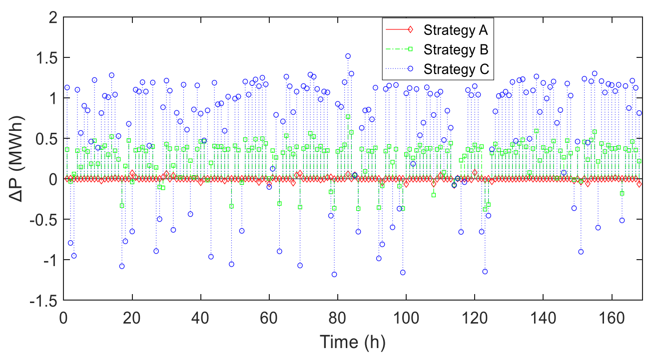

FIGURE 11. The generation/load power deviation under strategy A, B and C.

can be ignored in strategy A. Moreover, from the view of increasing the energy utilization, Fig. 11 reveals that the operation strategy of PHS between the strategy A and B is more reasonable.

The SoC of the upper reservoir in strategy A, B and C that is defined as ratio of the water quantity of the upper

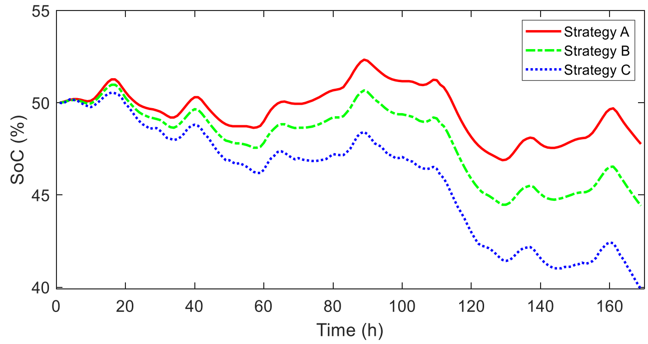

FIGURE 12. The SoC of the upper reservoir under strategy A, B and C.

TABLE 3. Optimal results under the typical strategy.

Items	Strategy A	Strategy B	Strategy C	unit
SIM	99.997	99.923	99.336	%
ER	6.084	193.957	445.404	\$
$P_{total}^{surplus}$	0.737	49.725	128.111	MW
$P_{total}^{shortage}$	0.790	4.660	23.038	MW
$T_{on}^{turbine}$	89	97	107	hours
T_{on}^{pumped}	79	71	61	hours
ΔSoC	-2.235	-5.581	-10.098	%

reservoir to reservoir capacity is shown in Fig. 12. As can be seen, the SoC respectively reaches the maximum value under the three strategies simultaneously at the 89th hour, but the SoC in strategy C is decreasing generally, the reason is that this is in the maximum ER scenario, consequently, the more maximum ER need more water quantity in upper reservoir to support. In this condition, the minimum constraint of SoC is still met, and this SoC curve represents the lower profile of the variation of the water quantity, thus, the security constraint of PHS system is satisfied.

Under the multi-objective optimization algorithm, the result of the Pareto front composed by the generation/load similarity and the economic revenue shown in Fig. 8. The analysis of the variation trends shown in Fig. 9 to 12 based on the results of Pareto front. the effectiveness of different operation strategies is effectively investigated and compared. The results of the system operation under the different strategies can be obtained.

D. COMPARED AND ANALYSIS OF OPTIMIZATION RESULTS

To further compare and analyze the optimization results in the three strategies, the SIM, ER, total power surplus ($P_{total}^{surplus}$) and shortage ($P_{total}^{shortage}$), the total operation time of hydro-turbine ($T_{on}^{turbine}$) and pumped (T_{on}^{pumped}) and the difference between the initial SoC and final SoC (ΔSoC) are listed in Tab. 3.

As can be seen, the variation of SoC in strategy C is the larger one, this is caused by the large water quantity to support

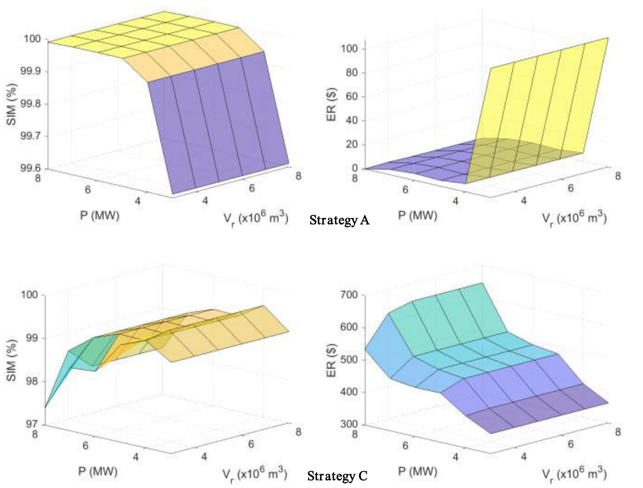

FIGURE 13. The effect of maximum power output of PHS and upper reservoir capacity on the SIM or ER.

the water consumption of hydro-turbine to make more profit. Moreover, there is still a negative variation of SoC under strategy A, the reason is that the total efficiency of PHS system is only 71.38 percent shown in Tab. 2, that is, 1MW energy absorbed by pumped but the hydro-turbine only can generate 0.7138MW energy under the condition of keeping the variation of SoC is zero, thus, it is required large water quantity to meet the equilibrium of absorption and generation.

Comprehensively compared the results shown in Tab. 3, it reveals that if taking SIM as the mainly factor and considering ER simultaneously, the operation interval between strategy A and B is more practicable. Because if the similarity (that is power quality) is compromised a little that can increase the economy more for PHS. On the contrary, the operation interval between strategy B and C is viable.

E. SENSITIVITY ANALYSIS

In this part, the SIM and ER are analyzed with changing the maximum power output (from 3 MW to 8 MW) and the capacity of upper reservoir (from 3×10^6 m^3 to 8×10^6 m^3) under strategy A and C. Fig. 13 shows the relationship of SIM or ER, maximum power output of PHS and upper reservoir capacity.

As can be seen, with the given upper reservoir capacity horizon, it does have no effect on the similarity and economy in strategy A. The similarity increases with the growth of maximum power output and reaches its maximum value at 5MW. Compared with power output limit, the reservoir capacity is less effect on the SIM and ER, because the magnitude of the reservoir capacity is very large relative to the maximum power output limit, thus, the reservoir capacity is less sensitivity about the SIM and ER. However, it is clear that in the strategy C, there is a decrease trend of SIM with the growth of maximum power output limit. Corresponding, it has an increase trend for ER. From the Pareto front shown in Fig. 8 can be explained that the higher upper power output limit value is, the more benefit PHS can get, thus, the similarity is corresponding lower.

VI. CONSLUSION

The concept of considering both the similarity of generation/ load and the economy of energy storage system is first proposed in MHP-PV-PHS hybrid off-grid system solved by means of the optimization algorithm. The optimization model and simulation program are developed. Based on the integrated analysis of the simulation results, conclusions can be made as follows: (1) The trade-off characteristics between generation/load similarity and the economic revenue of PHS are verified under the two single-objective optimization process. (2) The best, moderate and worst strategy for SIM selected from the Pareto front are analyzed, it reveals that the optimal operation strategy between the interval strategy A and B is more reasonable under considering the power supply quality in the off-grid condition. (3) The corresponding sensitivity analysis indicates that the power output limit value does have more effect on the SIM and ER than the upper reservoir capacity.

In addition, the MHP-PV-PHS hybrid system is only researched under the off-grid condition and one energy storage device, since the minimum and maximum power output of PHS are limited, there is still some power surplus and shortage even in the strategy A and no financial penalty in this work. Hence, the multiply energy storage unit coordinately optimization can be researched in the future work. Furthermore, the hosting capacity is a transactive approach that provides a way for the distribution network to be integrated with different types of energy systems, the hosting capacity analysis is a novel direction to research the distribution renewable energy.

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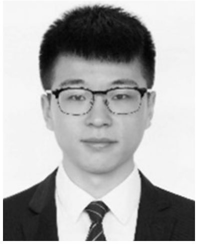

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