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RESEARCH ARTICLE

# Research on System Resource Optimization of Distribution Network Producer-Consumer System Considering Resilience and Economy

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**ABSTRACT** This article proposes a resource optimization strategy for the production-consumption system of a distribution network, which is based on both resilience and economic efficiency of electrical networks in the face of typhoon impacts. Firstly, based on the concept of producer-consumer groups, this paper has constructed a Distribution Network producer-consumer system (DN-PCs) unit model, including energy consumption, system control, and end-user loads. At the same time, this paper has put forward models for typhoon-distribution network line faults, resilience curves, and a resilience evaluation process to quantify resilience indicators of the distribution network. Furthermore, a multi-objective optimization model is developed with the objectives of minimizing economic losses and maximizing resilience indicators. The model is solved using the elitist mechanism Non-dominated sorting genetic algorithm (NSGA-II) and membership degree function to obtain compromise solutions. Finally, to validate the effectiveness of the proposed strategy, this paper has conducted a simulation analysis, take the IEEE 33-node system as an example. The results demonstrate that it is practical to enhance the resilience of electrical networks against typhoon disasters and improve the power supply capacity by configuring PCs units and controlling different flexible loads in the distribution network. Meanwhile, this strategy can improve the economic efficiency of the system. In the future, this strategy will provide power companies with a solution to enhance the power supply capacity of distribution networks.

**INDEX TERMS** Resilient power grid, producer-consumer system, distribution network, optimization of system resources, NSGA-II.

## I. INTRODUCTION

Power systems have been increasingly affected by various natural catastrophes and extreme events like man-made attacks in recent years due to global climate change and the complicated international political situation. Power system stability and societal stability have been seriously impacted by the growing frequency of various small-probability-high-risk hurricane weather catastrophes [1], [2]. In ten out of the eleven years between the years 2011 and 2021, more than 10 million consumers of electricity in the United States experienced power outages because of extremely bad hurricane weather. Denmark, Finland, Iceland, Norway, and Sweden—30% to 60% of power outages are attributed to extreme hurricane weather, according to a study by the European Network of Transmission System Operators for Electricity (ENTSO-E) [3].

Fig.1 shows the number of typhoons generated in the Western Pacific Ocean that landed in China from 2000 to 2020. According to the maximum average wind speed near the center of the typhoon bottom layer, it is divided into four levels: Less than 32m/s (Tropical storm), 32m/s-41m/s (Typhoon), 41m/s-50m/s (Violent typhoon) more than 50m/s (Super typhoon). As can be seen, it is essential to address how to increase the stability of electricity networks following storm disruptions at this time. In order to create resilient grid, many academics have introduced the idea of resilience into the grid.

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Resilience is a term used in materials science to describe a material's capacity to recover its initial structure following deformation [4].In terms of power networks, resilience power grid means that it can perceive the operation situation of power grid comprehensively, quickly and accurately, and cooperate with power supply Internal and external resources, active prediction and preparation of various disturbances (Natural and man-made disasters), active defense, A grid that quickly restores critical power loads and can self-learn and continuously upgrade [5]. Although the likelihood of severe events is low, measuring the capacity of the power system to withstand them has become a focus of study in recent years. The resilience curve is one method of depiction that has gained widespread acceptance [6]. The resilient grid curve reflects the ability of the power system to adjust its operation to reduce load loss during a fault and restore to its original operating state as soon as possible after the disturbance is over, in the event of extreme disaster disturbances and severe faults [7]. The specific process is shown in Fig.2: Prior to an incident, the grid system is maintained at normal levels. Following an extreme event, system functionality rapidly declines and is maintained at fault level, where the red line represents the system fault level. Implementation of restoration measures may improve system functionality to some extent, but may not reach pre-incident normal levels, due to possible damage to the relevant infrastructure. As the relevant infrastructure is restored, the grid reaches normal operating levels. In Fig.2, The shaded area indicates the level of resilience of the power system in response to that extreme natural hazard event; improving the resilience of the distribution network means reducing the shaded area.

Efforts have been made both domestically and internationally to enhance and evaluation the resilience of distribution networks, aiming to better withstand extreme events. In [8], distribution network resilience is strengthened by means of line reinforcement, double-circuiting, and reduced fault repair times, tailored to the hurricane's intensity and load level. In [9], a model for stall spacing and tower planning has been developed to enhance the network's hurricane resistance and improve its overall resilience. In [10], a multi-level, two-layer model for cyber-physical collaborative recovery is established, based on network flow theory, to enhance distribution network resilience from a recovery perspective. In [11] and [12], An optimal power usage scheduling in Smart Grid Integrated with Renewable Energy Sources for Energy Management, this method adjusted the relationship between economic and reliability. In [13], a decision method for the coordinated operation of distribution networks is proposed, balancing economy and reliability constraints by assigning different weights to the different demands of network operation under varying conditions. However, the literature does not take into account strategies for improving network resilience under unexpected conditions. In literature [14], [15], [16], [17], strategies such as distributed energy storage, strengthening distribution network infrastructure, distributed generation, and UAV restoration of distribution network communication are proposed to enhance the resistance of distribution network.

In literature [18], the author constructed a PV production and marketing model under the constraint of distribution network, through the reasonable dispatch of prosumers, the original volatile outputs of renewable energy can be stabilized, and the elasticity and resilience of the power systems can be improved. In literature [19], the author proposed a cooperative framework model between the distribution network and the transportation network under extreme conditions. He made good use of autonomous vehicles and shared vehicles as energy storage units to restore the power supply capacity of the distribution network after extreme events, so that both the distribution network and the transportation network could achieve a win-win situation. The major weaknesses of studies carried out so far are as follows:

(a) Many scholars have focused on improving the resilience of power grid from a supply-side perspective by transforming lines, replacing overhead lines with cables, and other conventional methods. However, the economic costs associated with these solutions are high and they do not effectively reduce the redundancy of the distribution network.

(b) Most assessments of distribution network resilience are conducted using conceptual or qualitative methods, which fail to quantify network resilience or establish a reasonable assessment system. This limits the accuracy of any enhancements made to the distribution network's resilience.

(c) Comprehensive studies of distribution network resilience are lacking, with most focusing solely on improving the recovery ability of the network during natural disasters and targeting only a single aspect of the network.

(d) Weather conditions are not taken into account when assessing the resilience of distribution networks.

(e) Economic factors are not considered in these assessments.

Based on the concept of Producer-Consumer systems (PCs) [20], this paper proposes a resource optimization method for enhancing the resilience of distribution networks against the impact of hurricane disasters, called the Distribution Network Producer-Consumer system (DN-PCs). The proposed DN-PCs optimization strategy not only further improves the power supply capacity of the distribution network, but also considers operational economy. Resilience curves are quantified, and a more accurate distribution network resilience assessment system is established.

## II. DISTRIBUTION NETWORK STRUCTURE DIAGRAM AND HURRICANE MODEL BASED ON PRODUCER AND MARKETER GROUP

### A. STRUCTURE DIAGRAM OF DISTRIBUTION NETWORK PRODUCER-CONSUMER SYSTEM GROUPS

The DN-PCs framework is depicted in Fig.3, with the system comprising of a distribution network, producer-consumer group, and traditional load. Within the constructed system, each producer and consumer group incorporates an energy production and consumption component as well as a User

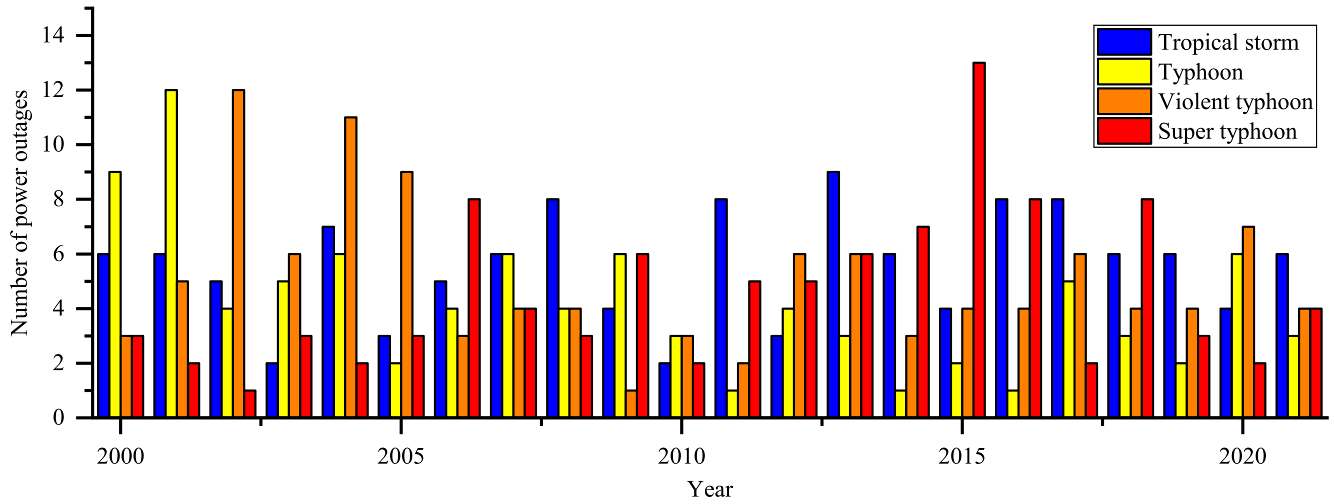

**FIGURE 1.** The number of large-scale power outages caused by different grades of typhoons in pacific coastal countries from 2000 to 2020.

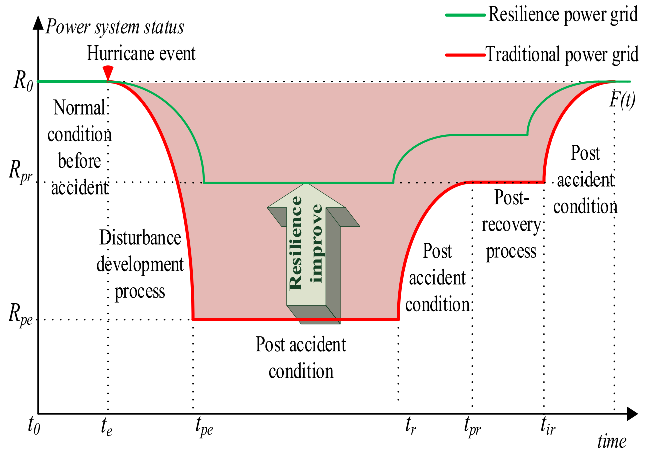

**FIGURE 2.** Resilience curves of distribution networks under natural disasters.

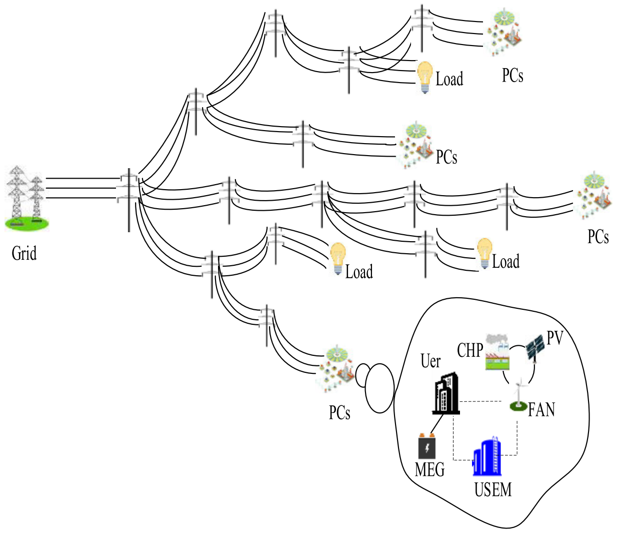

**FIGURE 3.** Distribution network-producer consumer system.

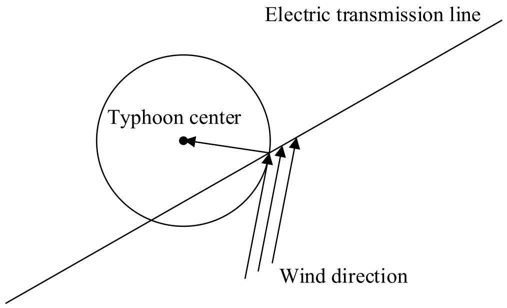

**FIGURE 4.** The relative location schematic diagram of lines and typhoon.

Energy Management System (USEM). The USEM facilitates the user's ability to purchase electricity from the upper grid, and also enables them to supply electricity to the upper grid in the case of extreme events resulting in supply constraints in the distribution network. The group of producers and consumers encompasses photovoltaic (PV), wind power (FAN), and mobile emergency generators (MEG), while the energy consumption component comprises conventional loads.

The paper has three key assumptions:

(a) the research focus is on the distribution network, with an emphasis on optimizing supply and demand side resources. As such, the transportation network is not taken into account in the modeling process.

(b) this paper differs from traditional line maintenance methods, instead utilizing resources such as MEG, FAN, PV, and backup power equipment to enhance the load resilience of the distribution network system. These resources enable prompt power provision at failure points following a disaster, with the paper quantifying distribution network system resilience primarily based on load recovery amount, without considering load recovery time.

(c) the paper assumes that the power grid company has established long-term contracts with users who can participate in the dispatch project. The contract specifies that during extreme natural disasters, the power grid company can optimize control of the controllable load component according to need and compensate participating controllable loads via low price discounts.

### *B. SET OF DISTRIBUTION NETWORK FAULT SCENARIOS UNDER HURRICANE DISASTERS*

As natural disasters occur infrequently, it is challenging to assess the effectiveness of distribution network regulation through a large number of actual fault cases as is done for reliability. In the DN-PCs resource optimization model, the construction of the model relies on a real-time line failure rate model under hurricane disasters. Probability methods are employed to generate a set of failure scenarios for the distribution network, which are then analyzed and evaluated to determine the network's resilience. As demonstrated in [21], the fault occurrence of a particular line at a given time is determined by the vertical wind speed affecting the line.

$$\begin{aligned} V_w(t) &= V(t)\sin\beta(t) \\ &= (A_1\exp(-((x-\mu_x(t))^2+(y-\mu_y(t))^2)/2\sigma_2^2) \\ &\quad - A_2\exp(-((x-\mu_x(t))^2+(y-\mu_y(t))^2))/2\delta_2^2) \\ &\quad \times \sin\beta(t) \end{aligned} \tag{1}$$

where $V_w(t)$ is the vertical effective wind speed of the line; $\mu_x(t)$, $\mu_y(t)$ is the coordinate of the hurricane center at time t; x, y are the transmission line coordinates; $V(t)$ is the wind speed of the line at time t; $\beta(t)$ is the angle between the line and the wind direction at time t; $A_1, A_2$ is the maximum wind speed coefficient; $\sigma_1, \sigma_2$ is the attenuation coefficient corresponding to the maximum wind speed coefficient, which is generally required: $A_1 > A_2, \sigma_1 > \sigma_2$

$$\lambda(t) = \lambda_p(t)L = \exp(aV_w(t)/V_d + b)L \tag{2}$$

$\lambda_p(t)$ is the outage rate of the line at time t, the unit is 1/(100km.h); $V_d$ is the line design wind speed, the unit is (m/s);a, b is constant, which can be found by statistical analysis of historical data.

The probability [21] that a transmission line fails over a period of time can be expressed as:

$$P(t_m) = 1 - \exp(-\int_0^{t_m} \lambda(t)dt) \tag{3}$$

$P(t_m)$ is the probability that a transmission line fails over a period of time $t_m$; $\lambda(t)$ is the outage rate of a certain segment of transmission line of length L at time t.

From equation 1, 2 and 3, it is evident that the failure rate of a given transmission line can be calculated by simulating various wind speed values. By simulating the sampling of different wind speeds, failure scenario sets of the distribution network under different weather conditions can be generated.

## III. OBJECTIVE FUNCTION AND CONSTRAINTS

In the context of improving the resilience of the distribution network with minimal economic cost under the influence of extreme weather, there exist two independent objectives: the first objective is to maximize the resilience of the distribution network, while the second objective is to minimize the fixed and variable costs (including investment, maintenance, and operation costs) of DN-PCs. These objectives need to be optimized while considering the constraints of the problem.

$$\min f = (-F_1, F_2) \tag{4}$$

($F_1$) is the resilience index function and is a dimensionless unit;($F_2$) is the economic objective function and unit is the RMB.

### *A. FIRST OBJECTIVE FUNCTION*

In the process of assessing distribution network resilience, the resilience objective function for the distribution network decreases with the increase in the amount of load lost to customer loads during hurricane weather, and vice versa. Hence, the resilience objective function can be expressed as follows:

$$\max F_1 = R = P_0/M\sum\nolimits_{i=1}^{M}\Delta P \tag{5}$$

$$\Delta P = \sum\nolimits_{i\in s}\varepsilon_i P\left(X_i\right) \tag{6}$$

where, $\Delta P$ is the total load loss for each class of load in a given scenario; s is the important load set; $X_i$ is a failure scenario of extreme events; $\varepsilon_i$ is the significant load factor of node $i$,the larger the load, the more important it is;$M$ is the sampling times of fault scenarios; $P_0$ is the initial total load weighted by load nodes when the distribution network system is in normal operation;$R$ is the ratio of the mean value of end-user load lost in the failure state of each scenario to the initial total load in the normal state, and the larger the value is, the greater the resilience of DN-PCs in the distribution network.

### *B. SECOND OBJECTIVE FUNCTION*

In the optimization model of DN-PCs, the economic objective function mainly comprises the cost of grid emergency resource scheduling, end-user load loss cost, and operation and maintenance cost of MEG. Therefore, the mathematical description of the second objective function is as follows:

$$\min F_2 = \min\{C_{\cos}^{DR} + C_{out}^{user} + C_m^{moile}\} \tag{7}$$

where, $C_{\cos}^{DR}$ is the dispatching cost of the grid company and users who can participate in the demand response (DR) project in case of typhoon failure; $C_{out}^{user}$ is the cost of economic loss caused by the end user not working properly;$C_m^{moile}$ is the maintenance cost invested in emergency power generation of DN-PCs units:

#### 1) OPERATION AND MAINTENANCE COST OF MEG

$$C_m^{moile} = \lambda_n \sum\nolimits_{\mathrm{m}}^{M}\sum\nolimits_{i}^{\Omega_N} c_m\alpha_{m,i} \tag{8}$$

$\lambda_n$ is the unit of operation and maintenance cost per unit capacity of MEG Yuan/kw; $c_m$ is the capacity of the $m_{th}$ MEG, unit kw; $\alpha_{m,i}$ is a binary variable; $\alpha_{m,i} = 1$ or 0 is represents whether node $i$has deployed the $m_{th}$ MEG; $\Omega_N$ is a node set of DN-PCs; $M$ is the total number of generators.

### 2) END-USER LOAD LOSS COSTS

$$\begin{aligned} C_{out}^{user} = &\sum\nolimits_i^{\Omega} \omega_{out.i} \bullet \sum\nolimits_t^{T} \\ &\times (\sum\nolimits_a^{\Omega_r} P_{r,a,i}^t + \sum\nolimits_a^{\Omega_g} P_{g,a,i}^t - P_i^t - P_{pv,i}^t \\ &- P_{fan,i}^t - \sum\nolimits_k^{\Omega_{CHP}} P_{out,k,i}^{CHP} + \sum\nolimits_k^{\Omega_{CHP}} P_{in,k,i}^{CHP}) \end{aligned} \tag{9}$$

where, $\omega_{out.i}$ is the cost of power outages due to natural disasters at node $i$ of the DN-PCs unit Yuan/kw; $P_i^t$ is the active power demand of node $i$ in the DN-PCs at time t after the disaster; $P_{pv,i}^t$ is the output power of the $\mathrm{K_{th}}$ PV in node i of the DN-PCs at time t; $P_{fan,i}^t$ is the output power of the $K_{th}$ wind power generation in node $i$of the DN-PCs at time t; $P_{out,k,i}^{CHP}$ is the output power of the $K_{th}$ CHP unit in node $i$ of the DN-PCs at time t; $P_{in,k,i}^{CHP}$ is the power consumed by the $K_{th}$ CHP unit in the node $i$of the DN-PCs at time t; $P_{r,a,i}^t$ is the rigid load demand of node $i$ at time t;$P_{g,a,i}^t$ is the rigid load demand of node $i$ at time t.

### 3) THE COST OF EMERGENCY RESOURCES CALLED BY THE POWER GRID

$$C_{\cos}^{DR} = \sum\nolimits_i^{\Omega_N} a \bullet f_{p,i} \bullet p_{r,i}^{DR} \tag{10}$$

where, $f_{p,i}$ is the electricity price of the normal electricity sold by node $i$ in the DN-PCs, in unit yuan /kw.h; The value of user coefficient $a$ varies with different capacities, Specific coefficient values can be referred to the literature [22];$P_{r,i}^{DR}$ is the amount of electricity that the flexible load can participate in the grid dispatch, unit yuan /kwh.

## C. CONSTRAINT CONDITION

### 1) MEG CONSTRAIN

In the DN-PCs unit, each MEG is limited to locating only one candidate pre-allocation node in advance. Additionally, each generator has a finite capacity, which can be expressed mathematically in a specific way.

$$\sum\nolimits_i^{\Omega_N} \alpha_{m,i} = 1, \quad \forall m \in M \tag{11}$$

$$0 \le P_{MEG}^t \le \sum\nolimits_m^{M} \alpha_{m,i} \bullet P_m^{\max}, \quad \forall i \in \Omega_N \tag{12}$$

$$0 \le Q_{MEG}^t \le \sum\nolimits_m^{M} \alpha_{m,i} \bullet Q_m^{\max}, \quad \forall i \in \Omega_N \tag{13}$$

where,$\alpha_{m,i}$ =1 or 0 represents node $i$ with or without deploying the $m_{th}$ MEG; $P_m^{\max}$ is the maximum active power emitted by the $m_{th}$MEG device; $Q_m^{\max}$ is the maximum reactive power emitted by the $m_{th}$ MEG device;

### 2) POWER FLOW CONSTRAINT

In this paper, the active power and reactive power of all lines and nodes should meet the energy conservation constraint, and the existing power and reactive power should maintain energy conservation.

$$\sum\nolimits_{(i,j)\in\Omega_N} p_{i,j}^t - \sum\nolimits_{(j,i)\in\Omega_N} p_{j,i}^t = p_i^t - P_i^t, \ \forall i,j \in \Omega_N \tag{14}$$

$$\sum\nolimits_{(i,j)\in\Omega_N} q_{i,j}^t - \sum\nolimits_{(j,i)\in\Omega_N} q_{j,i}^t = q_i^t - Q_i^t, \ \forall i,j \in \Omega_N \tag{15}$$

$$(p_{i,j}^t)^2 + (q_{i,j})^2 \le \alpha_{m,i}(S_{i,j}^{\max})^2, \ \forall i,j \in \Omega_N \tag{16}$$

$p_{i,j}^t$ $q_{i,j}^t$ are the active power and reactive power at time t on the pre-disaster branch (i, j);$p_i^t$ and $q_i^t$ are the active power and reactive power demand of each branch node $i$at time t before the disaster; $Q_i^t$, $P_i^t$ are is the reactive power and active power output of DN-PCs node $i$at time t before the disaster; $S_{i,j}^{\max}$ is the upper limit value of the apparent power of line (i, j).

### 3) NODE VOLTAGE CONSTRAINT

In this paper, the node voltage of each node should meet the upper and lower requirements of the node voltage:

$$U_{i,\min} \le U_i \le U_{i.\max} \tag{17}$$

$U_{i,\min}$, $U_{i.\max}$ are the minimum and maximum voltage value of node $i$;(in this paper, the maximum and minimum values are 12.66KV and 0 V ).

### 4) WIND TURBINE AND PV POWER OUTPUT CONSTRAINTS

In the DN-PCs unit, the operating power of the wind turbine and PV power generation equipment should be kept within their rated power range:

$$P_{FGi,\min} \le P_{FGi} \le P_{FGi,\max} \tag{18}$$

$P_{FGi,\min}$ and $P_{FGi,\max}$ is the minimum and maximum value of the adjustable power of the power generation equipment of node $i$; (in this paper, the maximum and minimum power are 3603.35KW and 0W).

### 5) NETWORK RECONFIGURATION CONSTRAINT

When extreme weather occurs, the reclosing of the DN-PCs needs to meet the branch capacity constraints, voltage constraints, switching action constraints, etc. The details are as follows:

$$\underline{U}_i \le U_i \le \overline{U}_i \tag{19}$$

$$\underline{P}_i^{DG} \le P_i^{DG} \le \overline{P}_i^{DG} \tag{20}$$

$$\underline{Q}_i^{DG} \le Q_i^{DG} \le \overline{Q}_i^{DG} \tag{21}$$

$$S_{i,j} \le S_{i,j,\max} \tag{22}$$

$$N_{total} \le N_{\max} \tag{23}$$

$\underline{U}_i$ and $\overline{U}_i$ is the upper and lower limit of the voltage amplitude of node $i$; $\underline{P}_i^{DG}$ and $\overline{P}_i^{DG}$ is the upper and lower limit of the active power value of renewable energy at node $i$; $\underline{Q}_i^{DG}$ and $\overline{Q}_i^{DG}$ is the upper and lower limit of the reactive power value of renewable energy at node $i$;$S_{i,j}$ is the apparent power of branch (i, j); $S_{i,j,\max}$ is the maximum capacity allowed to pass through the branch (i, j);$N_{total}$ is the sum of the number of actions of all switches in the reclosing cycle; $N_{\max}$ is the sum of the upper limit of the number of actions of all switches in the reclosing cycle.

### 6) LOAD CONSTRAINT

Grid loads consist of two main categories: flexible loads [23] and rigid loads [24]. One of the obvious characteristics of flexible load is to actively participate in the balance of power supply and demand, which is controllable. It is generally accepted that if the device is scheduled, its operating power reaches its maximum. $P_{\mathrm{a}}^{\max}$; If the device is terminated, its operating power can reach the minimum operating power $P_a^{\min}$ ( Is the minimum reserve power or is zero). For example, energy storage, electric vehicle air conditioning, etc. Its mathematical model is as follows:

$$\begin{cases} P_a^{\min} \le P_{r.a}^t \le P_a^{\max}, & \tau_a \le t \le \tau_a + T \\ P_{r,a}^t = 0, & t < \tau_a, \quad t > \tau_a \end{cases} \tag{24}$$

$$P_{r,a}^t = \alpha_{m,i} P_a^{\max} + (1 - \alpha_{m,i}) P_a^{\min}, \forall t \in [\tau_a, \tau_a + t] \tag{25}$$

$P_{r,a}^{\mathrm{t}}$ is the power consumed by the flexible load device at time t;$\alpha_{m,i}$ is a binary variable, $\alpha_{m,i}$ =1 or 0 indicates that device a is scheduled or interrupted; $P_a^{\min}$ and $P_a^{\max}$ is the minimum and maximum power of the load device $a$.

The rigid load is the load that must be satisfied by the user's life and work, which cannot be regulated by the grid and has a very low degree of control. The power of a rigid load in normal operation is generally constant. For example, refrigerators, elevators, lighting and so on belong to this kind of load. The mathematical model of the rigid load is as follows:

$$\begin{cases} P_{g,a}^t = P_{g,a}^t, & \tau_a \le t \le \tau_a + T \\ P_{g,a}^t = 0, & t < \tau_a, \quad t > \tau_a \end{cases} \tag{26}$$

$P_{g,a}^t$ is the power required to be consumed by the rigid load $a$at time t.

## IV. MODEL SOLUTION

The problem addressed in this paper is a multi-objective optimization problem that considers two objective functions: economy and resilience, which have different dimensions. To optimize multiple independent objectives simultaneously while adhering to problem constraints, we employ the non-dominated sorting genetic algorithm-II (NSGA-II) [25] with an elitism mechanism. NSGA-II algorithm is a classical multi-objective optimization method. NSGA-II algorithm can well deal with the optimal value conflict problem between grid toughness and economy. Besides, the algorithm has low complexity, fast calculation speed and good convergence in iteration. In each step of evolution, NSGA-II algorithm randomly selects resilience and economy group members as parents, and their offspring is considered as the next generation. Through continuous cross iteration with the next generation, the group evolves towards the optimal solution to get a set of Pareto optimal solutions about resilience and economy.

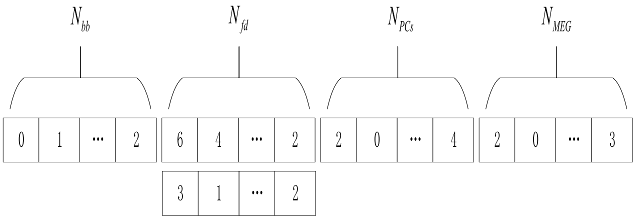

**FIGURE 5.** Chromosome structure.

During the process of population evolution, the first critical step is to determine the type of encoding to be used in solving the problem. Each chromosome in the population contains information about discrete decision variables and represents a candidate solution to the problem. As illustrated in Fig.5 below, each chromosome is composed of four distinct parts, which are explained in detail below.

1. The first part contains decision information about the types of sites and substations. This part has $N_{bb}$ genes indicating the number of existing substations and candidate substations. The value of each gene indicates the type of substation that should be installed at the candidate site, while a zero value indicates that no substation is installed at the candidate site.

2. The second part consists of two strings showing the network structure and feeder paths.

a. The first string shows the feeder structure based on an integer permutation. This string consists of $N$ integers whose values range from 1 to $N_{fd}$ First, the first integer in the string corresponds to the feeder to be installed. The process is then repeated for the next integer until the end of the string. If the structure of a feeder violates the radial constraint (making loops or connecting substations) the installation of this feeder is ignored and the next integer in the chromosome is considered. This feeder installation scheme guarantees that the final structure of the network will be radial.

b. The second string shows the type of feeder, and this string also contains the $N_{fd}$ gene.

3. The third part contains decision information for PCs location, which contains genes indicating the number of candidate sites to install PCs. A non-zero value for each gene indicates the capacity of PCs that must be installed at that candidate site, and a zero value indicates no PCs at that candidate site.

4. The fourth part is the location and capacity determination of the generator in the candidate site. This part contains $N_{MEG}$genes indicating the number of candidate sites to install generators. In this part, there is no generator at the position corresponding to each gene with a value of 0. On the contrary, nonzero values indicate the capacity of the selected generator at the corresponding location.

The algorithm begins by generating a random initial population, and at each iteration uses a non-dominated sorting method and calculates the crowding distance to sort population members and obtain a uniformly distributed solution frontier. Then, selection, crossover, and variation operators are applied to the existing population to create the next generation of children. After a predetermined number of iterations, a set of Pareto solutions to the integrated planning problem of the distribution network with improved resilience is obtained. Next, the resulting Pareto front is evaluated using the membership function [26], which assesses the comprehensive satisfaction of decision-makers with each non-inferior solution. The compromise solution is then selected based on the non-inferior solution with the largest comprehensive membership. The membership function is defined as follows:

$$\mu_i = \begin{cases} 1, & f_i^{\min} \geq f_i \\ \dfrac{f_i^{\max} - f_i}{f_i^{\max} - f_i^{\min}}, & f_i^{\min} \leq f_i \leq f_i^{\max} \\ 0, & f_i \geq f_i^{\max} \end{cases} \tag{27}$$

$$U = \sum\nolimits_{i=1}^{I} \mu_i \tag{28}$$

$f_i$ is the $i_{th}$ objective function value; $f_i^{\min}$, $f_i^{\max}$ are the minimum and maximum values of the$i_{th}$ objective function; $\mu_i$ is the membership value of the $i_{th}$ objective function value, which ranges from 0 to 1; $U$ is the comprehensive membership degree of the objective function;

## V. RESILIENCE ASSESSMENT AND EXAMPLE ANALYSIS

To verify the effectiveness of the proposed optimization strategy, we conducted simulation analysis on the IEEE-33 node test system using system energy supply and demand data, unit equipment parameters, and load data from literature [27], [28]. The simulations were performed in MATLAB R2020b with the YALMIP toolbox. The hardware environment used for the simulations was a laptop with an AMD Ryzen 5 2500U 2.00GHz CPU and 16GB RAM. To simulate the impact of extreme weather events, we utilized the parameter data of tropical cyclone "Nida," the fourth-strongest hurricane in 2016, compiled by the Joint Typhoon Warning Center (JTWC) as an example [29].

### A. RESILIENCE ASSESSMENT PROCESS

This paper assesses the resilience of DN-PCs by considering the integrated load loss amount, which is obtained by weighting each class of load nodes under extreme events. This approach accounts for both the magnitude of system fault loss during extreme events and the duration that DN-PCs is impacted. To model the probability of failure in the distribution network, distribution functions are typically used to construct failure scenarios under extreme events. In this paper, we utilize the Monte Carlo method [30]. Specifically, we randomly simulate failure scenarios of DN-PCs components using failure data, and solve for the load power of DN-PCs under each scenario using mathematical statistics. This approach allows us to compute the resilience index of the distribution network. The resilience evaluation process is illustrated in Fig. 6.

1) Obtain natural disaster information such as wind speed, direction and duration of typhoon;

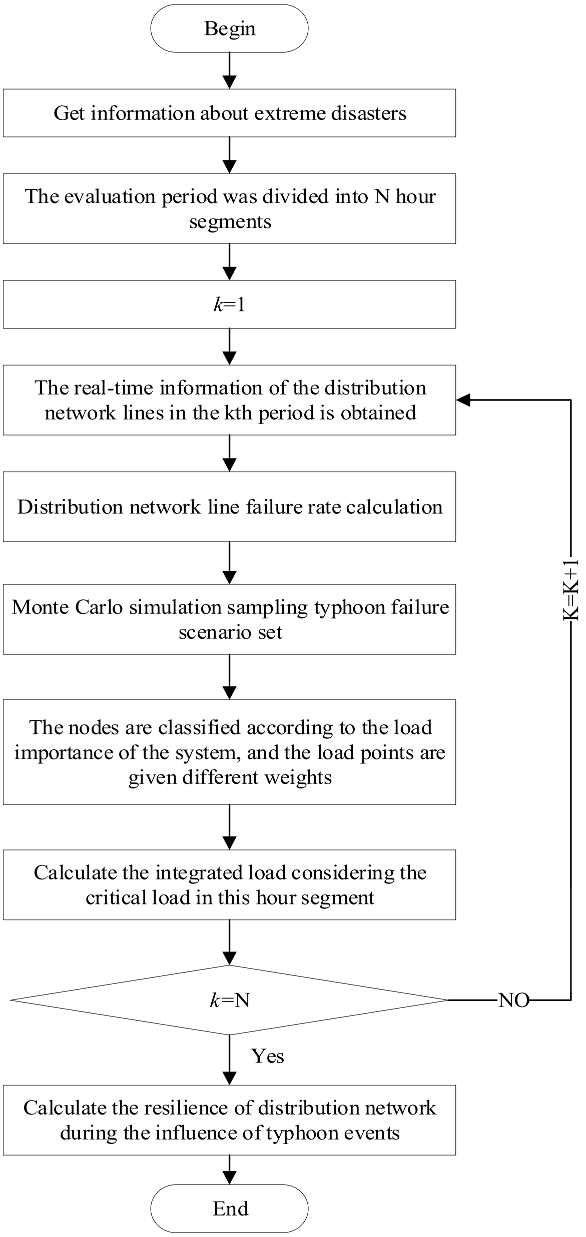

**FIGURE 6. Distribution network resilience assessment process.**

2) The typhoon login process was divided into N hours, *k*= 1;
3) In combination with formula (1), (2) and (3), Monte Carlo was used to simulate distribution network fault information in the $k_{th}$ period;
4) Assign node weight values according to the importance of distribution network load;
5) Calculate the average loss of comprehensive load in the *k*hour segment;
6) Determine whether the load loss index *N*= *k* in all hours has been calculated. if *N* equal k then go to step 7, if *N*is not equal to k then go to step 2;
7) Calculate the resilience value of distribution network under typhoon disaster.

**TABLE 1.** Source and load parameters in IEEE33-node test systems.

| Category | MG1 | MG2 |
|---|---|---|
| Total power source ( p.u ) | 0.075 | 0.09 |
| Total load ( p.u. ) | 0.12 | 0.0465 |

*Source and load parameters in IEEE33-node test systems MG1 and MG2*

**TABLE 2.** Compromise solutions.

| Parameter | Scenario | | |
|---|---|---|---|
| | Scenario1 | Scenario2 | Scenario3 |
| $F_1$ | 0.7766 | 0.7875 | 0.7987 |
| $F_2$/RMB | 456800 | 430920 | 421400 |

### B. IEEE 33-NODE TEST SYSTEM

In this paper, the multi-power cooperative recovery strategy is verified using the IEEE 33-node distribution network as the test system. The system consists of 32 branches, with an annual maximum load of 3603.35+j2258.47 KVA, are reference voltage of 12.66KV, and a reference capacity of 100MVA. The topology structure is depicted in Fig.7, and other parameters are provided in reference [31]. The test system includes five power clusters, connected to nodes B4, B11, B16, B25, and B30, respectively. There are two micro-grids, labeled MG1 and MG2. S3, S4, and S5 denote MG switches, and S1 and S2 represent contact switches for pre-set lines. The source and load parameters in MG1 and MG2 are shown in the table below. This paper only considers faults on the power grid line under typhoon disasters.

As shown in Fig.8, there are 32 loads in the IEEE33-node grid, which are divided into three levels according to the importance of the loads, including five first-level loads and six second-level loads. The Monte Carlo method is used to randomly generate the load weighting factors as shown in Fig. 8.

In order to verify the effectiveness of the optimization model proposed in this paper, three scenarios are selected for analysis:

Case 1: Assume an extreme typhoon natural disaster that forces the power grid lines to be disconnected from the upper power grid. The IEEE33-node power grid has a fault at branches B7-B8, B16-B17, and the fault location is shown in Fig.8 above. At this time, the power grid is divided into several micro-grids operating on isolated islands, and the distribution network maintains power by its own backup power supply.

Case2: On the basis of (1), PCs unit are considered to participate in the scheduling project while equipped with supply resources in the distribution network, where nodes B4, B25, B30, B11, B16 are connected to the PCs unit.

Case3: On the basis of satisfying the rigid load, reduce the proportion of flexible load in the DN-PCs. Among them, rigid load (50%) and flexible load (50%) are set by default.

### C. ANALYSIS OF SIMULATION RESULT

#### 1) ANALYSIS OF THE RESULTS UNDER DIFFERENT SCENARIOS IN EXTREME WEATHER

This paper employs the Pareto optimal strategy to address the issue of mutual exclusion of single objectives in the multi-objective optimization process, balancing the influence of the resilience objective and the economic objective factors of the single DN-PCs on the overall optimization objective. In Fig. 9, the Pareto optimum front is depicted, with the robustness index represented by the horizontal coordinate and the economic loss index by the vertical coordinate. A scaled objective function is used. ($w_2 = 2000000$ ). The two-objective Pareto optimum front under three scenarios is determined by various scenario patterns, and the normalized compromise solution (0.7700, 0.2284) is chosen by the membership function. (0.7755, 0.21546) (0.7837, 0.21070). During 500 rounds, Fig. 8 depicts the convergence contours of the resilience objective function and the economic objective function. Fig.10 shows the convergence curves of the economic objective function and the resilience objective function during 500 iterations in the process of solving the multi-objective optimization. When the NSGA-II algorithm reaches 150 iterations, both the economic objective and the resilience objective tend to be stable. It can be seen that the proposed NSGA-II algorithm has better convergence and can find the optimal solution of the objective function faster.

Meanwhile, Table 2 shows the compromise solutions of the objective function in different scenarios. According to the Pareto optimal frontier in Fig. 9 and Table 2, compared with scenario 1, the load loss cost of scenario 2 with PCs resources is reduced by nearly 20,000 yuan, and its resilience index is increased by 8.7%. It can be seen that reasonable equipped MEG and distributed power can stabilize the voltage of the DN-PCs in the case of failure. To provide a certain amount of active and reactive power to the important load nodes in the grid, so as to reduce the load cutting operation of the circuit breaker, effectively reduce the failure of the DN-PCs in the hurricane weather, so that the resilience of the distribution network is improved. Compared with scenario 3, the controllable load scheduling is added on the basis of scenario 2, and the load loss cost is further reduced and the resilience index is further improved. Compared with scenario 1, the load loss cost under hurricane disaster is reduced by about 35,400 yuan, which is 12.98% of the total load loss cost of scenario 1. In conclusion, the comprehensive configuration of PCs units in the distribution system can effectively improve the load resilience of the DN-PCs under extreme natural disasters, and then improve the resilience of the DN-PCs under natural disasters. At the same time, when the controllable load is scheduled, the load loss is further reduced, and the economic losses caused by disasters are significantly reduced.

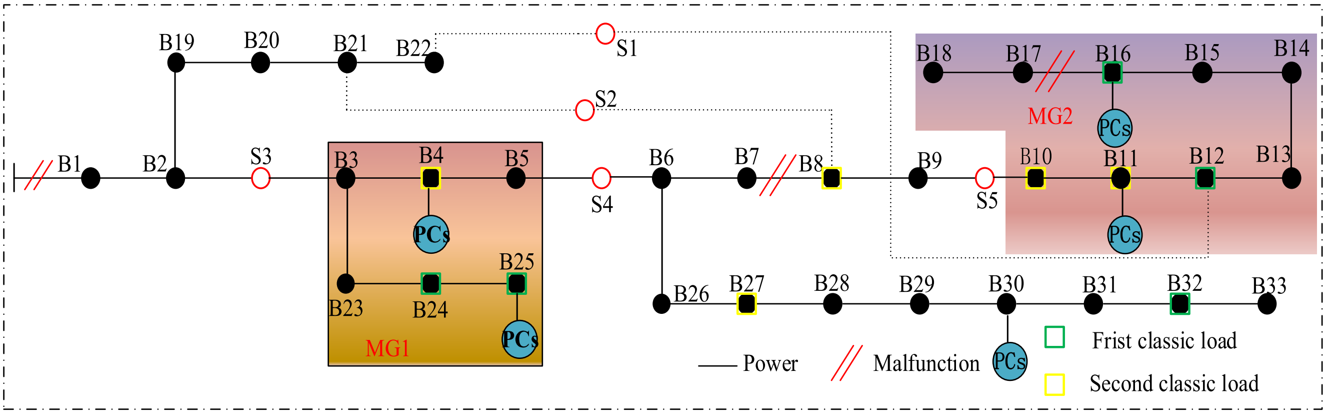

**FIGURE 7.** The IEEE33-node test system.

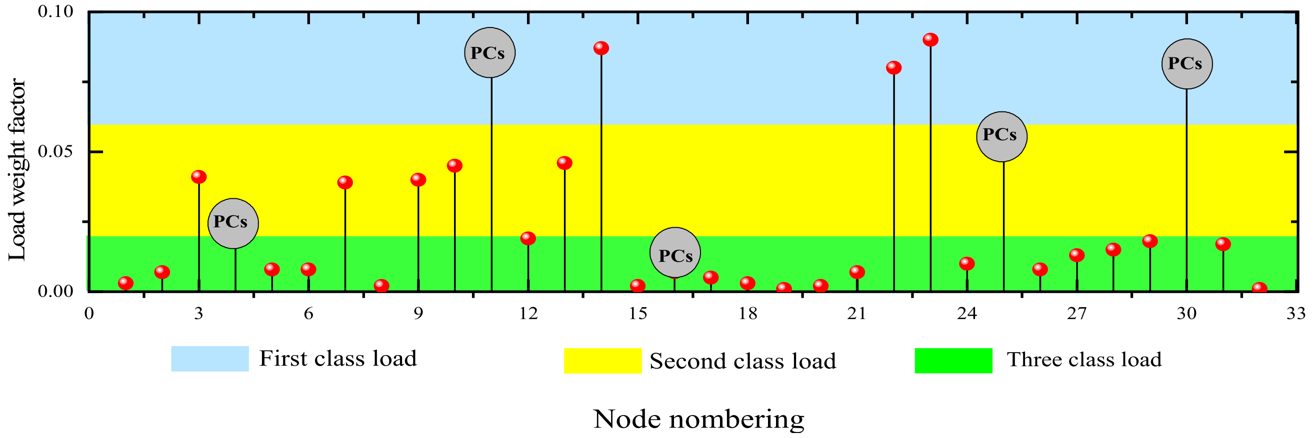

**FIGURE 8.** Load weights of the IEEE33-node test system.

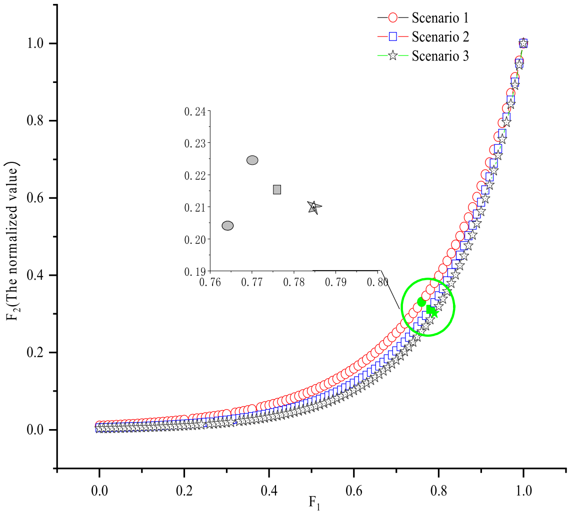

**FIGURE 9.** Pareto optimal front.

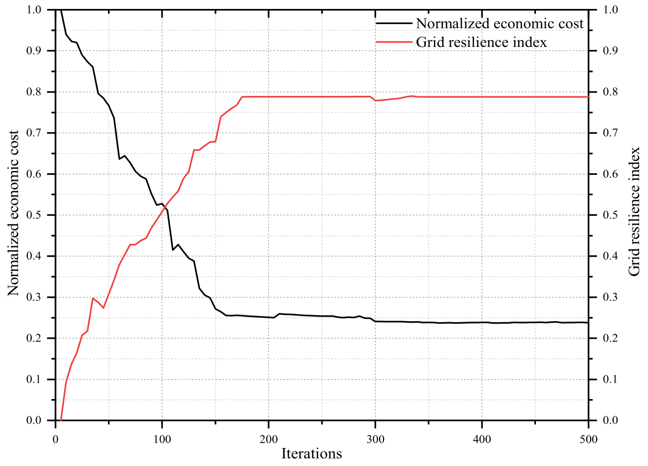

**FIGURE 10.** The number of iterations of the objective function.

### 2) INDLUENCE OF CONTROLLABLE LOAD RATIO ON RESILIENCE OF DN-PCS

Fig.11 shows the power supply recovery load curve of DN-PCs users with different proportions of controllable load before and after the hurricane disaster. Compared with the normal operation of the DN-PCs, the load curve of the DN-PCs drops sharply when the hurricane fault occurs in the distribution network at 7 o ’ clock, but it can be clearly seen that the load curve of 50% and 60% controllable load is much less than that of 30% user load in extreme weather.

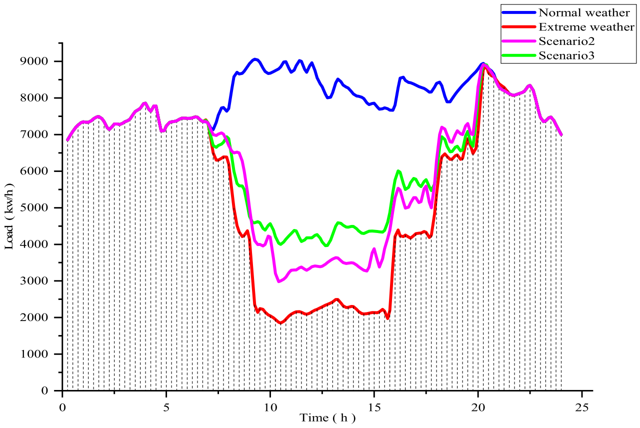

**FIGURE 11.** **Power supply recovery load curve of distribution network under hurricane weather.**

First, considering the access of PCs, when a disaster occurs, these PCs units can support their load users in time and reduce the loss of users' load as much as possible.

Second, when the controllable load is connected to the DN-PCs, the DN-PCs is impacted to a stable derating state under hurricane weather, and then in the whole process of fault repair, the controllable load in the PCs can support the continuous power supply of the load in the island, increase the proportion of the controllable load, and also reduce the output burden of the power generation unit. Therefore, increasing the proportion of controllable load can effectively increase the energy supply recovery of the DN-PCs, and improve the resilience of the distribution network.

## VI. CONCLUSION

This paper discusses the issue of distribution grid economics and resilience enhancement in the context of hurricane disasters, and it suggests an integrated multi-energy resource optimization method and resilience assessment process for DN-PCs units. The study's findings indicate that:

1)The resilience evaluation process constructed based on DN-PCs can well quantify the toughness index of the distribution network, accurately reflect the operating state of the distribution network, and provide some help for the future quantitative research on the toughness index of the distribution network.

2) When a hurricane or other natural disaster strikes, PCs unit modules configured in the distribution network can quickly respond to the power shortage in the power system. Compared with the non-configured PCs devices in the distribution network, the resiliency index increased by 8.7% and the economic index decreased by about 20,000 yuan, which can provide a distribution network planning scheme for the power emergency management department in the future. It can satisfy both resilience and economy well.

3) In the distribution network, the proportion of different flexible loads corresponds to different toughness values of the distribution network. With the increase of the proportion of flexible loads in the distribution network, the resilience values also increase correspondingly. In the face of extreme disasters, we can improve the power supply capacity of the distribution network by adjusting the proportion of flexible load.

The collaborative optimization allocation of DN-PCs units and flexible load resources suggested in this paper can maximize the comprehensive power supply capacity of distribution network system under extreme natural disasters, while taking into account the economy of system operation, which is of great significance for the resilience improvement of distribution network systems. The study's next phase will examine the effects of distributed power sources, distributed energy storage, and renewable energy on the distribution network's resilience to extreme weather events and to varying weather conditions. The study's next phase will examine the effects of distributed power, distributed energy storage, and renewable energy on the distribution network's resilience to extreme weather events and to varying weather conditions. Future research will also examine the effects of economic dispatch indicators, resilient grid regulatory policies, and information-grid convergence technologies on the grid's resilience.

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