

Joint Source-grid-storage Planning Method Considering Coupling Relationship of Water Abandonment Events

Qunmin Yan, *Member, IEEE*, Ruiqing Ma, *Senior Member, IEEE*, Xinzhou Dong, *Fellow, IEEE*, Rui Ma, *Senior Member, IEEE*, and Chen An, *Student Member, IEEE*

Abstract—Transmission blockage caused by structural defects of small hydropower distribution network and insufficient regulation flexibility, which has a certain coupling relationship in time series, is the main reason for water abandonment. Based on the characteristics of time-sharing multiplexing of energy storage system (ESS), utilizing the coupling relationship of water abandonment events and rationally configuring ESS can solve the problems of small hydropower transmission congestion and lack of regulatory flexibility. The causes of insufficient flexibility and transmission blockage resulting in water abandonment, and the coupling relationship with ESS are analyzed. A source-grid-storage collaborative planning model for small hydropower distribution network is established. The upper-level objective is to maximize on-site consumption of small hydropower and the profits of regional small hydropower investors. The lower-level objective is to minimize average voltage offset, the input of VAR compensation system (VCS) and the number of transformer tap changer operation. The YALMIP solver is used to solve the optimization problems. Taking the 90 MW small hydropower unit in a certain area as an example, collaborative planning and operation analysis is conducted. The results prove that the proposed method can improve the on-site consumption of small hydropower, increase the income of regional small hydropower investors, and can also increase the voltage quality of the distribution network.

Index Terms—Small hydropower, energy storage, transmission congestion, water abandonment, on-site consumption, collaborative planning.

Received: March 7, 2024

Accepted: September 12, 2024

Published Online: January 1, 2025

Qunmin Yan (corresponding author) is with the College of Automation, Northwestern Polytechnical University, Xi'an 710072, China, and with the School of Electrical Engineering, Shaanxi University of Technology, Hanzhong 723001, China (e-mail: yanqunm@163.com).

Ruiqing Ma and Rui Ma are with the College of Automation, Northwestern Polytechnical University, Xi'an 710072, China (e-mail: marq@nwpu.edu.cn; ruima@nwpu.edu.cn)

Xinzhou Dong is with the Department of Electrical Engineering and Applied Electronics Technology, Tsinghua University, Beijing 100084, China (e-mail: xzdong@tsinghua.edu.cn)

Chen An is with the School of Electrical Engineering, Shaanxi University of Technology, Hanzhong 723001, China (e-mail: chen970814@163.com).

DOI: 10.23919/PCMP.2023.000354

I. INTRODUCTION

In recent years, with the promotion of the national “carbon peaking and carbon neutrality” strategic goal, small hydropower, as a clean, safe, and efficient renewable energy source, has received renewed attention [1]. However, most small hydropower stations are located in remote mountainous areas and runoff-based power generation [2]. The randomness of incoming water can easily cause voltage quality fluctuations, and the uncertainty has strong seasonal operating characteristics [3]. These significant defects seriously restrict the on-site consumption capacity of small hydropower, causing problems with the safe and stable operation of the distribution network, and resulting in some water abandonment incidents. This also prevents small hydropower developers from maximizing the economic benefits. Energy storage system (ESS) can effectively achieve mutual coordination of hydropower, network and ESS [4], thus providing an effective method to solve the above problems.

Some scholars have conducted relevant researches on the joint planning of hydropower, distributed generations (DGs), and ESS. Reference [5] proposes a “bidirectional electricity price compensation” policy to incentivize hydropower to participate in the consumption of distributed wind power generation, while bundling ESS on the wind power side to improve the wind power game bidding ability. The results show that the policy can effectively improve the revenue of the hydropower-wind power joint system. Reference [6] proposes a complementary hydro-wind-PV-ESS scheduling scheme. The scheme can meet the stability of transmission power, and fully leverage the flexibility of hydropower and ESS, and effectively reduce the waste of electricity in the joint system. Reference [7] establishes a hydro-PV-gas-thermal-ESS joint optimization scheduling model based on chance constrained objective programming. The results show that the proposed coordinated scheduling model can improve the absorption capacity of renewable energy sources and the economic benefits of the system. Reference [8] establishes a new type of joint power generation planning

model for power systems under the dual carbon target, considering the collaborative optimization operation of source-grid-load-storage. Various power generation technologies, ESS, and other practical situations are comprehensively considered, and the lowest system investment and total operating costs are achieved. In [9], a two-stage stochastic programming model is established for optimal scheduling of hydropower, wind power, and pumped storage energy, using power load as a uncertain parameter for uncertainty modeling. Simulation shows that the proposed model has a certain improvement effect on system economy and environment. Based on the long-term planning of hydropower, combined with the characteristics of wind power, PV and pumped-storage, reference [10] proposes a medium to long-term optimization operation strategy for independent regional power grids in the dry season. The research results can effectively improve the efficiency of hydropower generation and avoid the risk of running out of water in hydropower stations during the dry season. In [11], a new unified scheduling planning is proposed for cascaded pumped storage power units. The results show that the proposed unified scheduling planning model can improve the economic benefits of the power system. Reference [12] unifies planning and integration of pumping stations between traditional cascade hydropower stations to form a hybrid pumped storage system, which increases the flexibility of hydropower generation, promotes the potential of renewable energy into the grid, and improves the economic benefits and energy efficiency of the system. Reference [13] studies the complementary characteristics of different power sources and proposes evaluation indicators for complementary energy systems of small hydropower-wind power, PV, and ESS. It takes into account the optimal capacity configuration of the ESS and improves the flexibility of the entire system. Reference [14] utilizes the regulation ability of pumped storage power stations to smooth fluctuations in the power generation of distributed energy sources such as small hydropower. A capacity optimization model is established for hybrid power generation systems such as basin water storage with the goal of economic optimization under multi-constraint conditions, which improves the economic benefits of hydropower-ESS system operation.

The above researches generally only consider single factors such as economy or flexibility in the overall system planning. However, there is no unified coordination that takes into account the economy and operational performance of the hydropower-ESS joint system. This paper comprehensively considers hydropower-ESS planning from the perspective of source-grid-storage coordination, in order to improve the on-site consumption capacity of small hydropower and the economic, safe and efficient operation of the distribution network. The reasons for insufficient oper-

ating flexibility and transmission congestion of the small hydropower distribution network are analyzed, and a small hydropower-grid-storage collaborative planning and operation model is established. This model not only considers the investment benefits of hydropower business, but also takes into account operational indicators such as voltage quality of the distribution network. It achieves the maximum utilization of hydropower resources and the effective utilization of distribution network resources. In response to the obvious seasonal characteristics of small hydropower, the YALMIP solver is used to solve the model, and the economy of the small hydropower distribution network after configuring energy storage is researched, as well as the impact of energy storage on different operating parameters of the power grid. The proposed strategy effectively improves the consumption rate of small hydropower and the economy of the small hydropower distribution network, while reducing water abandonment caused by insufficient peak shaving capacity and transmission line congestion. It can further reduce the annual average voltage offset and the number of transformer tap changer operations of the small hydropower distribution network.

II. ANALYSIS OF THE COUPLING RELATIONSHIP OF WATER ABANDONMENT EVENTS

A. Analysis of the Causes of Water Abandonment due to Insufficient Peak Regulation

The acceptance capacity of the power system for small hydropower is determined by the peak shaving depth of the flexible power supply [15], [16]. Due to the randomness and volatility of run-off small hydropower generation, when small hydropower is connected to the power grid and exceeds the system's acceptance capacity, there will be water abandonment caused by insufficient peak regulation [17], expressed as:

$$P_{aw1}, i(t) = \begin{cases} P_{net}, i(t) - P_R, i(t) & P_{net}, i(t) \geq P_R, i(t) \\ 0 & P_{net}, i(t) < P_R, i(t) \end{cases} \quad (1)$$

where $P_{aw1}, i(t)$ is water abandonment power due to insufficient peak shaving capacity at time t (24 hours in total) during the scheduling day i ; $P_{net}, i(t)$ is the power transmitted from the small hydropower distribution network to the large grid after on-site load consumption at time t during the scheduling day i ; and $P_R, i(t)$ is the acceptable hydropower of the system at time t during the scheduling day i .

The expression for $P_{net}, i(t)$ is given as:

$$P_{net}, i(t) = P_{sh}, i(t) - P_{load}, i(t) - P_{loss}, i(t) \quad (2)$$

where $P_{sh}, i(t)$ is the active power generated by the small hydropower; $P_{load}, i(t)$ is the on-site load consumption; and $P_{loss}, i(t)$ is the total network loss of the small hydropower distribution network system.

B. Analysis of the Causes of Water Abandonment due to Power Transmission Blockage

With the large-scale integration of renewable energy sources such as small hydropower into the grid, due to the time lag in power grid construction, when the power of small hydropower exceeds the transmission capacity of the lines, the power of the transmission lines will exceed the limit, resulting in transmission congestion and water abandonment [18]. The expression of the water abandonment power is given as:

$$P_{aw2}, i(t) = \begin{cases} P_{net}, i(t) - P_M & P_{net}, i(t) \geq P_M \\ 0 & P_{net}, i(t) < P_M \end{cases} \quad (3)$$

where $P_{aw2}, i(t)$ is the water abandonment power due to transmission blockage at time t during the scheduling day i ; while P_M is the maximum transmission capacity of the power grid transmission lines.

C. The Temporal Coupling Relationship Between Water Abandonment due to Insufficient Peak Regulation and Water Abandonment due to Power Transmission Blockage

The expressions in the previous two sections are used to calculate the water abandonments due to insufficient peak regulation and power transmission blockage in the same time sequence, while the two are coupled to obtain the total water abandonment. The expression for the total water abandonment is given as:

$$P_{AW}, i(t) = \max \{P_{aw1}, i(t); P_{aw2}, i(t)\} \quad (4)$$

where $P_{AW}, i(t)$ is the total water abandonment at time t during the scheduling day i .

$$P_{min} = \min \{P_M; P_R, i(t); P_{net}, i(t)\} \quad (5)$$

$$P_{AW}, i(t) = \begin{cases} P_{net}, i(t) - P_M & P_M = P_{min} \\ P_{net}, i(t) - P_R, i(t) & P_R, i(t) = P_{min} \\ 0 & P_{net}, i(t) = P_{min} \end{cases} \quad (6)$$

When the maximum capacity of the transmission line P_M is less than the transmission line power $P_{net}, i(t)$ and the upper limit of system peak shaving $P_R, i(t)$, the abandoned water is greater than zero. Adding ESS can absorb power to ensure that the transmission power of the transmission lines will not exceed the limit and prevent transmission congestion.

When the upper limit of system peak shaving $P_R, i(t)$ is less than the transmission line power $P_{net}, i(t)$ and the maximum capacity of the transmission line P_M , the abandoned water is greater than zero. Adding ESS can again absorb power to ensure that the system does not suffer from insufficient peak regulation.

When the transmission line power $P_{net}, i(t)$ is less than the upper limit of system peak shaving $P_R, i(t)$ and the maximum capacity of the transmission line P_M , it

indicates the transmission line power may not have reached the upper limit. At this time, the configured ESS can generate power, but the transmission line power after ESS configuration should not exceed $\min \{P_M; P_R, i(t)\}$.

III. ANALYSIS OF THE IMPACT OF ESS CONFIGURATION ON THE SOURCE SIDE AND NETWORK SIDE

A. The Impact of Energy Storage Configuration on Small Hydropower Units

Since most small hydropower stations are runoff type, their power generation capacity is naturally constrained by the amount of incoming water. During dry season, the power generation will drop sharply, while during rainy season, there will be a large amount of water abandonment [19]. The addition of energy storage devices can improve the on-site consumption capacity of small hydropower on the source side, and effectively reduce water abandonment during rainy season. This will maximize the utilization of water resources while also reduce transmission congestion caused by transmission line power exceeding limits. At the same time, because the ESS can play the role of peak shaving and valley filling, it not only increases the flexibility of the system, but also indirectly reduces the peak value of the net load, which can effectively reduce the peak shaving pressure of the power system [20].

B. The Impact of Energy Storage Configuration on Transmission Network

In the initial planning stage of the power grid, the matching relationship between the output power and the external power capacity of the small hydropower station should be fully considered [21], [22]. If the installed capacity of small hydropower is used as the basis for planning the transmission capacity of the external connecting transmission lines, then when the output of small hydropower is small during the dry season, a large amount of transmission capacity will be unutilized, resulting in a waste of investment. However, if the planning boundary of the small hydropower grid connection point is reduced and the selected value is inappropriate, there will be a potential risk of transmission congestion in the transmission lines. By configuring an appropriate ESS in the small hydropower area, the hydropower that exceeds the transmission capacity can be stored when the incoming water volume is large, and released when the incoming water volume is small. This can effectively reduce the probability of transmission blockage and improve utilization rate of external transmission lines. By configuring energy storage, the dependence of external transmission power on small hydropower power can be reduced.

IV. SOURCE-NETWORK-STORAGE COLLABORATIVE PLANNING MODEL

On the basis of the above analysis on the impact of

energy storage configuration on the planning of the power supply side and the power grid side, the energy storage output is adjusted on the power supply side to supplement and support the power grid and the connecting lines. On the power grid side, the node voltage distribution is adjusted by adjusting the tap of the on-load voltage regulating transformer and inputting VAR compensation system (VCS). A source-grid-storage collaborative planning model considering the coupling relationship of water abandonment events is constructed, and the upper-level long-term planning and the lower-level dynamic planning are realized through a two-layer model. The upper level takes the planning goals for maximizing the on-site consumption of small hydropower and the profits of regional small hydropower investors, and the control variables are the capacity and output power of the ESS. For the lower-level, it aims to minimize the average voltage offset of each node within 24 hours of the day, and the control variables are the on-load voltage regulating transformer tap and the VCS configured on the grid side.

A. Upper-level Model Planning

The upper-level model planning includes two objectives:

1) Maximizing on-site consumption of small hydropower, i.e.:

$$\max I = \frac{\sum_{t=1}^T (P_{\text{load}}^t + P_{\text{ESS}}^t)}{\sum_{t=1}^T P_{\text{sh}}^t} \quad (7)$$

where T is total period of one day, which is 24; P_{load}^t is the load consumed locally at time t ; P_{ESS}^t is the power absorbed by the energy storage device at time t ; and P_{sh}^t is the power generated by the small hydropower at time t .

2) Maximizing revenues for regional small hydropower investors, i.e.:

$$\max \lambda = A_p - B_p \quad (8)$$

where λ is the annual operating profit of small hydropower investment; A_p is the annual operating income; and B_p is the annual cycle investment cost.

The annual operating income and annual cycle investment cost can be expressed as:

$$A_p = \sum_{t=1}^{N_t} P_g \cdot I_t \quad (9)$$

$$B_p = B_c + B_t \quad (10)$$

where N_t is the period of operation of the small hydropower; P_g is the on-grid electricity price of the small

hydropower; I_t is the total on-grid electricity consumption in year t ; B_c is the installation and maintenance cost of the energy storage devices; and B_t is the cost of water resource utilization in year t .

B. Lower-level Model Planning

The lower-level formulates the specific operation plan of the source-network-storage collaborative system for each period according to the following rules:

1) The output of the small hydropower is given priority to meet local load demand and to maximize on-site consumption. Any surplus power will be allocated to charge the ESS, whereas if the ESS is full, the surplus power is transmitted to the power grid through the transmission lines.

2) When the hydropower output (e.g., during dry season) is insufficient to meet the power demand of the local load, power will be transmitted from the main grid to supplement the load demand gap and charge the ESS when the price of electricity is at the valley. In other non-electricity price valleys, priority is given to the ESS to supply power to the load, and if there is still a load shortage, power is purchased from the main grid.

Because voltage offset is an important indicator for the safe and stable operation of the system, based on the upper-level economic model, the lower-level model is built as a model with the goal of minimizing the average voltage offset of each node in the distribution network, i.e.:

$$\min F_1 = \Delta U = \frac{1}{24} \sum_{t=1}^T \left(\frac{1}{J} \sum_{j=1}^J \left| \frac{U_{j,\text{ta}}^t - U_{jN}}{U_{jN}} \right| \right) \quad (11)$$

where T is the total period of one day, and in this paper one day is divided into 24 periods; J is the total number of nodes in the distribution network system; $U_{j,\text{ta}}^t$ is the actual voltage amplitude of the j th node after adjustment by the transformer action at time t ; and U_{jN} is the rated operating voltage amplitude of the j th node.

C. Constraint Conditions

1) Constraint on power flow:

$$\begin{cases} P_j = V_j \sum_{k=1}^J V_k (G_{jk} \cos \theta_{jk} + B_{jk} \sin \theta_{jk}) \\ Q_j = V_j \sum_{k=1}^J V_k (G_{jk} \sin \theta_{jk} - B_{jk} \cos \theta_{jk}) \end{cases} \quad (12)$$

where P_j and Q_j are the active power and reactive power injected at node j , respectively; V_j and V_k are the voltage at nodes j and k , respectively; G_{jk} is the conductance between nodes j and k ; B_{jk} is the susceptance between nodes j and k ; and θ_{jk} is the voltage

phase angle difference between nodes j and k .

2) Constraint on the number of transformer tap actions:

When the reactive power of the distribution network is sufficient, the node voltage of the system can be adjusted by adjusting the tap of the transformer. Due to factors such as transformer manufacturing, when the tap of the transformer is adjusted, the number of actions per day should be strictly controlled within the limit, and the number of actions also should be reduced if possible. The minimum number of actions of the transformer tap is expressed as:

$$T_{j,\min} \leq T_j \leq T_{j,\max} \quad (13)$$

where T_j is the number of actions of the transformer tap at node j in one day; while $T_{j,\min}$ and $T_{j,\max}$ are the minimum and maximum numbers of actions in one day.

3) Constraint on VCS:

In order to ensure the voltage quality of the small hydropower distribution network system, on the premise of ensuring safe and stable operation of the system, the economic operation level should also be taken into consideration, and the capacity of VCS should be minimized.

$$\Delta Q_{\min} \leq \Delta Q \leq \Delta Q_{\max} \quad (14)$$

where ΔQ_{\min} and ΔQ_{\max} are the minimum and maximum values of the switching capacity of the VCS, respectively.

4) Constraint on node voltage:

$$U_{j,\min}^t \leq U_j^t \leq U_{j,\max}^t \quad (15)$$

where U_j^t is the actual voltage amplitude of the j th node at time t ; while $U_{j,\max}$ and $U_{j,\min}$ are the maximum and minimum values of the actual operating voltage amplitude of the j th node, respectively.

5) Constraint on small hydropower output:

$$\begin{cases} P_{\text{sh},\min}^t \leq P_{\text{sh}}^t \leq P_{\text{sh},\max}^t \\ Q_{\text{sh},\min}^t \leq Q_{\text{sh}}^t \leq Q_{\text{sh},\max}^t \end{cases} \quad (16)$$

where $P_{\text{sh},\min}^t$ and $P_{\text{sh},\max}^t$ are the minimum and maximum active power of the small hydropower at time t , respectively; while $Q_{\text{sh},\min}^t$ and $Q_{\text{sh},\max}^t$ are the minimum and maximum reactive power of the small hydropower at time t , respectively.

6) Constraint on power balance:

$$\sum_{t=1}^T (P_{\text{sh}}^t - P_{\text{AW}}^t) = \sum_{t=1}^T (P_{\text{load}}^t + P_{\text{loss}}^t + P_{\text{ESS}}^t + P_{\text{NET}}^t) \quad (17)$$

where P_{sh}^t is the power generated by the small hydropower at time t ; P_{AW}^t is the water abandonment power of the small hydropower at time t ; P_{load}^t is the load consumed locally at time t ; P_{loss}^t is the total network

loss of the system at time t ; P_{ESS}^t is the power absorbed by the ESS at time t ; and P_{NET}^t is the power transmitted to the large power grid after the small hydropower distribution network maximizing on-site consumption at time t .

7) Constraints on maximum transmission capacity and peak shaving upper limit:

$$P_{\text{NET}}^t \leq \min\{P_{\text{M}}; P_{\text{R}}, i(t)\} \quad (18)$$

8) Constraint on state of charge (SOC) of ESS:

$$SOC_{\min}^t \leq SOC^t \leq SOC_{\max}^t \quad (19)$$

where SOC^t is the SOC of ESS at time t ; SOC_{\min}^t and SOC_{\max}^t are the respective minimum and maximum allowable SOC of ESS.

9) Constraint on capacity balance of ESS:

$$E_{\text{start}} = E_{\text{end}} \quad (20)$$

where E_{start} is the initial remaining capacity of ESS; and E_{end} is the final remaining capacity of ESS.

10) Constraint on upper and lower limits of ESS capacity:

$$0 \leq E^t \leq E_{\text{N}} \quad (21)$$

where E^t is the remaining capacity of ESS at time t ; and E_{N} is the rated capacity of ESS.

11) Constraint on upper and lower limits of ESS power:

$$0 \leq P^t \leq P_{\text{N}} \quad (22)$$

where P^t is the charging and discharging power of ESS at time t ; and P_{N} is the rated power of ESS.

12) Constraint on charging and discharging efficiency of ESS:

$$\begin{cases} P_{\text{C2}}^t = \frac{\eta P_{\text{C1}}^t \Delta t}{E_{\text{N}}} \\ P_{\text{D2}}^t = \frac{P_{\text{D1}}^t \Delta t}{\eta E_{\text{N}}} \end{cases} \quad (23)$$

where P_{C1}^t is the charging power of the small hydropower to ESS at time t ; P_{C2}^t is the actual charging power of ESS at time t ; η is the charging and discharging efficiency of ESS; P_{D1}^t is the discharge power of ESS at time t ; and P_{D2}^t is the actual discharge power of ESS at time t .

D. The Impact of Energy Storage Configuration on Transmission Network

First, the known quantities are input to the model, including the original output curve of the small hydropower, typical load curve, parameters of the energy storage equipment and network parameters. Then, the unknown quantities that will be solved by the two-level

optimization model and the upper and lower levels constraint conditions are set. Subsequently, the objective functions of the upper and lower levels are respectively defined and the KKT conditions of the lower-level optimization are added as constraints to the upper-level optimization. The two-level optimization problem is then transformed into a single level optimization problem [23]. Finally, the YALMIP solver is used to solve and obtain the optimal solution of the two-level optimization problem. The specific solution process is shown as Fig. 1.

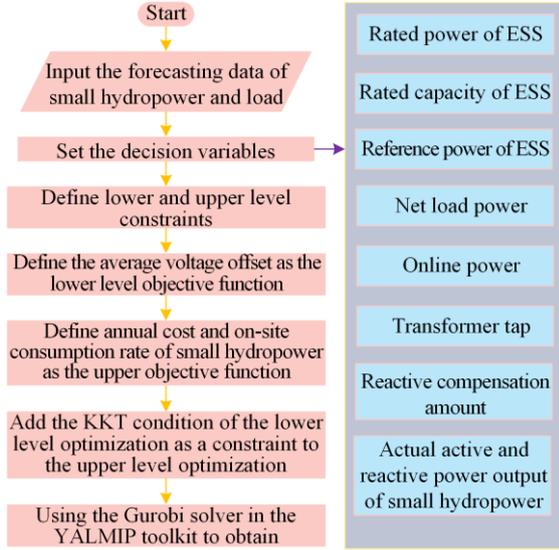


Fig. 1. Flow chart of model solving.

V. EXAMPLE ANALYSIS

A. Example Parameters

The network topology diagram of the small hydropower distribution network is shown in Fig. 2. In the system, the upper limit of the total transmission capacity of the dedicated 10 kV transmission lines is 36 MW, and the total installed capacity of the small hydropower group is 90 MW. The ESS, VCS and load are all set on the 10 kV side. During simulation analysis, the base power of the system is 100 MVA, the base voltage is 10 kV, and the maximum number of transformer tap actions is limited to 8 times per day.

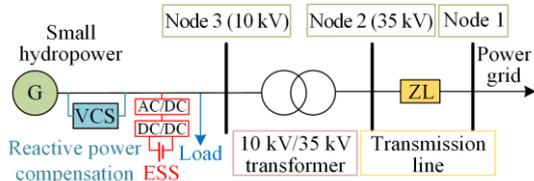


Fig. 2. Network topology diagram.

According to the actual annual operation of small hydropower, this paper sets April to October as the rainy season, and the remaining months as the dry season. The daily output curve of the rainy season, the daily output curve of the dry season and the typical daily load curve are shown as Fig. 3.

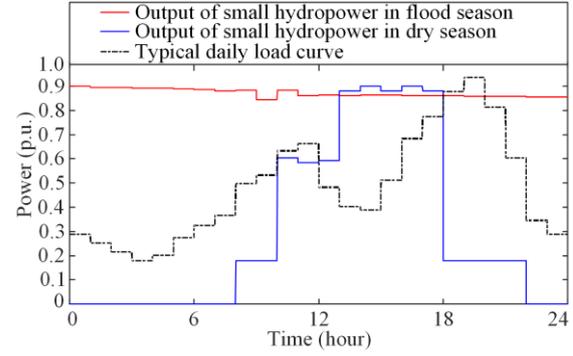


Fig. 3. Small hydro and load data.

The energy storage device is based in the lithium iron phosphate battery that has been widely used. Its parameters are shown in Table I. According to the data in Table I, the operating life of lithium iron phosphate battery is around 8.2 years [24].

TABLE I
KNOWN PARAMETERS OF ESS

Parameters	Value
η_c (%)	0.97
η_D (%)	0.97
C_p (¥/kW)	1500
C_E (¥/kWh)	3000
C_M (¥/kWh)	0.05
Cycle life/ time (100% DOD)	3000

B. Configuration of Energy Storage and its Impact on Economy

In view of the seasonal characteristics of small hydropower, this paper mainly analyzes the impact of ESS on the system operation conditions during rainy season and dry season. Four operating conditions are studied, including: with ESS in rainy season, without ESS in rainy season, with ESS in dry season and without ESS in dry season. Finally, based on the annual system operation status, ESS is configured with the goal of maximizing the annual revenue of the small hydropower operators and minimizing the voltage offset of the distribution network.

Due to the addition of ESS, the consumption rate of the small hydropower is improved. Considering the cost of ESS and the benefits brought by configuring ESS, the YALMIP solver is used to determine the rated capacity and rated power of ESS. At the same time, the annual revenue of the regional small hydropower investors is calculated, and the results are shown in Table II. It can be seen that after adding ESS, the annual revenue increased from the original 22.34×10^6 ¥ to 23.00×10^6 ¥, an increase of 2.97%.

TABLE II
ESS PARAMETERS AND ANNUAL REVENUE OF REGIONAL SMALL HYDROPOWER INVESTORS OBTAINED BY OPTIMIZATION SOLUTION

Parameters	Value
Rated capacity of ESS (MWh)	131.8651
Rated power of ESS (MW)	25.5263
Without ESS (¥)	22.34×10^6
With ESS (¥)	23.00×10^6

C. The Impact of ESS Configuration on Small Hydropower Consumption Rate and Water Abandonment

The water abandonment and actual output of the small hydropower during the rainy season are shown in Fig. 4. After ESS is configured during the rainy season, the water abandonment of the small hydropower is significantly reduced. Due to economic considerations, the small hydropower cannot achieve full generation even with ESS during rainy season, but its utilization rate increases significantly. The consumption rates of the small hydropower during the rainy season are shown in Fig. 5, indicating significant improvement after configuring ESS when compared to that without ESS.

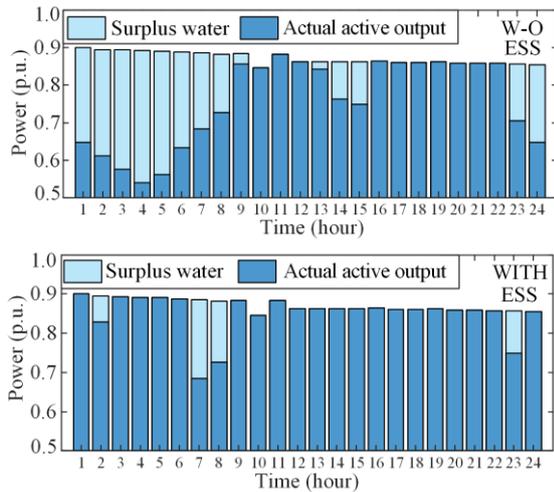


Fig. 4. Actual output of small hydropower during rainy season.

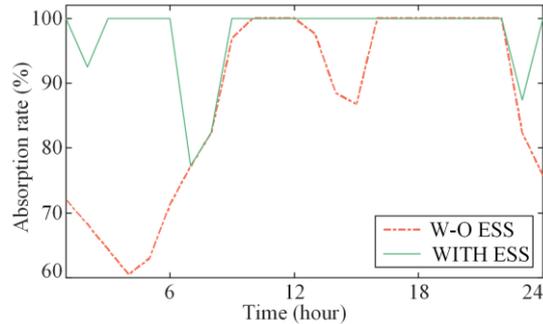


Fig. 5. Consumption rate of small hydropower during rainy season.

The output and consumption rate of the small hydropower during the dry season are shown in Figs. 6 and 7. When there is no ESS configuration in the dry season, the actual output and consumption rate of the small hydropower depends on the constraints of load and transmission line. Even during the dry season, the consumption rate cannot reach 100%. After configuring ESS, the small hydropower can achieve full generation during dry season, ensuring a 100% consumption rate.

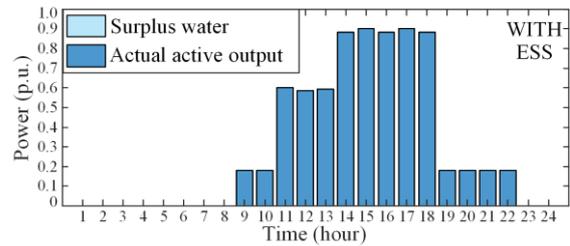
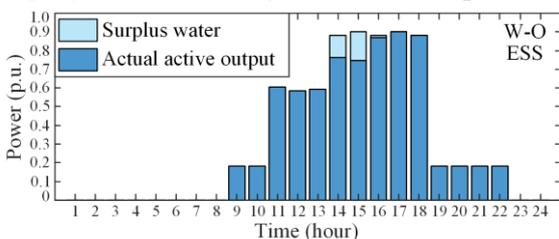


Fig. 6. Actual power output of small hydropower during dry season.

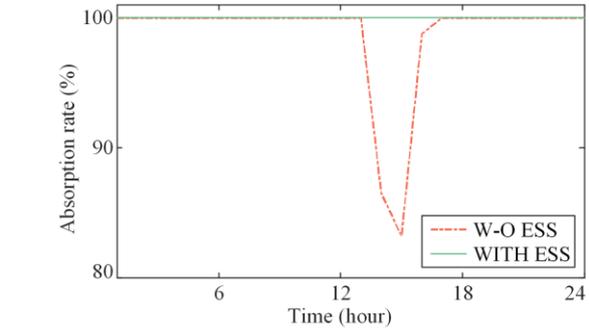


Fig. 7. Consumption rate of small hydropower during dry season.

D. The Impact of ESS Configuration on Net Load Power

The load power distribution during the rainy season is shown in Fig. 8. It can be seen that the net load (the power supplied from main grid to the load) is not 0 even when there is no energy storage configuration during the rainy season, which cannot effectively meet the on-site consumption of the small hydropower. After adding ESS, the load is completely powered by the small hydropower units, which effectively utilizes the space-time translation characteristics of energy storage to solve the problem of on-site consumption of the small hydropower.

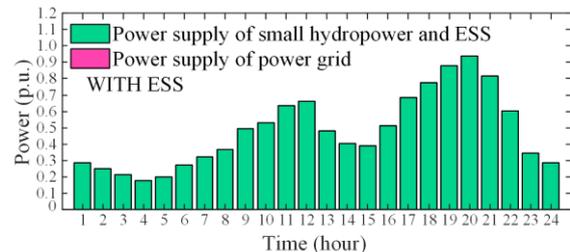
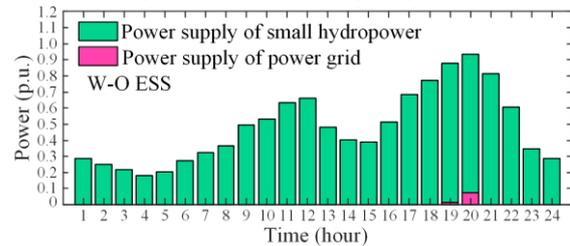


Fig. 8. Load power distribution during rainy season.

The situation during the dry season is more complex. ESS not only needs to solve the problem of on-site consumption of the small hydropower, but also needs to adjust the net load curve. For smaller voltage offset, the net load curve should be as smooth as possible. The load power distribution during the dry season is shown in Fig. 9. As seen, when there is no energy storage configuration,

the net load curve fluctuates sharply, and the net load proportion is relatively large (small hydropower supply proportion is small). In order to ensure safe and stable operation of the system during peak power consumption periods, some loads have to be cut off. After adding ESS, the net load curve becomes relatively smooth, the on-site consumption of the small hydropower is increased, and the load can be fully satisfied.

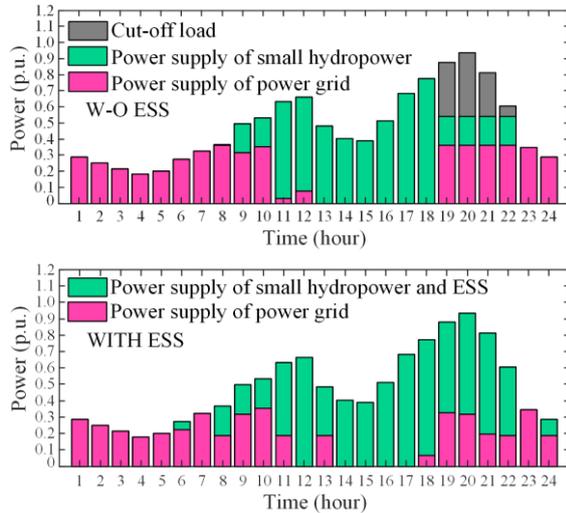


Fig. 9. Load power distribution during dry season.

E. The Impact of ESS Configuration on the Transmission Power of Transmission Lines

When analyzing the impact of ESS configuration on the transmission power of the transmission lines, positive values represents power being transmitted from the small hydropower to grid, and negative values represents power being supplied from the grid to load (net load).

The transmission line power during the rainy season is shown in Fig. 10. As seen, without the addition of ESS, due to the randomness of the water during the rainy season and the fluctuation of the load, the transmission line power fluctuates significantly. After adding ESS, the transmission line power does not fluctuate and is always maintained at the maximum transmission capacity of the transmission lines, thus fully utilizing the power output of the small hydropower and improving the its on-site consumption ability.

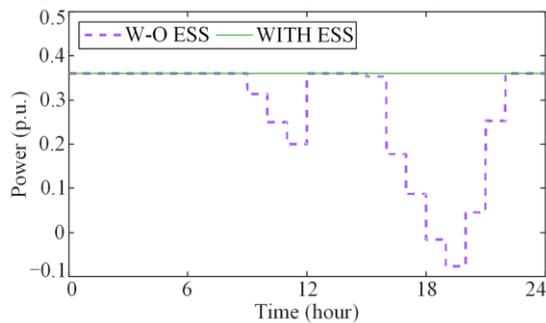


Fig. 10. Transmission line power during rainy season.

The transmission line power during the dry season is shown in Fig. 11. As seen, without the addition of ESS, the transmission line power fluctuates significantly.

During 12–18 h, the load is at a low period while the output of the small hydropower is at its maximum. At this time, the power flows from the small hydropower unit side to the grid side through the transmission lines, thus increasing the power on the grid significantly. During the period 18–21 h, there is load peak and low output from the small hydropower. At this time, power flows from the grid side to the load at the small hydropower distribution network side through the transmission lines, i.e., the net load power is significantly increased.

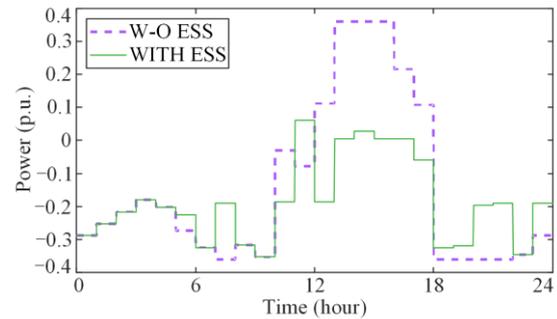


Fig. 11. Transmission line power during dry season.

After adding ESS, the transmission line power curve becomes much smoother. Through the adjustment of power distribution by ESS, the power fluctuation of the transmission lines is reduced, thereby improving the node voltage quality of the distribution network.

F. Capacity Allocation of ESS

The capacity allocation of ESS during the rainy season is shown in Fig. 12. It can be seen that during the rainy season, the ESS is mainly used to adjust the active output of the small hydropower units and the grid power. This not only improves the on-site consumption rate of the small hydropower, but also makes the transmission line power smoother, thereby improving voltage offset.

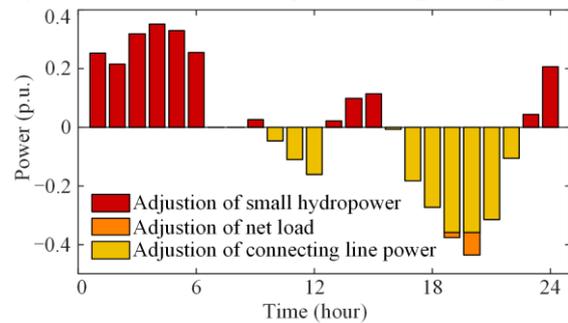


Fig. 12. Capacity allocation of ESS during rainy season.

The capacity allocation of ESS during the dry season is shown in Fig. 13. It can be seen that during the dry season, the ESS is used to adjust the active output of the small hydropower and power on the grid, as well as used to adjust the power distribution of load power supply, i.e., the net load curve. It not only improves the on-site consumption rate of the small hydropower, but also makes the transmission line power smoother to improve the voltage offset. It also fully meets the load demand to ensure that there is no load cutoff.

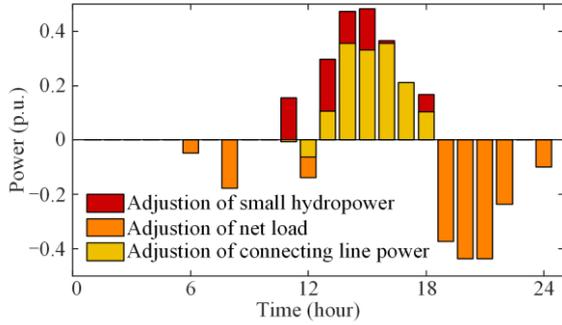


Fig. 13. Capacity allocation of ESS during dry season.

G. The Impact of ESS Configuration on Voltage Offset

Table III shows the maximum and minimum reactive power input, maximum daily action time of transformer tap in a year and the annual average voltage offset under four different configurations of ESS and VCS. The rated capacity of ESS is 131.87 MWh, and the rated power is 25.53 MW. VCS1 has a large capacity with 11 Mvar inductor and 4 Mvar capacitor, whereas VCS2 has a small capacity of 7 Mvar inductor. L represent inductor and C represents capacitor in Table III.

It can be seen from Table III that when the large-capacity VCS1 is configured and ESS is added, the annual average voltage offset is reduced from 5.24% (without ESS) to 3.09%. The voltage offset with ESS is reduced by 41.03% compared to that without ESS. When the small-capacity VCS2 is configured and ESS is added, the annual average voltage offset is reduced from 7.42% (without ESS) to 4.29%. The voltage offset with ESS is reduced by 42.18% compared to that without ESS. It can be seen that the configuration of ESS improves the voltage quality.

Reducing the action time of transformer tap can extend its service life, thereby improving the economy of the entire system. Table III shows that the maximum daily action time of the transformer tap in a year is significantly reduced due to the addition of ESS. At the same time, sufficient capacity of VCS also can reduce the action time of transformer tap.

TABLE III
REACTIVE POWER INPUT, TRANSFORMER ACTION TIME AND VOLTAGE OFFSET UNDER DIFFERENT ESS CONFIGURATION AND VCS CAPACITY

Working condition	Configuration of system			
	With ESS+ VCS1	W-O ESS+ VCS1	With ESS+ VCS2	W-O ESS+ VCS2
Rainy season Q_{max} (Mvar)	11/L	11/L	7/L	7/L
Rainy season Q_{min} (Mvar)	8.85/L	3.71/L	5.61/L	0.50/L
Dry season Q_{max} (Mvar)	7/L	11/L	7/L	7/L
Dry season Q_{min} (Mvar)	4/C	4/C	0	0
Action time of transformer tap	2	6	5	8
Annual average voltage offset (%)	3.09	5.24	4.29	7.42

The voltage fluctuation curve when configuring the large capacity VCS1 is shown in Fig. 14. It can be seen that during the rainy season, the voltage is high because the transmission line power is always at its maximum capacity. After configuring ESS, the voltage fluctuation of the system is reduced. During the dry season, configuring ESS has a significant effect on the optimization of voltage fluctuation. Overall, the voltage quality is optimized and meets the requirements.

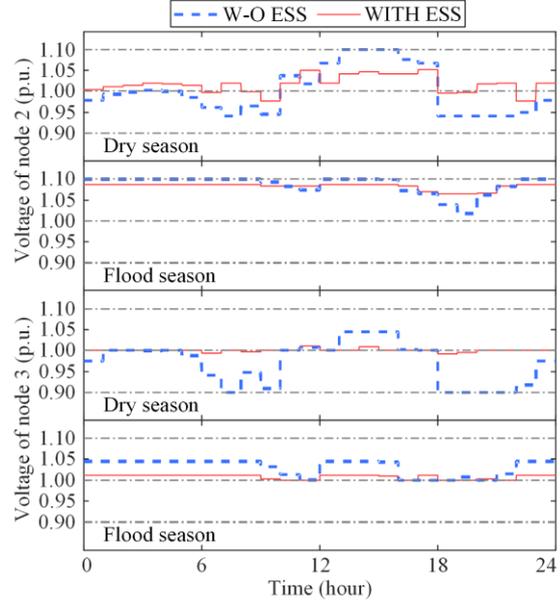


Fig. 14. Voltage fluctuation curve with VCS1.

Figure 15 shows the voltage fluctuation curve when the small capacity VCS2 is configured. It can be seen that the voltage quality of the system with ESS meets the requirements, but the voltage quality of the system without ESS does not comply.

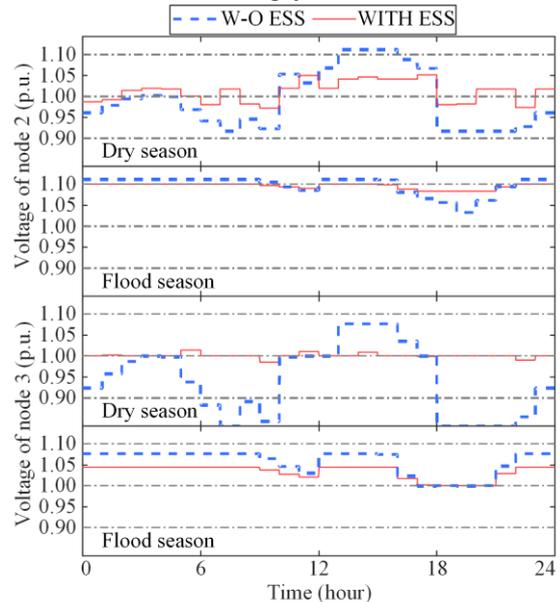


Fig. 15. Voltage fluctuation curve with VCS2.

In summary, for the system with ESS, configuring a VCS with larger capacity can obtain better voltage

quality, but even a small VCS can help to make the voltage quality meet the requirements while reducing costs. Better voltage quality or lower cost of VCS can be selected according to actual needs of the project.

VI. CONCLUSION

This paper analyzes the reasons for small hydropower transmission congestion and insufficient regulation flexibility. It comprehensively considers the impact of the configuration of ESS on small hydropower distribution networks, and establishes a source-grid-storage collaborative planning and operation model for the small hydropower distribution network. It takes into account the revenue of small hydropower investors and the safe and stable operation of small hydropower distribution networks. A simulation analysis is conducted using a small hydropower group in a certain region as an example. The economics of ESS configuration is studied. The focus is on analyzing the impact of the configuration of ESS on the consumption rate and water abandonment of small hydropower, transmission line power and node voltage of distribution networks, etc. The results show that the proposed method can effectively improve the on-site consumption capacity of small hydropower and voltage quality. And at the same time, it also improves the safe operation level and economy of the distribution network.

ACKNOWLEDGMENT

Not applicable.

AUTHORS' CONTRIBUTIONS

Qunmin Yan: writing-original draft and formal analysis. Ruiqing Ma: resources. Xinzhou Dong: conceptualization. Rui Ma: software. Chen An: data curation. All authors read and approved the final manuscript.

FUNDING

This work is supported by the General Program of the National Natural Science Foundation of China (No. 62176146).

AVAILABILITY OF DATA AND MATERIALS

Please contact the corresponding author for data material request.

DECLARATIONS

Competing interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

AUTHORS' INFORMATION

Qunmin Yan received a master's degree in power electronics and power transmission from Northwestern

Polytechnical University (NPU), Xi'an, China, in 2009. Professor Yan is currently the dean and professor with the School of Electrical Engineering at Shaanxi University of Technology. His main research interests include electrical power system analysis and electrical power quality control, small hydropower grid connected operation scheduling strategies, energy storage configuration.

Ruiqing Ma received a Ph.D. degree in detection technology and automation equipment from the School of Automation, Northwestern Polytechnical University (NPU), Xi'an, China, in 2007. Dr. Ma is currently a professor and doctoral supervisor with the Department of Electrical Engineering at the School of Automation at NPU. His main research interests include servo control and electric actuation of rare earth permanent magnet motors.

Xinzhou Dong received the master's degree and Ph.D. degree from the School of Electrical Engineering at Xi'an Jiaotong University, Xi'an, China, in 1991 and 1996, respectively. Dr. Dong is currently a professor and doctoral supervisor with the Department of Electrical Engineering and Applied Electronics Technology at Tsinghua University, Beijing, China. His main research interests include electrical power system fault analysis, relay protection, fault traveling wave theory, traveling wave protection, traveling wave distance measurement, wavelet transform applications, channel free protection, system protection for grid safety, and integrated protection for intelligent substations.

Rui Ma received the dual Ph.D. degree in electrical engineering from both the University of Technology of Belfort-Montbéliard (UTBM), Belfort, France, and Northwestern Polytechnical University (NPU), Xi'an, China, in 2018 and 2019, respectively. Dr. Ma is currently an associate professor with the School of Automation at NPU. His main research interests include fuel cell modeling, fuel cell applications, real-time simulation systems and machine learning.

Chen An received the dual bachelor's degrees in electrical engineering from both the University of Strathclyde, Glasgow, UK, and Northeast Electric Power University (NEEPU), Jilin, China, in 2020 and 2021, respectively. Since September 2022, she has been a graduate student in the School of Electrical Engineering, Shaanxi University of Technology, Hanzhong, China. Her main research interests include electrical power system analysis, microgrid scheduling strategies, and energy storage configuration.

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