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Distributed photovoltaic supportability consumption method considering energy storage configuration mode and random events

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In order to improve the control capability of distributed photovoltaic support, a distributed photovoltaic support consumption method based on energy storage configuration mode and random events is proposed. A networked and constrained parameter analysis model for distributed photovoltaic power supply control was constructed. Based on the direct flexible mode of optical storage, an AC/DC voltage level control model for distributed solar power supply control was constructed. In the operation mode of DC hybrid distribution network, the demand response tracking identification method was used to analyze the uncertain characteristic parameters of distributed solar power supply load, and combined with the planned energy storage capacity parameters, the distributed solar power supply load and photovoltaic output were estimated. By configuring the optimal energy storage capacity, adjusting the power distribution of the microgrid, and integrating the analysis of uncertain factors and random events in the energy storage configuration mode, the design of distributed photovoltaic support consumption has been achieved. The experimental results show that the distributed photovoltaic absorption control using this method has lower load requirements, can effectively reduce the exchange power of the interconnection line, and improve the configuration scale, system reliability, and economy of the photovoltaic energy storage system.

KEYWORDS

energy storage configuration mode, distributed photovoltaic, supportability consumption, DC hybrid distribution network, demand response, energy storage capacity

1 Introduction

With the popularization of distributed energy and power grid, people pay more attention to the research on distributed photovoltaic indemnificatory consumption. According to the energy characteristics of different regions and actual application scenarios, a distributed photovoltaic indemnificatory consumption model is established to reduce energy expenditure and improve the management level of distributed photovoltaic efficient consumption system structure and operation mode (Wang Chun et al., 2023). By theoretical analysis and experimental research, the research on distributed photovoltaic supportability consumption control under the constraints of energy storage configuration mode and random events is realized. According to the advantages analysis of power quality, power supply reliability and return on investment, the joint characteristic analysis method of photovoltaic power generation, energy storage coordination and DC mode is adopted to realize the comparative analysis of the cost and surplus grid access mode, and the dynamic analysis model of distributed photovoltaic supportability consumption is established. Combined with the dynamic scheduling of distribution network participants in major leagues (Zhihui et al., 2022). According to the analysis of the common characteristics of distribution network operators and multi-microgrids, the control ability of distributed photovoltaic supportability can be improved, and the adaptive control of consumption can be realized through the analysis of the cost of large alliance cooperative game mode. The research on related distributed photovoltaic supportability consumption methods is of great significance in promoting the clean energy construction of power grid and optimizing the network design (Xiang et al., 2021).

At present, the distribution scheme of Nash negotiation distribution mechanism is used to establish a distributed photovoltaic supportability consumption model, and the cooperative surplus is distributed by dynamic coupling control method. Combined with the analysis of the planar organizational structure characteristics of distribution network operators and multi-microgrid, the power flow parameter analysis model of load supply is constructed to improve the stability of distributed photovoltaic support. In reference (Dehghani Tafti et al., 2023), a distributed photovoltaic supportability consumption model based on the analysis of distribution network power flow and source-load uncertainty characteristics is proposed. The dynamic characteristics analysis of distribution network security and loss is adopted to realize the elimination of photovoltaic supportability, but this method has a big error in the analysis of two-stage stochastic optimization model. Reference (Pei et al., 2023) proposes a photovoltaic grid supportability consumption method based on the retail electricity price mechanism, which realizes photovoltaic supportability consumption control according to the transmission network loss estimation and the setting of the electrical distance between the two parties. However, this method has poor reliability in detecting and scheduling the source-load uncertain parameters of photovoltaic microgrid and low accuracy in detecting the source-load uncertain output (Yunfeng et al., 2016).

In response to the above issues, this article proposes a distributed photovoltaic guaranteed consumption method based on energy storage configuration mode and random events. The article considers the randomness of distributed photovoltaic systems themselves, and also delves into the impact of energy storage configuration modes, market electricity prices, electricity demand, and other external random events on system operation. At the same time, the article combines the analysis of planned energy storage capacity parameters to establish a load and photovoltaic output estimation model for distributed photovoltaic supporting consumption. This model can comprehensively consider the uncertain characteristic parameters of renewable energy output, provide accurate load and photovoltaic output prediction information for the system, and provide important support for the optimal configuration of energy storage equipment and the stable operation of the system. Experimental tests have shown that the method used in this article has good convergence in distributed photovoltaic consumption control, with a maximum load demand of only 12.346 KW and a lower load demand. It can effectively reduce the exchange power of parallel lines, improve the configuration scale, system reliability, and economy of photovoltaic energy storage systems.

2 Networking and constraint parameter analysis model of distributed photovoltaic supportability consumption control

2.1 Networking model of distributed photovoltaic supportability consumption control

In order to realize the construction of distributed photovoltaic indemnificatory consumption model with energy storage configuration mode and random events, firstly, the network structure model of distributed photovoltaic indemnificatory consumption control is constructed, and the network parameter analysis model is established by considering the risk loss model parameter analysis of multi-microgrid, combining with the participant benefit settlement and market clearing analysis (Zou et al., 2018). When the energy storage battery needs to meet the charging and discharging power constraints, the distribution of distributed photovoltaic indemnificatory consumption control nodes is obtained as shown in Figure 1.

According to the distribution model of the distributed photovoltaic power supply control nodes shown in Figure 1, the load characteristics of users, and the power scheduling method, and based on the power consumption characteristics of users, a scheduling priority model for distributed photovoltaic power supply water is obtained, as shown in Formula 1:

$$c_k = \begin{cases} x_k \, if \quad m_k + U(-1,1)^* (m_k - l_k) < x_k \\ \bar{x}k \quad if \quad m_k + U(-1,1)^* (m_k - l_k) > \bar{x}_k \\ m_k + U(-1,1)^* (m_k - l_k) \quad otherwise \end{cases} \tag{1}$$

where, $k = 1, 2, \ldots, n, U(-1,1)$ indicates that the user's load elasticity is between (−1,1). The dynamic scheme of microgrid power purchase for load power supply is analyzed, and the factors such as load elasticity, credit and power generation ratio are comprehensively considered, and the correlation coefficient between user's load characteristics and power dispatching is expressed by U, Based on the actual load transfer during peak hours in historical dispatching, it is obtained that the dynamic correlation matching coefficient of distributed photovoltaic supportability is $a = \frac{s}{n}, \mathrm{b} = \frac{f}{n}, \mathrm{c} = {p}/{n},$ and then a, b, c are respectively called the fusion parameters such as the same degree, differences and oppositions in the supportability of distributed photovoltaics are used to obtain optimized allocation values, as shown in Formula 2:

$$u_{AB} = a + bi + cj \tag{2}$$

where, $a + b + c = 1$. According to the above analysis, a credit analysis and consumption control networking model of users' participation in demand response is constructed, and the

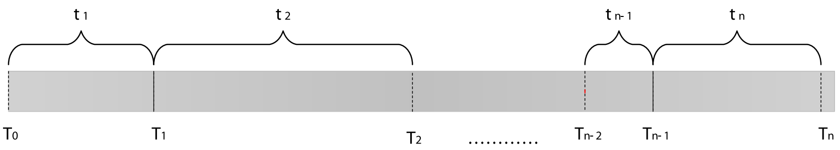

FIGURE 1
Distribution of distributed photovoltaic supportable consumption control nodes.

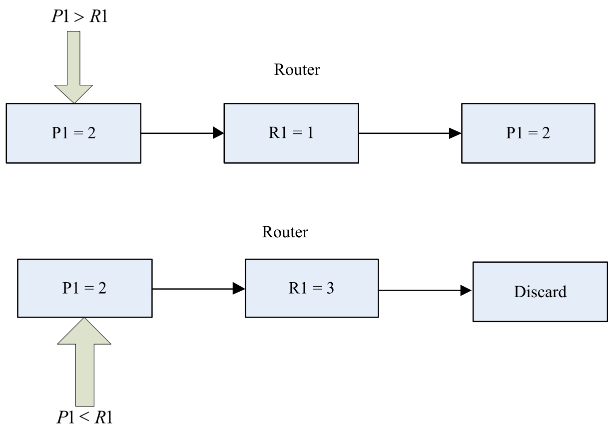

FIGURE 2
Framework of point-to-point electric energy transaction in distribution network.

TABLE 1 Analysis model of driving parameters of photovoltaic distribution network.

Items	Parameters	Unit
Working frequency	117.624	KHz
High frequency isolation transformer parameters	0.225	—
Equivalent crystal oscillator	23.525	H
Historical current source value	12.252	mH
Secondary current	235.248	A
Output dynamic range	−70~+70	dB

dynamic adjustment of distributed photovoltaic consumption is realized by combining the ratio equilibrium distribution of expected transfer quantity (Sun, 2011).

2.2 Analysis of constraint parameters of distributed photovoltaic supportability consumption

In the operation mode of DC hybrid distribution network, the characteristic parameters of source-load uncertainty in the process of distributed photovoltaic consumption are analyzed by demand response tracking identification method, and the target weight of load correlation after demand response is constructed by combining with the parameter analysis of planned energy storage capacity, as shown in Formula 3:

$$w^{k-1} = \left(w_1^{k-1}, w_2^{k-1}, \cdots, w_m^{k-1}\right)^{\mathrm{T}} \tag{3}$$

In order to avoid the shadowing caused by the linear normalization of index values, the cluster analysis is carried out on n consumption elements of distribution network in the kth floor, and the parameters of demand response dynamic allocation model are obtained according to the discount electricity price analysis in normal and valley periods, as shown in Formula 4:

$$\rho(\mathbf{G}) = \inf\{\lambda \mid \mathbf{G}\mathbf{v} \le \lambda\mathbf{v}, \text{For certain } \mathbf{v} > \mathbf{0}\} \tag{4}$$

Considering the demand response and the uncertainty of source and load, the inertia dynamic distribution variables λ and $\mathbf{v}$ are introduced to cluster the operation scenarios of microgrid considering the uncertainty of source and load, and the process state parameters of distributed photovoltaic supportability consumption constraint are obtained as shown in Formula 5:

$$\begin{array}{ll} \min & \lambda \\ & \mathbf{G}(\mathbf{s})\mathbf{v} \le \lambda\mathbf{v} \\ s.t. & \sum_{l=1}^{L} s_l = \Gamma \\ & \mathbf{b} \le \mathbf{s} \le \mathbf{u} \\ \text{var:} & \mathbf{s}, \mathbf{v}, \boldsymbol{\lambda} \end{array} \tag{5}$$

However, due to the convergence of the initial electricity price and the initial load, it is obtained that the outer capacity distribution of the energy storage system meets $\sum_{l=1}^{L} s_l = \Gamma$, and the space planning algorithm is adopted to guide the main body of the microgrid to meet the power flow constraint, and the configuration model of distributed photovoltaic energy storage in the coordinated win-win mode for all participants is obtained as $g(\mathbf{s}) = \sum_{l=1}^{L} s_l$, so that a monomial $\tilde{g}(\mathbf{s})$ can be represented by Formula 6:

$$g(s) \ge \tilde{g}(s) = \prod_{l=1}^{L}\left(\frac{s_l}{\alpha_l}\right)^{\alpha_l} \tag{6}$$

According to the above analysis, in the operation mode of DC hybrid distribution network, the characteristic parameters of source-load uncertainty in the process of distributed photovoltaic consumption are analyzed by demand response tracking identification method, and the load and photovoltaic output estimation model of distributed photovoltaic supportability consumption is established by combining with the parameter analysis of planned energy storage capacity (Yunfeng et al., 2021).

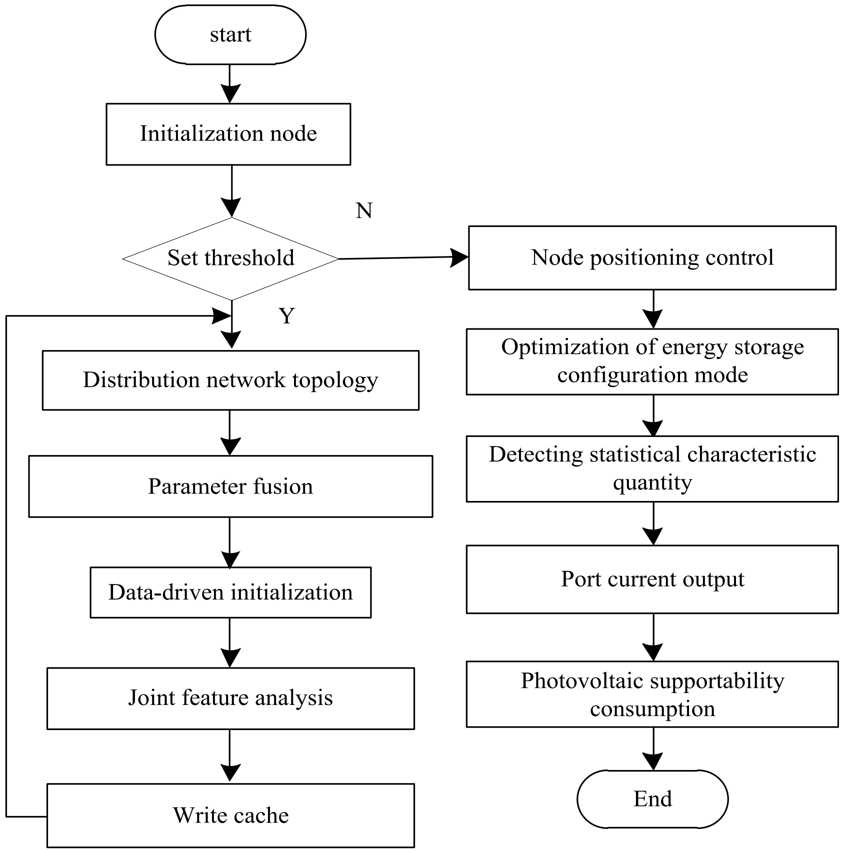

FIGURE 3
Implementation flow chart.

TABLE 2 Simulation scenes and parameters.

Parameters	Value	Parameter	Value
High/low voltage winding	2.54	Field current	23 mA
Maximum moment position of magnetic density	(0,3)	Load	150 KW
Poisson's ratio of winding cake	0.654	Weaken	0.832 pJ/(bit·m^4)
switching frequency	1600 Hz	Data-driven weight coefficiant w	1.31

3 Distributed photovoltaic supportability consumption optimization

3.1 Load and photovoltaic output estimation of distributed photovoltaic supportability consumption

With the objective function of guiding the main body of microgrid to meet the power flow constraints, the load and photovoltaic output estimation model of distributed photovoltaic indemnificatory consumption is established (Chen et al., 2022). In order to ensure the safety and economic benefits of distribution network, the framework structure of point-to-point electric energy transaction of distribution network is constructed, as shown in Figure 2.

Since microgrid may be distributed at different nodes in the distribution network, if the fitness function of dynamic programming under the second-stage income distribution mechanism is set, then in the sense of first-order Taylor approximation, the distribution network has the ability of reactive power optimization, and the distribution network node set is obtained by using the dynamic subspace fusion mechanism, and the nearby $\alpha_l(k) = s_l(k-1)/\sum_i s_i(k-1)$ satisfies the convergence solution, and the convergence parameter of distribution network power flow constraint is $\tilde{g}(\mathbf{s})$, and the branch terminal node set with J as the first-end node is the convergence solution, and $g(\mathbf{s}(k)) = \tilde{g}(\mathbf{s}(k))$ is obtained. By

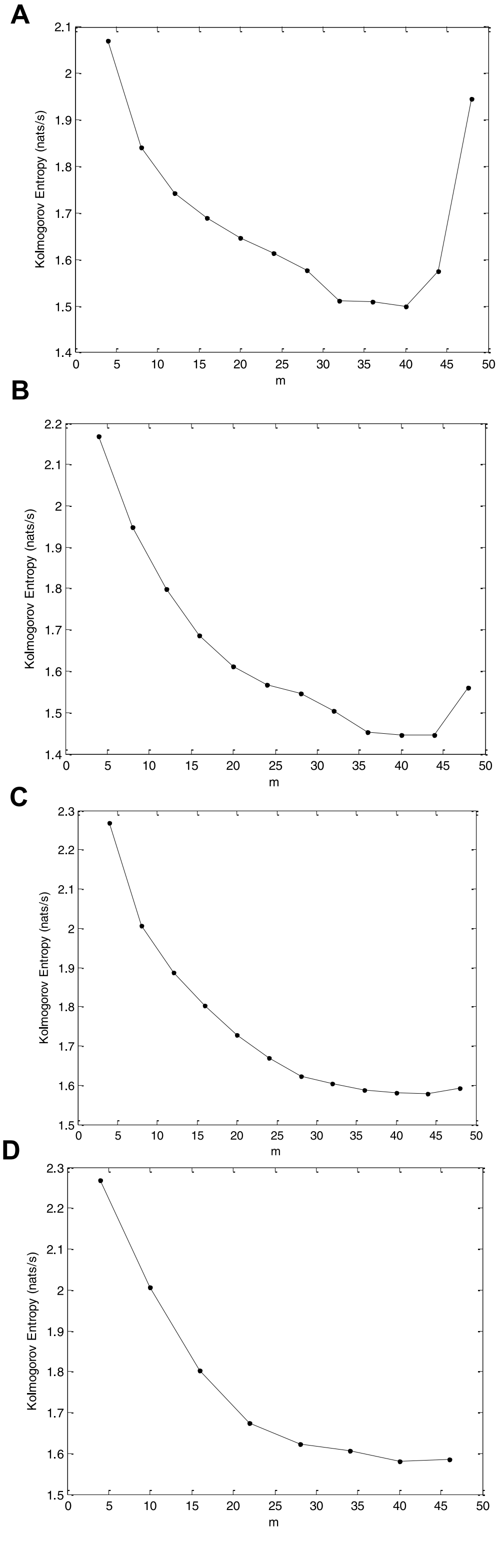

FIGURE 4
Results of consumption control under different configuration model parameters. **(A)** m=4, τ=12. **(B)** m=4, τ=15. **(C)** m=4, τ=10. **(D)** m=5, τ=10.

using the differentiated characteristic decomposition model, it is obtained that the approximate problem satisfies the feasible characteristic solution: $g(\mathbf{s}(k)) = \tilde{g}(\mathbf{s}(k))$ represents the active and reactive power on branch ij in T period (Yang et al., 2022). The output of reactive power compensation device in distribution network meets the approximate sequence convergence condition. Combined with the parameter analysis of planned energy storage capacity, the load and photovoltaic output estimation model of distributed photovoltaic supportability consumption is established, and the load and photovoltaic output estimation of distributed photovoltaic supportability consumption is realized according to the uncertainty characteristic parameter analysis of renewable energy output (Yunfeng et al., 2017).

3.2 Distributed photovoltaic supportability consumption and optimization of energy storage configuration mode

The distribution matrix of energy storage equipment charging and discharging satisfying constraint conditions is introduced as shown in Formula 7:

$$\varsigma = \left(s_{ij}\right)_{m\times n} \tag{7}$$

wherein, $s_{ij} = \begin{cases} d_{ij}/\theta_{i,} & Benefit\ index \\ \theta_i/d_{ij,} & Cost\ index \end{cases}$, which indicate the charging and discharging state value of energy storage, with 0 being off and 1 being on.

According to the above analysis, the parameters of the capacitor bank operation model are analyzed, and the operation goal of the microgrid surplus on-grid mode is to maximize the distribution weight matrix $w^k = (w_1^k, w_2^k, \cdots, w_m^k)^{\mathrm{T}}$ and the analysis model of the power sold and purchased by the microgrid to the distribution network is constructed. The microgrid is an active participant in the distributed power transaction, and the consumption evaluation matrix is obtained according to the risk cost analysis of multi-microgrid interaction, and the formula is as shown in Formula 8:

$$\begin{aligned} E = w^k \cdot \varsigma = (e_1, e_2, \cdots, e_n) \\ = (w_1, w_2, \cdots, w_m) \cdot \begin{bmatrix} s_{11} & \cdots & s_{1n} \\ \vdots & \ddots & \vdots \\ s_{m1} & \cdots & s_{mn} \end{bmatrix} \end{aligned} \tag{8}$$

where, $e_j = \sum_{k=1}^{m} w_k \cdot s_{kj}$. To sum up, considering the source-load uncertainty risk, combined with the optimization of energy storage parameter configuration, and based on CVaR stochastic programming, the neighborhood $neighbor(L_i) = \{L_{i1}, L_{i2}\}$ of distributed photovoltaic supportability evaluation is obtained, as shown in Formula 9:

$$\begin{aligned} i1 &= \begin{cases} i-1 & i \neq 1 \\ CL & i = 1 \end{cases} \\ i2 &= \begin{cases} i+1 & i \neq C_L \\ 1 & i = C_L \end{cases} \end{aligned} \tag{9}$$

According to the fusion analysis of uncertain factors of energy storage configuration mode and random events (Zhang et al., 2019), the design of distributed photovoltaic supportability is realized, and the data amount of regional network adjustment is obtained as shown in Formula 10:

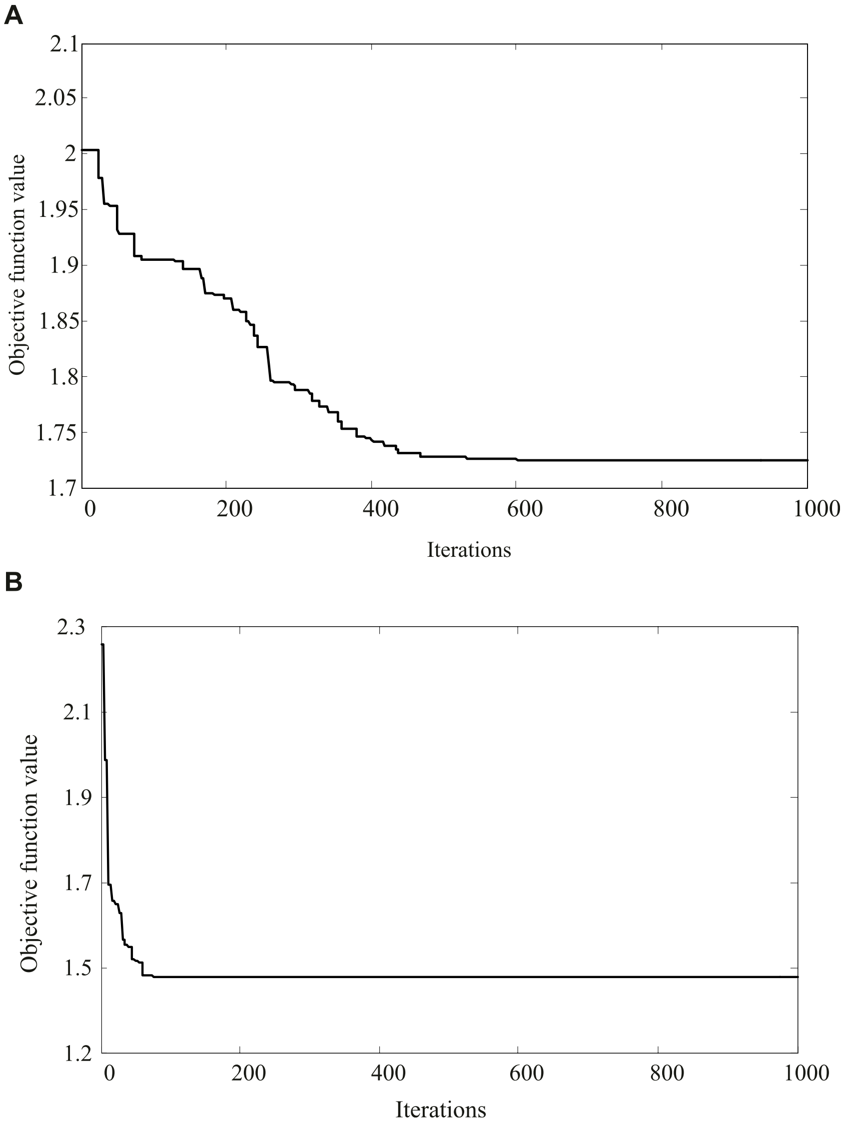

FIGURE 5
Comparison of convergence of consumption control with different methods. **(A)** Traditional method. **(B)** This method.

TABLE 3 Comparison of load demand (KW).

Test object	Reference (Dehghani Tafti et al., 2023)	Reference (Pei et al., 2023)	This method
Grid 1	20.649	15.069	7.614
Grid 2	26.227	13.831	7.029
Grid 3	26.708	14.559	7.754
Grid 4	27.145	13.489	11.748
Grid 5	28.250	12.170	10.365
Grid 6	25.782	11.377	9.610
Grid 7	25.903	12.100	9.728
Grid 8	24.398	11.784	9.163
Grid 9	25.095	14.953	12.346
Grid 10	21.663	13.730	6.237

TABLE 4 Exchange power reduction rate of the contact line (%).

Number of iterations/times	Reference (Dehghani Tafti et al., 2023)	Reference (Pei et al., 2023)	This method
10	45	30	65
20	44	32	64
30	46	31	70
40	45	32	69
50	42	29	68
60	41	28	72
70	40	26	70
80	39	30	69
90	38	31	68
100	40	33	66

$$G = \frac{1}{N}\sum_{k=1}^{N}\left[x_k - \frac{1}{N}\sum_{k=1}^{N}x_k\right] \tag{10}$$

wherein, N is the characteristic matching point of machine variable ζ and dispatching decision variable x, x_k is the caused network loss and voltage deviation, and it is divided into the characteristic distribution set $D_{R_f} = \sum_{j=1}^{L} I_j{}^{R_f}\ (j = 1, 2, ..., L)$ of participant interest settlement and market clearing. After calculating the network fee Cnet, the cooperative benefits of multi-microgrid alliance are as shown in Formula 11:

$$K = 1/\left\|x_L^i - x_S^i\right\| \tag{11}$$

wherein, x_L^i is the number of active power constraints of distribution network nodes, and x_S^i is the adjustment component of distribution network power flow constraints that are non-convex nonlinear constraints. Based on the parameter analysis of cooperative alliance cost minimization model, combined with the above analysis, according to the uncertainty characteristic parameter analysis of renewable energy output (Athari and Wang, 2018), the optimal capacity of energy storage is configured to fully adjust the power distribution of microgrid. The Pswarm algorithm searches the optimal solution by simulating the behavior of flock foraging. The particles search in a global range for the globally optimal solution. In the PSO algorithm, the underlying solution of each optimization problem is treated as a "particle" that moves in a multidimensional search space to find the optimal solution. At the core of the particle swarm algorithm is the velocity and position update formula of the particles.Suppose that in a D-dimensional search space, the position of particle i is expressed as $x_i = \{x_1, x_2, \cdots, x_D\}$,The speed is expressed as $v_i = \{v_1, v_2, \cdots, v_D\}$.Each particle has an individual optimal position $pbest_i = \{p_1, p_2, \cdots, p_D\}$, and the global optimal locations for the entire population $gbest_i = \{g_1, g_2, \cdots, g_D\}$ (Sun et al., 2022; Dehghani Tafti et al., 2022; Zheng et al., 2023).

The speed and position of particle i are updated in each iteration with mathematical expressions as shown in Formula 12:

(1) Speed update formula:

$$v_{id}^{k+1} = v_{id}^{k} + c_1 rand_{1,d}^{k}\left(pbest_{id}^{k} - x_{id}^{k}\right) + c_2 rand_{2,d}^{k}\left(gbest_{id}^{k} - x_{id}^{k}\right) \tag{12}$$

wherein, c_1、c_2 is the learning factor, $rand_{1,d}^{k}$、$rand_{2,d}^{k}$ is the random number between [0,1], v_{id}^{k} is the velocity of the particle i in dimension D at the k-th iteration.

(2) Position-based update formula as shown in Formula 13:

$$x_{id}^{k+1} = x_{id}^{k} + v_{id}^{k+1} \tag{13}$$

wherein, x_{id}^{k} is the position of the particle i in the dimension D at the k -th iteration.

In each iteration, the velocity and position of the particles are updated according to the above formula, until the maximum number of iterations is satisfied, the iteration is stopped, and the global optimal solution is output (Ge et al., 2022; Rekioua, 2023; Zhou et al., 2024).

And the design of distributed photovoltaic supportability is realized according to the fusion analysis of energy storage configuration mode and uncertain factors of random events. The implementation flow is shown in Figure 3.

4 Experimental test

In order to verify the performance of this method in realizing distributed photovoltaic indemnificatory consumption control, experimental tests are carried out. The distribution dimension of electromagnetic parameters of distribution network is 120, the characteristic coefficient of winding that microgrid can't match at the same time is 0.25, the power frequency excitation coefficient is 0.182, the minimum load is 14267 MW, the reliability index parameter of historical output sequence is 0.034, the coil current at Tk time is 24 mA, and the confidence level is 0.95. See Table 1 for the analysis model of driving parameters of photovoltaic distribution network.

According to the experimental scenes and parameter settings in Tables 1, 2, the simulation experiment of distributed photovoltaic supportability consumption estimation is run, and the consumption control results under different configuration model parameters are given, as shown in Figure 4.

From the analysis of Figure 4, it is known that the optimal configuration parameters of consumptive energy storage are m = 4 and m = 10 considering the installed capacity, energy storage capacity and comprehensive cost of the system. On this basis, different methods are adopted to realize the consumptive convergence analysis of distributed photovoltaic protection, and the comparison results are shown in Figure 4. And the convergence value is not as ideal as the method in this paper.

From the analysis of Figure 5, it is known that the method in this paper has good convergence in distributed photovoltaic consumption control, and the load demand is tested, and the comparison results are shown in Table 3.

According to Table 3, the highest load demand of this method is only 12.346 KW, while the highest load demand of literature (Dehghani Tafti et al., 2023) and literature (Pei et al., 2023) is 28.250 KW and 15.069 KW. It shows that the load demand of this method is low, which can effectively reduce the exchange power of parallel lines, and improve the configuration scale, system reliability and economy of photovoltaic energy storage system.

To further verify the effectiveness of this method, the reduction rate of exchange power will be analyzed, and the results are shown in Table 4 below.

According to Table 4, the highest reduction rate of this method reached 72%, while the highest load demand of literature (Dehghani Tafti et al., 2023) and literature (Pei et al., 2023) reached 46% and 32%. Moreover, with the increase of iterations, the reduction rate of the method fluctuates slightly, but remains stable overall, indicating that the method can maintain good performance in many cases. This shows that the method proposed in this paper is more effective in optimizing the energy management and energy storage configuration of distributed PV systems.

5 Conclusion

This article proposes a distributed photovoltaic guaranteed consumption method based on energy storage configuration mode and random events. A networked control model for distributed photovoltaic guaranteed consumption was constructed, combined with the direct flexible mode of optical storage, and an AC/DC voltage level control model was established. The demand response tracking method of DC hybrid distribution network was used to analyze the uncertainty characteristic parameters of source load. A load and photovoltaic output estimation model was established based on the planned energy storage capacity parameters. To address the uncertainty of renewable energy output, allocate the optimal energy storage capacity to adjust the power distribution of microgrids. By integrating the energy storage configuration mode with the uncertainty factors of random events, the optimization design of distributed photovoltaic guaranteed consumption has been achieved. By integrating the energy storage configuration mode with the uncertainty factors of random events, this method can adapt to different operating conditions and demand changes, and has high flexibility. The experimental results show that the method has good convergence in distributed photovoltaic consumption control, with a maximum load demand of only 12.346 KW and a low load demand. The maximum reduction rate of the method proposed in this paper reaches 72%, and although the reduction rate fluctuates slightly with the increase of iteration times, it remains stable overall, indicating that the method can maintain good performance in various situations. Although the method proposed in this article performs well in reducing the exchange power of interconnection lines and improving the self-sufficiency of distributed photovoltaic systems, configuring a larger capacity energy storage system may increase the initial investment cost of the system. Cost benefit analysis is a key factor to consider in practical applications.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

YC: Writing–original draft, Writing–review and editing. GY: Writing–original draft, Writing–review and editing. YY: Writing–original draft, Writing–review and editing. YZ: Writing–original draft, Writing–review and editing. TZ: Writing–original draft, Writing–review and editing. XC: Writing–original draft, Writing–review and editing.

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Conflict of interest

Authors YC, GY, YY, YZ, TZ, and XC were employed by State Grid Shanxi Electric Power Company Yuncheng Power Supply Company.

Publisher's note

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