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ORIGINAL RESEARCH

Allocation method of coupled PV-energy storage-charging station in hybrid AC/DC distribution networks balanced with economics and resilience

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Abstract

The hybrid AC/DC distribution network has become a research hotspot because of the wide access to multiple sources and loads. Meanwhile, extreme disasters in the planning period cause huge losses to the hybrid AC/DC distribution networks. A coupled PV-energy storage-charging station (PV-ES-CS) is an efficient use form of local DC energy sources that can provide significant power restoration during recovery periods. However, over investment will happen if too many PV-ES-CSs are installed. Therefore, it is important to determine the optimal numbers and locations of PV-ES-CS in hybrid AC/DC distribution networks balanced with economics and resilience. Firstly, the advantages of PV-ES-CS in normal operation and extreme disasters are analysed and the payment function is quantified accurately. Secondly, a bi-level optimal allocation model of PV-ES-CS in hybrid AC/DC distribution networks is established. In this model, the payment function using Nash equilibrium to balance economics and resilience is addressed at the upper-level, and the typical scenarios are simulated, and the optimal results are obtained using the genetic algorithm in lower level. Finally, a series of examples are analysed, which demonstrate the necessity of balancing economics and resilience, and advantages of DC lines in network restoration after disasters.

1 | INTRODUCTION

In recent years, with the wide access to multiple renewable energy sources and distributed loads, hybrid AC/DC distribution networks have become a research hotspot, considering the capability of DC technology in power shifting and flows [1–4]. Moreover, a coupled PV-energy storage-charging station (PV-ES-CS) is a key development target for energy in the future that can effectively combine the advantages of photovoltaic, energy storage and electric vehicle charging piles, and make full use of them [5]. The photovoltaic and energy storage systems in the station are DC power sources, which can be more easily connected to DC lines than AC. Therefore, it is important to decide the amounts and locations of PV-ES-CS in hybrid AC/DC distribution networks, considering economics.

On the other hand, improving the resilience of distribution networks has become an urgent problem because of the huge losses caused by increasingly frequent extreme disasters [6, 7]. As a controllable energy source, PV-ES-CSs have huge potential for load restoration after disasters. The hybrid AC/DC distribution networks also have the ability to improve resilience, where DC lines can flexibly interconnect with other AC lines in case of network failure. Consequently, the resilience improvement effect under high-impact and low-probability (HILP) events should be fully considered when planning the amounts and locations of PV-ES-CS in the hybrid AC/DC distribution networks.

The existing research on coordinated planning of multiple sources and loads in a hybrid AC/DC distribution network mainly focuses on the economics under normal conditions and the development of models considering the uncertainty of sources and loads. Huang et al. [8] established a cooperative optimization operation strategy for multiple energy storage systems in a hybrid AC/DC distribution network, which was based on the collaboration of electricity price, grid connection mode, and energy storage systems. Haytham et al. [9] established a new stochastic planning model of distributed generation (DG) in a hybrid AC/DC distribution system that aimed to minimize the installation and operation costs of distributed generations, and Monte Carlo simulations were used to process the stochastic optimization. Bilal et al. [10] took the minimum annual cost and the minimum probability of power supply loss as the objectives, and optimized the PV and energy storage system (ESS) for a hybrid AC/DC microgrid in a remote area through a multi-objective genetic algorithm. Zhang et al. [11] proposed the economic evaluation method of urban medium-voltage hybrid AC/DC distribution networks, which considered the uncertainty of DGs and loads and quantified the benefits of the AC/DC hybrid distribution network. Zhang et al. [12] proposed a coordinated planning method for DGs, capacitor banks and intelligent flexible soft switches in active distribution networks that fully considered the time sequence characteristics of DGs and loads. Liu et al. [13] proposed a two-stage random management scheme to minimize the expected operation cost of a hybrid AC/DC distribution network, considering the flexibility and power transfer capability of mobile ESS.

Currently, the research on PV-ES-CS mainly focuses on economic modelling. Liu et al. [14] established a bi-level optimal programming model for PV-ES-CS, considering capacity allocation and user electricity prices. Based on the electric load of different types of buildings and the data of electric vehicle charging stations in Beijing, Sun et al. [15] analysed the economic and environmental benefits of integrated charging stations at different scales using the capacity optimization model. Alonzo et al. [16] estimated the energy balance, annual energy cost and cumulative CO2 emissions under different scenarios of PV-ES-CS, and evaluated their feasibility in the United States and China.

The current optimal configuration of PV-ES-CS can be improved with the utilisation of the fault restoration capability of the hybrid AC/DC distribution. In addition, the above documents did not consider the HILP events in the DG configuration model of hybrid AC/DC distribution networks. Even though the economics under normal operation are good, the losses caused by an extreme event may far exceed the benefits brought by the improvement of normal economics over many years. Hence, the advantages of a hybrid AC/DC distribution network for fault restoration should be considered.

Compared to AC distribution networks, hybrid AC/DC distribution networks can enhance resilience because they have higher line transfer capabilities and an interconnected topology. In AC distribution networks, the network restoration is addressed by using circuit breakers or to separate the faulty part, and the power is resupplied from the high-voltage networks. In hybrid AC/DC distribution networks, the network restoration can also be addressed by using circuit breakers, sectionizors or voltage source converters (VSCs) to separate the faulty part, and the power can also be re-supplied by distributed resources through the control of VSCs. For hybrid AC/DC distribution networks, the outputs of the VSCs between AC and DC lines need to be considered in the allocation of PV-ES-CSs, as opposed to the fact that only the locations and capabilities of local power sources need to be considered in AC distribution networks. After the occurrence of an extreme event, the DC lines can use its ability for flexible interconnection. At the same time, as a restoration resource, the PV-ES-CSs are able to supply power to the critical loads through the DC lines, thus breaking the constraint of the radial AC lines and significantly improving the resilience of the hybrid AC/DC distribution networks. The difficulty is that the probability of extreme events is too small, and it is hard to accurately quantify and estimate. Hence, the traditional calculation method based on a probability risk has a large error, and it is not easy to normalize the normal economics. Resilience under extreme disasters and economics in the normal period are mutually exclusive because the improvement of resilience will lead to the decline of economics [17]. Therefore, it is important to decide the amounts and locations of PV-ES-CS in a hybrid AC/DC distribution network balanced with economics and resilience. Nash equilibrium simulates the negotiation process on both sides of the game and truly reflects the magnitude difference between the optimization objectives so as to obtain a more reasonable equilibrium solution [17, 18]. Therefore, it is feasible to choose the Nash equilibrium method as the balance between economics and resilience.

Based on the above analyse, an optimal planning strategy for PV-ES-CSs in hybrid AC/DC distribution networks considering the normal operation conditions and their resilience under extreme events is proposed. Firstly, the advantages of PV-ES-CS in normal operation and extreme disasters are analysed and the payment function is quantified accurately. Secondly, a bi-level optimal allocation model of PV-ES-CSs in hybrid AC/DC distribution networks is established. In the upper level, this model deals with the payment function using Nash equilibrium to balance economics and resilience, and in the lower level, this model simulates three typical scenarios and calculates the optimal results using the genetic algorithm. Finally, rationality and effectiveness are validated by a series of examples.

The main contributions of this work are listed as follows:

(1) This paper proposes a novel bi-level framework for the allocation of PV-ES-CS in hybrid AC/DC distribution networks, where resilience and economics are optimized simultaneously. Meanwhile, the characteristic of PV-ES-CS is fully considered in the allocation method, and it is meaningful for the development of hybrid AC/DC distribution networks in the future.
(2) A Nash equilibrium-based model is utilized to solve the bi-level, multi-objective optimization problem. The economics and resilience of PV-ES-CS are regarded as two players in the game, which is greatly different in diversity of dimensions, time span and probabilities. The planning results show an accurate investment to enhance the resilience of hybrid AC/DC distribution networks after disasters.

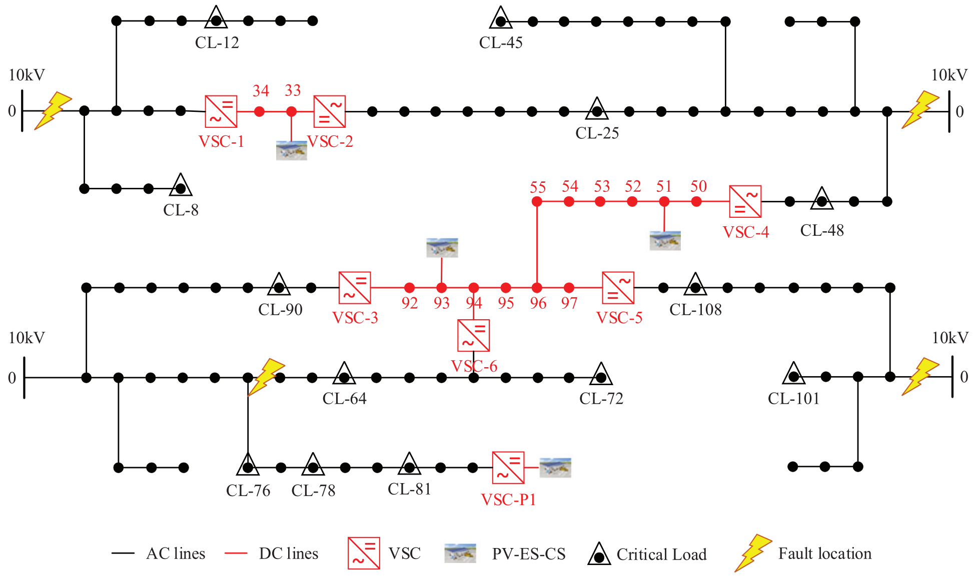

FIGURE 1 Schematic diagram of coupled PV-energy storage-charging station (PV-ES-CS) configuration in hybrid AC/DC distribution network.

2 | PROBLEM DESCRIPTION

As shown in Figure 1, the aim of this paper is to find the optimal number and locations PV-ES-CS to be allocated, which can maximize the potential fault restoration of the existing hybrid AC/DC distribution networks under extreme disasters, and maintain economic efficiency under normal operation.

During occurrences of severe events like powerful typhoons, earthquakes, heavy rainstorms and floods, certain lines within the hybrid AC/DC distribution network might become disrupted or collapse. If some of the DC lines are still functional, even if one of the AC lines fails, the node located downstream of the fault can still connect with the other AC lines through the DC lines to avoid a blackout. However, this will cause the load on some lines to be too large, resulting in overloading, voltage violations and other problems. Therefore, it is necessary to increase the restoration power resources in distribution networks to ensure the quality of the power supply as well as recovering more loads.

PV-ES-CS can combine the advantages of photovoltaic, energy storage and electric vehicles to complement their shortcomings. The energy storage can effectively store the energy generated by the PV panels and reduce the uncertainty of PV outputs. PV can also provide power for energy storage, overcoming the shortage of limited capacity of energy storage. In addition, EVs can make full use of their advantages of flexible mobility and balance the power distribution of each station according to the demand of different lines and loads, which can provide power support and avoid the waste of resources.

Under normal operation conditions, the construction of PV-ES-CSs in hybrid AC/DC distribution networks has the following three advantages: First, the expenses and maintenance costs of inverters can be reduced because there is no need to install VSCs between PV-ES-CS and DC lines. Second, revenue can be obtained by providing an EV charging service. Finally, when the PV output is high during the daytime, the surplus electric energy can be fed into the grid, which can also generate some profits. Therefore, it is necessary to balance economics and resilience, because the installation costs of PV-ES-CS are partially reduced compared to installing them individually. The total object of the optimal issue is:

$$\begin{aligned} obj.\ & \max F_{\text{resilience}} \\ & \min F_{\text{economy}} \end{aligned} \tag{1}$$

where $F_{\text{resilience}}$ indicates the index of resilience and F_{economy} means the index of economics.

3 | ECONOMICS AND RESILIENCE INDEX OF HYBRID AC/DC DISTRIBUTION NETWORK CONTAINED PV-ES-CS

3.1 | Economics

Under normal operation, according to the maximum net present value of PV-ES-CS [19], income from the station during the whole planning period

$$NPV = N_{\text{PV-ES-CS}} \left[\sum_{y=1}^{Y} \frac{PFY(y)}{(1+r)^{y-1}} - C_{\text{PV-ES-CS}}^{\text{build}} \right] \tag{2}$$

where $N_{\text{PV-ES-CS}}$ is the number of PV-ES-CSs. Y is the planning period. y is each year during the Y, $1 \le y \le Y$. $PFY(y)$ is the annual profit of PV-ES-CS. r is discount rate. $C_{\text{PV-ES-CS}}^{\text{build}}$ is the infrastructure construction cost of PV-ES-CS.

$$C_{\text{PV-ES-CS}}^{\text{build}} = C_{\text{PV}}^{\text{build}} + C_{\text{ESS}}^{\text{build}} + C_{\text{pile}}^{\text{build}} + C_{\text{else}}^{\text{build}} + C_{\text{land}} \tag{3}$$

where $C_{\text{PV}}^{\text{build}}$ is the purchase and installation costs of PV facilities, including solar panels and PV supports. $C_{\text{ESS}}^{\text{build}}$ is the purchase and installation costs of energy storage facilities, including energy storage batteries and protection devices. $C_{\text{plie}}^{\text{build}}$ is the investment and construction cost of an electric vehicle charging pile. $C_{\text{else}}^{\text{build}}$ is the investment and construction costs of other supporting facilities in the power station. C_{land} is the land use fee.

Annual profit of PV-ES-CS:

$$PFY(y) = \sum_{d}^{D} \sum_{h=1}^{H} PFH(h) - C_{\text{PV-ES-CS}}^{\text{operation}} \tag{4}$$

where $PFH(h)$ is the hourly profit of PV-ES-CS. h is the time of operation in hours, $1 \leq h \leq H = 24$. d is the day, $1 \leq d \leq D = 365$. $C_{\text{PV-ES-CS}}^{\text{operation}}$ is the annual operation and maintenance costs.

$$C_{\text{PV-ES-CS}}^{\text{operation}} = C_{\text{PV}}^{\text{operation}} + C_{\text{ESS}}^{\text{operation}} + C_{\text{pile}}^{\text{operation}} \tag{5}$$

where $C_{\text{PV}}^{\text{operation}}$, $C_{\text{ESS}}^{\text{operation}}$ and $C_{\text{pile}}^{\text{operation}}$ is the operation and maintenance costs of photovoltaic, energy storage and electric vehicle charging piles. This part of the cost includes equipment replacement to maintain normal operation within a reasonable range.

The hourly profit of PV-ES-CS is

$$PFH(h) = E_{\text{EV},h} \cdot \left(P_{\text{EV},h} + P_{\text{S},h}\right) + E_{\text{out},h} P_{\text{out},h} - E_{in,h} P_{\text{in},h} \tag{6}$$

where $E_{\text{EV},h}$ is the power provided by the power station to the owner within o1 h. $P_{\text{EV},h}$ and $P_{\text{S},h}$ is the electricity purchase price of the owner and the service fee charged by the power station during this period. $E_{\text{out},h}$ and $P_{\text{out},h}$ is the electricity delivered by the power station to the grid and the on-grid electricity price during this period. $E_{\text{in},h}$ and $P_{in,h}$ is the electricity purchased from the grid and the electricity price purchased by the power station during this period.

3.2 | Resilience

The probability of extreme disasters in the whole planning period is small. But once it happens, it will cause great damage to the distribution network. The frequency of suffering from extreme disasters in an area can be measured by the return period [20]. The return period refers to the average number of time intervals between repeated occurrences of an event in many trials. Especially in meteorology and environmental science, it refers to the average interval between the occurrences of a certain natural phenomenon in history.

$$RP(c) = T_{\text{history}} / N(c) \tag{7}$$

where $RP(c)$ is the return period of cth disaster in a year. T_{history} is the total time of observation and recording of disaster events. $N(c)$ is the total historical occurrence of cth disasters.

TABLE 1 Example table.

c	Classification	Return period (year)	Frequency
1	Earthquake ($M > 5$)	1700	0.01176
2	Hurricane ($S > 32.7$ m/s)	1.63	12.28571
3	Lightning	0.024	830
4	Snowstorm (prep > 20 mm)	70	0.28571
5	Tornado (EF > 1)	100	0.2
6	Tsunami	∞	0

Abbreviations: M, earthquake magnitude; S, speed of wind; prep, precipitation; EF, enhanced fujita scale.

Frequency of the occurrence of certain extreme disasters in the whole planning period:

$$F_{\text{dis}}(c) = Y / RP(c) \tag{8}$$

Taking a southeast coastal city in China as an example, the return period of typical extreme disasters and the predicted number of occurrences in the planning period are shown in Table 1 by consulting relevant historical meteorological and seismic records.

As the degree of each natural disaster is different, the statistics of historical data in Table 1 only consider the degree of possible failure of distribution network elements. For example, earthquakes with a Richter scale greater than 5, typhoons with a central wind speed greater than 32.7 m/s, snowstorms with accumulated precipitation greater than 20 mm, and tornadoes larger than EF1 are selected.

The resilience improvement effect of PV-ES-CS in a hybrid AC/DC distribution network can be measured by the reduction of power outage loss to the critical load, which can be restored. The more PV-ES-CS installed, the more power outage loss from the critical load can be avoided, which means resilience is improved. The definition is as follows:

$$RES = \sum_{c=1}^{6} F_{\text{dis}}(c) \int_{0}^{T_R} \left(\sum_{i=1}^{N} C_{\text{kWh}}^{i} p_{\text{loss}}^{i}(c) S_{\text{load}}^{i}(c,t) P_{\text{load}}^{i}(t) \right) dt \tag{9}$$

where RES is the reduction of outage losses for critical loads after disaster. T_R is the post-disaster recovery period. N is the total number of critical load nodes in hybrid AC/DC distribution network. C_{kWh}^{i} is the outage losses per kWh of ith critical load. $p_{\text{loss}}^{i}(c)$ is the blackout probability of the ith critical load under cth extreme disaster. $S_{\text{load}}^{i}(c,t)$ is the recovery status of ith critical load under cth extreme disaster at the tth hour, which is a binary variable. 1 indicates that the load is restored within this hour, while 0 indicates that the load has no electrical connection with any PV-ES-CS, or has connection but there is no longer power left for it. $P^i_{load}(t)$ is the power demand of ith critical load at the tth hour.

The definition of $S^i_{load}(c,t)$ is

$$S^i_{load}(c,t) = \begin{cases} 1, \left(J^i_j = 1\right) \wedge \left(R^i_{load}(t) > P^i_{load}(t)\right) \\ 0, \left(J^i_j = 0\right) \vee \left[\left(\left(J^i_j = 1\right) \wedge \left(R^i_{load}(t) < P^i_{load}(t)\right)\right)\right] \end{cases} \tag{10}$$

$$J^i_j = \begin{cases} 1, \left(L_j = 1\right) \wedge \left(\exists T^i_j = 1\right) \\ 0, \left(L^i_j = 0\right) \vee \left[\left(\left(L^i_j = 1\right) \wedge \left(\forall T^i_j \neq 1\right)\right)\right] \end{cases} \tag{11}$$
$$i \in [1, N], j \in [0, N_{PV\text{-}ES\text{-}CS}]$$

where J^i_j indicates whether there is an electrical connection between the ith critical load and the jth PV-ES-CS. $R^i_{load}(t)$ means the quantity of electricity remained for ith critical load at the tth hour. When $L_j = 1$, it means there is a PV-ES-CS installed at the location j. T^i_j represents the topology after disasters. When $T^i_j = 1$, there are lines between the ith critical load and the jth PV-ES-CS.

3.3 | Nash equilibrium

According to Sections 3.1 and 3.2, the more PV-ES-CSs configured in the hybrid AC/DC distribution networks, the more outage losses can be reduced in the planning period, and the stronger the resilience. But at the same time, more PV-ES-CS means that the level of investment will greatly increase and the economics will reduce. Therefore, the economics and resilience of distribution networks are mutually exclusive, and they belong to non-cooperative relationships in game theory.

Nash equilibrium is an important means to deal with non-cooperative games. When the choices of both sides of the game reach an equilibrium point, any participant who chooses a strategy beyond the equilibrium point will not get any additional benefits. They have no motive to deviate from the equilibrium point when the participants reach Nash equilibrium. If all participants predict that a particular Nash equilibrium will occur, then the Nash equilibrium must exist, which is a consistent prediction of the outcome of the game and all participants make the best response to other participants.

At present, it has been proven that the solution of Nash equilibrium falls on the Pareto frontier [18]. Multi objective Pareto generates a set of solutions, but requires an indicator to select the most suitable one. At this time, Nash equilibrium can determine the comprehensive optimal solution of the two objective functions to help the model select the best scheme.

Taking resilience and economics as both sides of the game, their comprehensive interests should be maximized.

$$\max \left(u_R(x) - d_R\right)\left(u_E(x) - d_E\right) \tag{12}$$

$$u_R(x) = RES \tag{13}$$

$$u_E(x) = NPV \tag{14}$$

where $u_R(x)$ and $u_E(x)$ represents the income vector of both sides of the game, which corresponds to the level of resilience and economics in different numbers and locations of PV-ES-CS. d_R and d_E indicates the negotiation break point of the game. If the two sides of the game do not reach an agreement on (d_R, d_E), the negotiation break down and the income is 0 at this time.

4 | A BI-LEVEL OPTIMIZED CONFIGURATION MODEL OF PV-ES-CS IN HYBRID AC/DC DISTRIBUTION NETWORK

In order to accurately balance the economics and resilience of configuring PV-ES-CS in the hybrid AC/DC distribution network, it is necessary to describe it on two types of time scales. One is to calculate the economics in the whole planning period, and the other is to calculate the resilience in the post-disaster recovery period. Therefore, a bi-level programming model is proposed. The upper level optimizes the economics and resilience of the entire planning period and generates the amounts and locations of PV-ES-CS. The lower level calculates the economics and resilience of the hybrid AC/DC distribution network under three typical scenarios according to the amounts and locations of PV-ES-CS generated and transmits them to the upper level.

4.1 | The upper level

4.1.1 | Objective function

The weighted sum scalarization technique is not suitable for transforming multi-objective problems into single-objective problems. In addition, the epsilon-constraint method and the non-dominant sorting genetic algorithm (NSGA-II) cannot handle the differences in dimensions, time spans, and probabilities between multiple objectives [17]. Therefore, considering resilience and economics as two participants, a bargaining model is proposed to find Pareto's optimal boundary and achieve Nash equilibrium in the allocation of PV-ES-CS.

Equation (9) is changed according to the linear invariance of Nash equilibrium.

$$\min F_{up} = \frac{d_R d_E}{\left(d_R - u_R(x)\right)\left(d_E - u_E(x)\right)} \tag{15}$$

where F_{up} is the objective function of the upper level.

4.1.2 | Constraint condition

Equation constraints include Equations (2)–(9), where Equations (2)–(6) represent economic constraints in the whole planning period, and Equations (7)–(9) represent resilience constraints in the recovery period after extreme disasters.

The inequality constraint is shown in Equation (13):

$$\begin{cases} u_{\mathrm{R}}(x) < d_{\mathrm{R}} & \text{(a)} \\ u_{\mathrm{E}}(x) < d_{\mathrm{E}} & \text{(b)} \\ \frac{\partial u_{\mathrm{R}}(x)}{\partial x} \cdot \frac{\partial u_{\mathrm{E}}(x)}{\partial x} < 0 & \text{(c)} \\ 0 \le x \le \bar{n}_{\text{PV-ES-CS}} & \text{(d)} \end{cases} \tag{16}$$

Equations (16a) and (16b) indicate that the need for the value of economic and resilient payment functions is less than their respective investment margins. Equation (16c) is one of the necessary conditions for the application of Nash equilibrium, which indicates that the income trend of both sides of the game should be opposite. Equation (16d) indicates that the number of PV-ES-CS should not exceed the upper limit of the economic investment margin.

Controllable energy storages in PV-ES-CS are mainly used in the post-disaster restoration process. PV and EV provide the energy supplement for ES, which can reduce the uncertainty of PV-ES-CS. Therefore, the minimum electricity that PV-ES-CS can provide is determined by the capacities of ES, and the maximum value is determined by the capacities of PV, ES and EV together. To ensure that there are enough energy left for restoration, the upper limit of electricity is obtained based on the probability model of PV outputs and EV discharging and the 80% confidence level.

The power of PV is influenced by the intensity of sunlight, which can generally be seen as following a beta distribution. Its probability density function is:

$$f(r) = \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)} \cdot \left(\frac{r}{r_{\max}}\right)^{\alpha-1} \cdot \left(1 - \frac{r}{r_{\max}}\right)^{\beta-1} \tag{17}$$

where r and $r_{\max}$ (W/m) are actual and maximum light intensity. α and β are shape parameters of beta distribution. Γ represents gamma function.

Obtain the probability density function of PV based on the probability density function of light intensity:

$$f(P_{\mathrm{PV}}) = \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)} \cdot \left(\frac{P_{\mathrm{PV}}}{R_{\mathrm{M}}}\right)^{\alpha-1} \cdot \left(1 - \frac{P_{\mathrm{PV}}}{R_{\mathrm{M}}}\right)^{\beta-1} \tag{18}$$

where R_{M} is maximum output power of the square array, $R_{\mathrm{M}} = A\eta r_{\max}$.

Assuming that the number of EVs actually participating in distribution network dispatching follows normal distribution, the discharge amount of EVs also follows normal distribution below.

$$f(PEV) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left[-\frac{(PEV-\mu)^2}{2\sigma^2}\right] \tag{19}$$

where μ is mathematical expectations, σ^2 is variance.

In summary, the constraints of the PV-ES-CSs are as follows:

$$\begin{cases} P_{\mathrm{ES\,min}} \le P_{\mathrm{ES}} \le P_{\mathrm{ES\,max}} \\ E_{\mathrm{ES},t} + \int_t^{t+1} P_{\mathrm{ES}} dt = E_{ES,t+1} \\ E_{\mathrm{ES\,min}} \le E_{\mathrm{ES},t} \le E_{\mathrm{ES\,max}} + E_{\mathrm{PV}} + E_{\mathrm{EV}} \end{cases} \tag{20}$$

where P_{ES} is charging and discharging power of ES. $P_{\mathrm{ES\_min}}$ and $P_{\mathrm{ES\_max}}$ are lower and upper limits of charging and discharging power for ES. $P_{\mathrm{ES\_t}}$ and $P_{\mathrm{ES\_t+1}}$ are energy storage at time t and $t+1$. $E_{\mathrm{ES\_min}}$ and $E_{\mathrm{ES\_max}}$ are upper and lower limits of energy storage capacity.

For ES in PV-ES-CS and schedulable electric vehicles, it should be ensured that the stored energy during the recovery phase is fully utilized.

$$E_{\mathrm{ES},n} = 0 \tag{21}$$

$$E_{\mathrm{EV},n} = 0 \tag{22}$$

where $E_{\mathrm{ES\_}n}$ and $E_{\mathrm{EV\_}n}$ are energy storage and electric vehicle energy after n hours.

4.2 | The lower level

The lower level contains three sub-objectives: minimum network loss under normal operation, maximum recovery capability under normal faults, and maximum recovery capacity under extreme disasters.

The total objective function of the lower level is:

$$\min F_{\mathrm{down}} = \frac{P_{\mathrm{total}}^{\mathrm{loss}}}{F_{n-R} + R_{ES}} \tag{23}$$

where $P_{\mathrm{total}}^{\mathrm{loss}}$ is total power loss of hybrid AC/DC distribution network. F_{n-R} is the recovery ability under normal faults.

4.2.1 | Power loss under normal operation

AC and DC line power-balanced constraints are [21]:

$$i_{ij}^{\mathrm{AC}} = \frac{\left(P_{ij}^{\mathrm{AC}}\right)^2 + \left(Q_{ij}^{\mathrm{AC}}\right)^2}{u_i^{\mathrm{AC}}} \tag{24}$$

$$i_{ij}^{\mathrm{DC}} = \frac{\left(P_{ij}^{\mathrm{DC}}\right)^2 + \left(Q_{ij}^{\mathrm{DC}}\right)^2}{u_i^{\mathrm{DC}}} \tag{25}$$

where i_{ij}^{AC} and i_{ij}^{DC} is the current between nodes i and j of AC and DC lines. u_i^{AC} and u_i^{DC} is the voltage at node i of AC/DC lines. P_{ij}^{AC}, Q_{ij}^{AC}, P_{ij}^{DC} and Q_{ij}^{DC} is the active power and reactive power flowing between nodes i and j of AC and DC lines.

The power loss of AC line is:

$$P_{ij}^{\text{ACloss}} = \frac{\left(P_{ij}^{\text{AC}}\right)^2 + \left(Q_{ij}^{\text{AC}}\right)^2}{\left(u_i^{\text{AC}}\right)^2} r_{ij}^{AC} \tag{26}$$

It is assumed that the DC line is a symmetrical structure with a neutral line, and the power loss of the DC line is [1]:

$$P_{ij}^{\text{DCloss}} = \frac{\left(P_{ij}^{\text{AC}}\right)^2}{2\left(u_i^{\text{DC}}\right)^2} r_{ij}^{\text{DC}} \tag{27}$$

The total power loss of AC/DC hybrid distribution network is:

$$P_{\text{total}}^{\text{loss}} = \sum_{i=1,j\neq i}^{n_{\text{AC}}} P_{ij}^{\text{ACloss}} + \sum_{i=1,j\neq i}^{n_{\text{DC}}} P_{ij}^{\text{DCloss}} + \sum_{i=1}^{n_{\text{VSC}}} P_i^{\text{VSCloss}} \tag{28}$$

where n_{AC}, n_{DC} and n_{VSC} are the number of AC lines, DC lines and voltage source converters. P_i^{VSCloss} is the power loss of ith VSC, which is 2% of the line power [22].

4.2.2 | Recovery ability under normal failure

Under normal operation of distribution network, some nodes will lose power due to equipment aging, human error etc. At that time, PV-ES-CS can provide part of the power, leaving time for maintenance and response.

Normal fault restoration capability of hybrid AC/DC distribution network with PV-ES-CS is:

$$F_{n-R} = \begin{cases} C_{\text{PV-ES-CS}}^{\text{provide}}, & C_{\text{PV-ES-CS}}^{\text{provide}} \leq C_{loss\_load}^{\text{need}} \\ C_{\text{loss\_load}}^{\text{need}}, & C_{\text{PV-ES-CS}}^{\text{provide}} > C_{\text{loss\_load}}^{\text{need}} \end{cases} \tag{29}$$

$$C_{\text{PV-ES-CS}}^{\text{provide}} = \sum_{i=1}^{n_{\text{near}}} E_i^{\text{PV-ES-CS}} P_{\text{in},h} \tag{30}$$

$$C_{\text{loss\_load}}^{\text{need}} = \sum_{i=1}^{n_{\text{load}}} P_i^{\text{loss}} T_R P_{\text{in},h} \tag{31}$$

where $C_{\text{PV-ES-CS}}^{\text{provide}}$ is all fault restoration capabilities provided by PV-ES-CS. $C_{\text{loss\_load}}^{\text{need}}$ is the recoverability to meet all power loss requirements. n_{near} is the PV-ES-CS number with an electrical connection to the blackout load. $E_i^{\text{PV-ES-CS}}$ is the power that a single PV-ES-CS can provide. n_{load} is the number of blackout loads under a normal fault. P_i^{loss} is the power demand of a blackout load.

4.2.3 | Recoverability under extreme disasters

Recoverability under six common extreme disasters is considered in a hybrid AC/DC distribution network containing PV-ES-CS. Considering the situations after disasters are complicated and uncertain, six typical fault scenarios are selected to calculate and analyse the effect of resilience enhancement. Equation (8) is used to describe the effect of different amounts and locations of PV-ES-CS on the recovery ability. Node failure probability $p_{\text{loss}}^i(c)$ comes from historical data on load blackout under different disasters. The installation position of the PV-ES-CS can be divided into two situations: one is directly connected to the DC line, and the other is connected to the AC line through the VSC. The advantage of direct connection with a DC line is to saves on the investment and maintenance costs of VSC, but it is difficult to provide power support for critical loads far away from DC lines. Therefore, after calculating the resilience in this section, it is necessary to transfer the data to the upper level for equilibrium game and final determination.

4.3 | Solution

Although the tractable power flow model and model reformulation can solve the network reconfiguration problem [17], this paper formulates the multi-objective equilibrium problem as a bi-level model that balances the economics and resilience, as solved by the NSGA-II. The amounts and locations of PV-ES-CS are converted to binary codes. Due to the large number of nodes, chromosomes are divided into 16 segments, which represent sixteen candidate locations. Each segment consists of four binary digits. The population size is 1000 and the maximum number of iterations not exceeding 100. The probabilities of crossover and variation are 0.6 and 0.1. The individual with the largest fitness value is found through a series of replication, crossover and mutation operations, which is the best allocation plan. The detailed steps of the solution are shown in Figure 2.

Step 1: Initialize the set **A** of amounts and locations of PV-ES-CS, and the set of topology and node information.
Step 2: Calculate $P_{\text{total}}^{\text{loss}}$, F_{n-R} and RES in the lower level using Equations (18), (19) and (8).
Step 3: If maximum iterations are executed or the convergence conditions of the lower level are satisfied, turn to Step 4; otherwise, return to Step 2.
Step 4: Calculate the objective of the upper level as shown in (12). If maximum iterations are executed or the convergence conditions of the upper level are satisfied, turn to Step 5; otherwise, return to Step 2 after updating the set **A**.

Step 5: Record the optimal fitness of objectives and get the best allocation strategy balanced resilience and economics.

5 | CASE STUDIES

5.1 | Simulation background

Feasibility and advantages of the proposed PV-ES-CS configuration strategy are validated by the case studies. Section 5.1 describes the background of the case. Section 5.2 verifies the benefits of balancing economics and resilience. Section 5.3

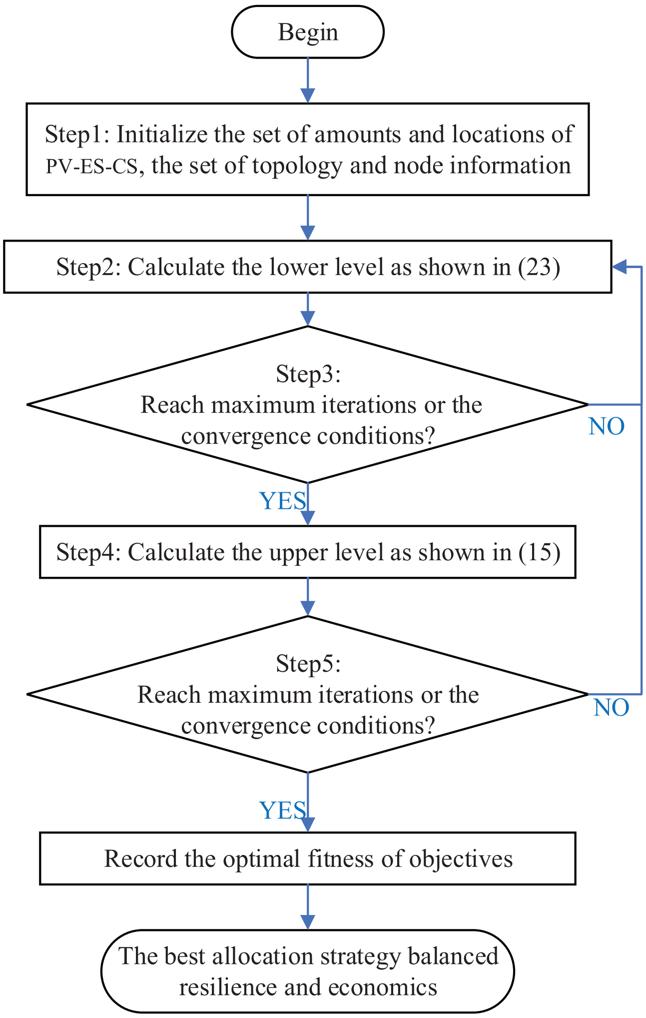

FIGURE 2 Solving steps of PV-ES-CS configuration model in AC/DC hybrid distribution network.

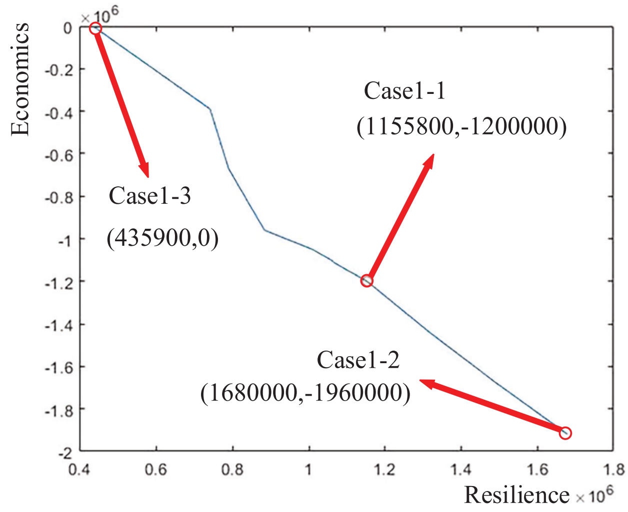

FIGURE 3 Results of Case 1 and the pareto frontier.

analyses the influence of the regulation effect of the hybrid AC/DC distribution network on the final result.

The topology shown in Figure 1 consists of four AC lines as the main distribution network. The end of the AC line is connected with other AC lines through VSC and DC lines, where the AC voltage is 10 kV and the DC voltage is ± 10 kV. There are 112 AC and DC nodes in the topology, including 13 critical load nodes, which are represented by "critical load (CL)-" in the figure. Detailed data are listed in Table A1, Appendix. A single PV-ES-CS can provide 1000 kWh and the maximum output power is 800 kW. VSC-1 and VSC-3 adopt constant DC voltage control to ensure stable operation of DC lines, while the remaining VSCs adopt PQ control to flexibly control the direction and size of line power transmission.

5.2 | The necessity of balancing economics and resilience

In order to verify the benefits of balancing the normal economics and extreme disaster resilience of a hybrid AC/DC distribution network in this paper, the following case studies are designed for comparison.

Case1-1: Take the balanced Equation (12) of economics and resilience as the objective function. The multi-objective genetic algorithm proposed in Section 4.3 is used to solve the model.

Case1-2: Only take the resilience Equations (8) and (10) as the objective function. Change the multi-objective genetic algorithm solution mentioned in Section 4.3 to a single-objective operation solution.

Case1-3: Only take the economics Equation (11) as the objective function. Change the multi-objective genetic algorithm solution mentioned in Section 4.3 to a single-objective operation solution.

The average solution time is 43.67 s for 20 tests under the condition of Case1-1, which is available for a planning issue. The solution results and Pareto frontier are shown in Figure 3.

Case1-1 corresponds to the point (1,155,800, −1,200,000) in Figure 3, which is the best result after the balance between normal economics and resilience under extreme disasters. At this time, the optimal number of PV-ES-CS configurations is 4, and the configuration location is shown in Figure 3. This point means that the calculated resilience level is 1,155,800 CNY and the number of PV-ES-CS is 4 now. This configuration mode can reduce the outage loss to 1,155,800 CNY for a hybrid AC/DC distribution network. The economics are −120,000,000 CNY, which means the total cost of configuring these four PV-ES-CS is 1,200,000 CNY.

Case1-2 corresponds to the point (1,680,000, −1,960,000) in Figure 4, the amounts of PV-ES-CS in hybrid AC/DC distribution network are 8. Compared with Case1-1, the total investment increased by 63.33%, although the toughness increased by 45.35%, which means that unnecessary additional investment has occurred. The calculation results based on the improvement of resilience ignore the economic investment within a certain limit. 8 PV-ES-CS will cause light and power abandonment under normal operation.

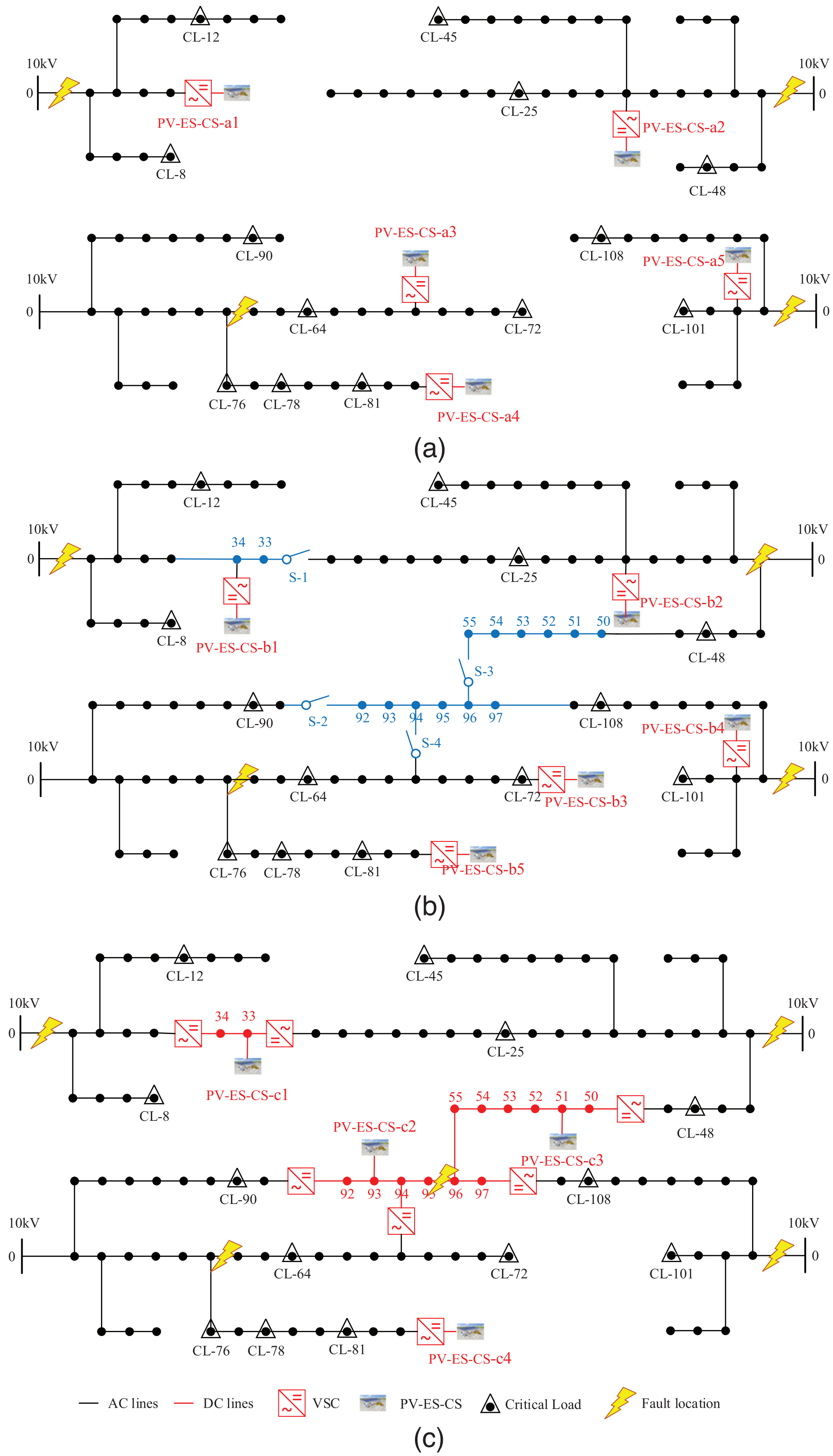

FIGURE 4 Results and the topology of Case 2.

TABLE 2 Results of Case 2.

Case	Number of PV-ES-CS	Resilience	Economics
2-1	5	1,033,700	−1,443,500
2-2	5	1,106,500	−1,439,400
2-3	4	1,151,200	−1,200,000
2-4	4	1,155,800	−1,200,000

Case1-3 corresponds to the point (4,359,000) in Figure 4. The amount of PV-ES-CS is 0, which means the required economic investment is also 0 CNY. Compared with Case1-1, the ability to withstand extreme disasters decreased by 62.29%. If saving investment and expenses is only focussed, although the investment and maintenance costs of PV-ES-CS will be saved, only relying on the flexible interconnection characteristics of DC cannot provide sufficient resilience in case of extreme disasters.

Therefore, the comparison of the above three examples shows that the configuration of PV-ES-CS in the hybrid AC/DC distribution network should not be based on the single goal of economics or resilience, but should make full use of the advantages of both sides to find a reasonable configuration strategy.

5.3 | The necessity of considering the advantages of DC fault restoration

In order to fully illustrate the role of flexible interconnection characteristics of DC lines in fault restoration, the following calculation examples are set for comparative analysis when simulating the impact of several extreme disasters on the hybrid AC/DC distribution network in the whole planning period.

Case2-1: Remove all DC lines from the original topology, and only retain the original AC lines. On this basis, use the calculation conditions of Case1-1 to solve.

Case2-2: Change all DC lines in the original topology into AC lines, and add interconnection switches at the end of AC lines. On this basis, use the calculation conditions of Case1-1 to solve.

Case2-3: The topology is the same as Case1-1. Assuming that the DC line 95–96 is broken due to extreme disasters, the calculation conditions of Case1-1 are used to solve the problem.

Case2-4: All conditions are the same as Case1-1.

The topology and configuration results of Case2-1, Case2-2 and Case2-3 are shown in Figure 4.

In Table 2, Case2-1 removes all interconnected DC lines. At this time, power transfer between AC lines cannot be carried out. All branches containing important loads are equipped with PV-ES-CS, and the number is 5. Compared with Case2-4, the resilience level decreased by 20.29%, and the economics also decreased by 10.56%. This is because the power required by CL-8 and CL-12 is small, and the PV-ES-CS-a1 installed at node 4 has some power left after recovering CL-8 and CL-12. This part of the electricity cannot support other branches with demand, resulting in a waste of resources.

Compared with Case2-4, the resilience level of Case2-2 has decreased by 4.26% and the economics have decreased by 19.95%. But it has improved compared with Case2-1. This is because each AC line is connected to other branches through an interconnection switch, which can improve the power supply ability between branches to a certain extent. However, restricted by the unidirectional power flow constraints of AC lines, it is still

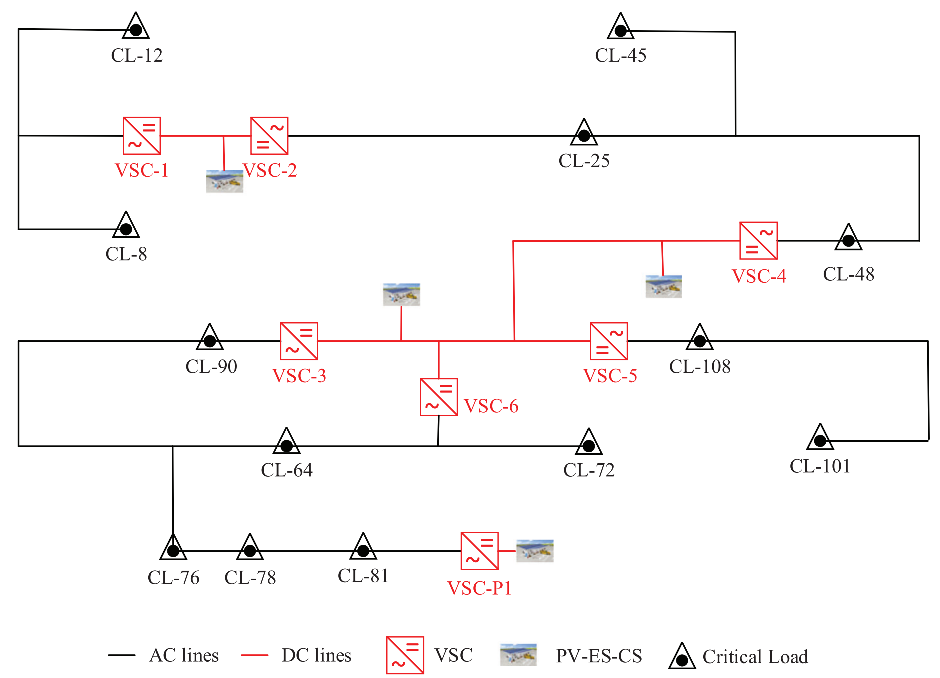

FIGURE 5 Simplified topology of typical post-disaster scenario.

unable to balance the power supply capacity of each PV-ES-CS and the demand of each important load to the greatest extent.

Compared with Case2-4, in the case of DC line failure, the Case2-3′s economics are only reduced by 0.398%, and the resilience level remains unchanged. Case2-3 and Case2-4 fully illustrate the strong power transmission and flexible regulation capability of DC lines. For example, after restoring CL-8 and CL-12, the remaining power of PV-ES-CS-c1 at node 4 can also be transferred to CL-25, CL-45 and CL-48 with large power demands through DC lines, which ensures that the power supply capacity of PV-ES-CS matches the demand of each critical load.

The above cases show that the flexible interconnection characteristics of DC power should be fully considered when configuring PV-ES-CS in the hybrid AC/DC distribution network, and the role of PV-ES-CS as a post-disaster power support power source should be maximized to ensure the continuous power supply of critical loads within a certain investment range.

5.4 | Post-disaster recovery process of typical scenario

A typhoon is selected as a typical scenario to analyse the post-disaster recovery process in hybrid AC/DC distribution network. It is assumed that the network loses all power sources form the unity grid after disaster. Topology is simplified as shown in Figure 5 according to the locations of critical loads.

Due to the flexibility of DC lines, PV-ES-CSs are electrically connected to all critical loads, which need to be restored orderly according to the weight provided by Table A1 in Appendix. If loads are operating at rated power for 4 h, it is considered complete recovery. Less than 4 h is considered partial recovery, and 0 h is considered unable to recover. Four PV-ES-CSs can provide 4000 kWh. CL-78, CL-8, CL-72, CL-76, CL-12, CL-81 and CL-25 can operate for 4 h, which belongs to complete recovery. For CL-45, there is still 200 kWh left, which is capable of running for 0.48 h and belong to partial recovery. Other critical loads cannot be restored. This process can achieve a recovery rate of 78.3% for hybrid AC/DC distribution networks.

6 | CONCLUSION

An optimal planning strategy for PV-ES-CS in hybrid AC/DC distribution networks considering normal operation conditions and resilience under extreme events is proposed in this paper. The bi-level planning model based on balanced variables accurately depicts the payment function under normal operation and extreme disasters, and the optimal configuration scheme of PV-ES-CS in a hybrid AC/DC distribution network is calculated by the genetic algorithm.

(1) The Nash equilibrium method is used to effectively deal with the difficulty in normalization between different objectives. Compared with the single consideration of economics or resilience, the effect is respectively increased by 63.33% and 62.29%.
(2) The flexible power transmission capability of the DC line is fully considered in the optimal configuration of PV-ES-CS. Compared with no interconnection line and through an interconnection switch, the comprehensive effect is improved by 30.85% and 24.21%, respectively. Moreover, the configuration strategy in this paper can also maintain good robustness when there is a fault in the DC line. Compared with the DC line without failure, the resilience is only reduced by 0.398%.
(3) The proposed method has wider applicability. It overcomes the limitation that the diversity of dimensions, time spans and probabilities when the economics and resilience need to be balanced. This method can be used in any allocation problem if the two objects have an opposite trend. Besides, PV-ES-CS can be replaced by other local power sources.

AUTHOR CONTRIBUTIONS

Ziyao Ma: Data curation; formal analysis; methodology; software; visualization; writing—original draft. **Lu Zhang**: Conceptualization; project administration; resources; validation; writing—review and editing. **Yongxiang Cai**: Investigation. **Wei Tang**: Funding acquisition; supervision. **Chao Long**: Writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data available in article supplementary material-The data that supports the findings of this study are available in the supplementary material of this article.

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APPENDIX

TABLE A1 Data of critical load.

Node number	Load size (kW)	Power losses (CNY/kWh)	Weight
CL-8	200	100	2
CL-12	45	150	5
CL-25	45	150	7
CL-45	420	90	8
CL-48	60	140	10
CL-64	60	140	9
CL-72	90	130	3
CL-76	90	130	4
CL-78	420	90	1
CL-81	60	140	6
CL-90	60	140	11
CL-101	60	140	12
CL-108	60	140	13

Abbreviation: CL, critical load.