Research of Islanding Operation and Fault Recovery Strategies of Distribution Network Considering Uncertainty of New Energy

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Abstract: With the problems of fault handling in the distribution network, few studies concern the correlation between islanding operation and fault recovery. Thus, this paper proposes an islanding operation and fault recovery strategy for the distribution network considering the uncertainty of new energy. Firstly, the objectives of the distribution network islanding division scheme and operation optimization are established. Combined with distribution network radiation constraints, islanding power supply capacity, safety constraints, and distributed generator (DG) operation constraints, a rolling optimization method is used to construct the distribution network islanding division and operation model. Secondly, in the fault recovery stage, considering the characteristics of the island operation stage, a node load weight value is designed. A distribution network fault recovery model is then constructed with the goals of ensuring greater load power supply recovery, improving electricity satisfaction, and reducing network losses and switching times. Thirdly, considering the randomness of intermittent DGs such as wind power and photovoltaics, an uncertainty model of intermittent DGs is constructed. A solution method for the distribution network islanding operation and fault recovery model considering uncertainty is proposed by combining scenario generation reduction methods and second-order cone programming theory. Finally, the proposed method’s feasibility and effectiveness are verified using the improved IEEE 33-node distribution network. The results show that in the islanding division stage, the node voltage consistently remains between 1.08 pu and 1.1 pu when new energy achieves up to 34.09% and 48.65%, and the line losses represent approximately 0.22% to 0.26% of the total load when the initial energy levels of the storage are at 50% and 80%. In the fault recovery stage, compared to the method without network reconstruction, the system shows significant power loss reductions of approximately 11.9%, 13.6%, and 14.2% in three respective cases.

Keywords: distribution network; islanding operation; fault recovery; uncertainty; rolling optimization; distributed generation

1. Introduction

With the rapid development of new energy technology [1], distributed generators (DGs) such as wind power and photovoltaic power generation are increasingly connected to the distribution network. On the one hand, the integration of a DG increases the complexity of the distribution network structure and power flow. On the other hand, these DGs have significant uncertainties. These factors pose great challenges to the fault handling of the distribution network [2]. The handling of distribution network faults can be divided into two stages depending on whether the superior power grid has restored power supply. When a fault occurs in multiple areas (the distribution system and superior power grid) and if the superior power grid cannot provide power to the distribution network, the distribution network needs to integrate and coordinate the DG resources within it. This integration forms a small-scale distribution island to ensure the power supply of important...
loads. This stage is called the island division and operation stage. After the power supply of the superior power grid is restored, the power outage load in the distribution network needs to be restored on the basis of island operation. This stage is known as the fault recovery stage. Possessing a reasonable islanding and operation strategy, as well as an effective fault recovery strategy, is of great significance in reducing power outage time in distribution networks. These strategies also help to improve power supply reliability [3–5].

The islanding division of the distribution network is a prerequisite for achieving islanding operation [6]. A reasonable islanding division method is not only conducive to maintaining the operation of important loads but also helps in avoiding further expansion of the fault range. Reference [7] aimed to maximize power supply restoration, user satisfaction with electricity usage, and minimize demand response costs for island division. This approach can effectively improve user satisfaction within the island. Reference [8] took into account multiple attributes of load and user preferences in island partitioning, reflecting the comprehensive importance of load and overcoming the shortcomings of considering only a single attribute of load. Reference [9] aimed to maximize the load capacity in isolated islands and constructed an elastic isolated microgrid, enhancing its ability to resist local interference. References [10,11] considered the uncertainty of distributed power generation such as wind power, photovoltaic, and electric vehicles. The reasonable utilization of DG or other adjustable resources is particularly important when operating in isolated distribution networks [12,13]. Reference [14] took into account the output characteristics of small hydropower stations, gas power stations, energy storage systems, wind farms, and photovoltaic power stations. It included AC power flow constraints, radial constraints of distribution networks, and steady-state safety constraints. Additionally, this reference introduced a rolling optimization model for real-time operation of distribution network islands. Reference [15] mainly focused on evaluating the impact of wind and photovoltaic uncertainty on the elasticity of distribution networks. This study employed a risk-limited scheduling method and determines the scheduling strategy for a certain time period of the distribution network through multiple decision-making stages. This strategy can further enhance the flexibility of the distribution network islanding operation under uncertain conditions of wind and photovoltaic power. Reference [16] analyzed the influence of demand side responses on distribution network reconstruction. In this analysis, the moderating effect of time-of-use electricity prices on price incentive electricity loads was considered. By taking into account the uncertainty of various DGs, an optimization model for distribution network reconstruction was established which enhanced the operational economy of the distribution system. Reference [17] addressed the issue of integrating active management measures, like network reconstruction, with reactive power optimization. Meanwhile, a distribution network optimization model rooted in mixed-integer second-order cone programming was formulated and subsequently solved.

In the recovery stage of distribution network faults, on the one hand, although the superior power grid has restored power supply to the distribution network, the superior power grid faults may not have been completely eliminated and are still in a relatively fragile stage, with a weak power supply capacity. On the other hand, there are node voltage and power flow constraints in the distribution network, and relying solely on the higher-level power grid to restore the power supply may cause the distribution network voltage and power flow to exceed limits. Therefore, it is still necessary to fully utilize various resources of the distribution network to achieve as much load power recovery as possible [18]. Reference [19] introduced a distribution network fault recovery strategy, melding islanding with network reconstruction. This approach aimed to tackle the challenge of partial load power non-recovery during the fault recovery process in distribution networks integrated with DGs. Given a predominant integration of clean energy, reference [20] put forth a distribution network reconstruction model that factored in demand response. This model adeptly harnessed demand response to diminish the expenses associated with distribution network reconstruction and to curtail the abandonment rate of wind and solar energy, subsequently bolstering the distribution network’s capacity to assimilate clean energy.
Reference [21] utilized multiple distributed power sources and energy storage systems to quickly recover important loads and proposed an active distribution network post-disaster power supply recovery model. This model can effectively reduce economic losses caused by extreme events that lead to power outages and improve the resilience of the distribution network. Reference [22] considered the complexity of distribution network fault recovery, as well as the randomness and volatility of a new energy output. This reference established a mathematical model based on uncertain bilevel programming theory, which enables rapid fault recovery of distribution networks in complex environments. Reference [23] established a distribution network fault reconstruction model that considers active management measures for distribution networks with adjustable DGs and adjustable capacitor banks. This approach used second-order cone relaxation technology to transform it into a mixed-integer second-order cone programming model. The fault reconstruction results of the distribution network can maintain the system voltage within a reasonable range. Building on this, reference [24] utilized resources such as multi-type DGs, flexible loads, and energy storage. It also considered the black start capability of distributed power sources and energy storage, as well as fault recovery time and maintenance sequence. This reference proposed a comprehensive reconstruction and island partitioning fault recovery method which can optimize fault maintenance strategies and improve the reliability of distribution network fault recovery. Reference [25] focused on the problem of fault reconstruction in electric and gas distribution systems. This study took into account the characteristics of multi-resource unbalanced operations in electric and gas distribution systems under extreme weather conditions. It constructs a multi-time period collaborative fault reconstruction model for the development of comprehensive electric and gas distribution systems and proposes a two-stage model solving method.

The above literature is of great significance for achieving islanding operation and fault recovery in distribution networks after faults, but there are still shortcomings. Firstly, existing research often treats the islanding operation and fault recovery of distribution networks as two separate issues, somewhat neglecting their correlation. Generally speaking, the troubleshooting time is not fixed, making it difficult to accurately determine the autonomous operation time of distribution islands. During the operation of isolated islands, both new energy and load may undergo large-scale changes, so the island division scheme may alter, leading to changes in user satisfaction with electricity consumption. The load that has not been categorized as an isolated island and the load that has been classified as an isolated island in stages might experience subpar electricity satisfaction. This aspect needs meticulous attention during the fault recovery phase. Secondly, existing distribution network islanding and operation models predominantly rely on new energy and load data prior to the fault. They comprehensively consider new energy and load prediction data within a fixed time period (such as 24 h) after the fault to develop islanding and operation plans. However, the troubleshooting time exhibits variability. The fault may be rectified within a short span (like within 24 h) or might remain unresolved for an extended duration (beyond 24 h). Thus, using predicted data within a fixed time period to draft island division and operation plans may not always be optimal.

In response to the above issues, this paper proposes a distribution network islanding operation and fault recovery strategy that considers the uncertainty of new energy. Firstly, a rolling optimization method was used to construct a distribution network islanding and operation model. Secondly, in the fault recovery stage, fully considering the characteristics of isolated operation in the distribution network can ensure more load power supply recovery while improving electricity satisfaction.

2. Island Division and Operation Model of Distribution Network

2.1. Objective Function

The islanding and operation of distribution networks represent a complex nonlinear optimization problem that requires the simultaneous consideration of numerous objectives
and constraints. When determining the island division and operation plan in this paper, the following principles are considered:

1. The principle of prioritizing important loads: In order to ensure the stability and reliability of the power grid, it is necessary to classify the loads according to their importance and give them different weights. When a fault occurs, the power supply of important loads should be ensured first to ensure the normal operation of the power grid.

2. The principle of maximum load: When allocating load to each isolated island, ensure that the total load matches the power supply capacity of the DG in the island in order to fully utilize the capacity of the DG and reduce the loss of power load. At the same time, it is also necessary to avoid the occurrence of DG overload.

3. The principle of minimum network loss: in order to ensure the economic operation of isolated islands and provide power to the load as much as possible, the active power loss of isolated islands should be minimized when formulating island plans.

Based on the above principles, this paper adopts the weighted method to establish the objective function of the islanding and rolling optimization operation in the distribution network as follows:

$$\text{min} \sum_{k \in \Omega} \sum_{i \in N_k} \sum_{t \in T} \alpha_{i,k} P_{i,k,t} + \mu_{\text{loss}} \sum_{k \in \Omega} \sum_{ij \in E_k} \sum_{t \in T} R_{ij} I_{ij,k,t}$$

where $T = \{t, t + \Delta T, \ldots, t + \tau_{f} \Delta T\}$ represents the solution period for rolling optimization.

In Equation (1), the weight value assigned to the load $\alpha_{i,k}$ can drive important loads to be divided into isolated islands, ensuring the power supply of important loads; $\alpha_{i,k} P_{i,k,t}$ ensures the minimum amount of load removal, meeting the principle of maximum load during island operation; $R_{ij} I_{ij,k,t}$ is the line loss, which conforms to the principle of minimum network loss.

After the failure in the distribution network and the superior power grid, the distribution system may not be able to utilize the superior power grid for fault recovery. Due to the randomness and lag of fault maintenance time, each island in the distribution network needs to operate independently based on island division, and it is difficult to accurately determine the time when distribution islands need to operate independently. The output of wind power and photovoltaic DGs carries uncertainty and the short-term prediction accuracy of their output is higher than that of long-term prediction. Using short-term prediction of DG output can reduce the uncertainty of scheduling. Therefore, this paper adopts a rolling optimization method to gradually determine the distribution island operation plan for each scheduling period (assuming the interval between adjacent scheduling periods is $\Delta T$), that is, when scheduling, multiple time steps are considered but only the scheduling plan for the next time step is issued. When the next scheduling period arrives, the above process is repeated for rolling optimization to achieve feedback correction. The scheduling period can be determined based on the actual situation, generally taking $\Delta T = 15$ min. The scheduling plan for the $t$-th scheduling period is obtained by solving a joint optimization model within the time periods $T = \{t, t + \Delta T, \ldots, t + \tau_{f} \Delta T\}$. At the same time, the use of the rolling optimization is also beneficial for improving the efficiency and accuracy of the solution.

2.2. Constraint Condition

In the rolling optimization model, due to the fluctuation of new energy and load, the islanding partition schemes obtained during different scheduling periods may be different. Even for adjacent scheduling periods, the islanding partition results might differ. Continuous changes in island division schemes will result in frequent switching actions, which is not conducive to extending the lifespan of switches and can also reduce user satisfaction with electricity consumption. Therefore, this paper stipulates that assuming island partitioning is carried out during the scheduling period $t$, the island partitioning
scheme can only be reformulated when the changes in new energy and load exceed a certain threshold shown in Equation (2). In other words, after islanding during scheduling period \( t \), if the changes in new energy and load during the future scheduling periods do not exceed the threshold defined by Equation (2), the islanding scheme for period \( t \) will continue to be used. Furthermore, it is worth noting that although the island division scheme may be implemented for a period of time, the DG output within the island still needs to be continuously optimized during each scheduling period.

\[
\begin{align*}
    \sum_{i \in N} |p_{i,k,t}^L - p_{i,k,t}^L| &> \sigma^L \quad \forall k \in \Omega \\
    \sum_{i \in N} |p_{i,k,t}^\text{wind} - p_{i,k,t}^\text{wind}| &> \sigma^\text{wind} \quad \forall k \in \Omega \\
    \sum_{i \in N} |p_{i,k,t}^\text{PV} - p_{i,k,t}^\text{PV}| &> \sigma^\text{PV} \quad \forall k \in \Omega
\end{align*}
\]

(2)

The switch state of the proposed islanding model for the power grid needs to meet the constraint conditions:

\[
\sum_{k \in \Omega} y_{i,k} = 1 \quad \forall i \in N_{DG}
\]

(3)

\[
y_{ij,k} \leq y_{i,k} \quad \forall ij \in E, k \in \Omega
\]

(4)

\[
y_{ij,k} \leq y_{j,k} \quad \forall ij \in E, k \in \Omega
\]

(5)

where \( y_{i,k} \) and \( y_{ij,k} \) represent the states of node \( i \) and line \( ij \) in distribution island \( k \). When the value is 1, it indicates that node \( i \) and line \( ij \) are in operation, and when the value is 0, it indicates that node \( i \) is disconnected from line \( ij \); \( N_{DG} \) represents the set of nodes in the distribution network; \( N_{DG} \) represents the set of DG nodes in the distribution network; the number of distribution lines in this group is represented by \( |L| \). Equation (3) indicates that DG in the distribution network must be divided into a certain distribution island; Equations (4) and (5) indicate that if the distribution line \( ij \) is divided into islands \( k \), the nodes at both ends must also be divided into the same island.

To ensure the radial topology of the distribution network, the following topological constraints need to be considered.

\[
0 \leq P_{ij,t} \leq M_e \varphi_{ij,t} \quad \forall ij \in E, t \in T
\]

(6)

\[
0 \leq Q_{ij,t} \leq M_e \varphi_{ij,t} \quad \forall ij \in E, t \in T
\]

(7)

\[
\varphi_{ij,t} \geq 0 \quad \forall i \in N \setminus N_{S}, t \in T
\]

(8)

\[
\varphi_{ij,t} = 0 \quad \forall i \in N_{S}, t \in T
\]

(9)

\[
\varphi_{ij,t} + \varphi_{j,i,t} = 1 \quad \forall ij \in E \setminus E_{F}, t \in T
\]

(10)

\[
\varphi_{ij,t} + \varphi_{j,i,t} = 0 \quad \forall ij \in E_{F}, t \in T
\]

(11)

\[
\sum_{ij \in E} \varphi_{ij,t} \leq 1 \quad \forall i \in N, t \in T
\]

(12)

where \( N \setminus N_S \) represents the removal of set \( N \) from set of \( N_S; E \setminus E_F \) represents the removal of \( E \) from set \( E_F \). When the value of \( \varphi_{ij,t} \) is 1, it represents that the power flow direction is from node \( i \) to node \( j \), and when the value of \( \varphi_{ij,t} \) is 0, it indicates that there is no power flow in the line; \( ij \in E \) represents the node \( j \) that belongs to the line set \( E \).

It is worth noting that if Equation (2) is not satisfied, meaning there is no need to develop a new island scheme, then the switch state constraint and the radial topology constraint of the distribution network will naturally be satisfied. As a result, there is no need to consider the constraints of Equations (3)–(12) in rolling optimization. In order to
ensure the stable operation of the island system, the total load in the island should not exceed the power generation capacity of the DG in the island, i.e.,

$$\sum_{i \in N_k} P_{i,t}^{DG} \geq \sum_{i \in N_k} p_{i,t}^{L} \quad \forall t \in \Gamma, k \in \Omega.$$  

Due to the widespread integration of new energy sources such as wind power and photovoltaic in the distribution network, $p_{i,t}^{DG}$ may have uncertainty. The uncertainty handling methods for $p_{i,t}^{DG}$ will be explained in Section 4.

The island rolling optimization operation needs to meet safety constraints; that is, the line flow and node voltage amplitude cannot exceed the limit, as shown in Equations (14) and (15).

$$-S_{ij}y_{ij} \leq P_{i,t} \leq S_{ij}y_{ij} \forall i \in E, t \in T$$  

$$U_{\min} y_{i} \leq U_{i,t} \leq U_{\max} y_{i} \forall i \in N, t \in T$$  

Due to the radial distribution island topology mentioned above, a second-order cone relaxation form of the distribution system power flow model can be established based on the branch power flow model to describe the voltage power relationship in Equations (14) and (15).

$$U_{i,j,t}^2 - U_{i,t}^2 \geq P_{i,j,t}^2 + Q_{i,j,t}^2 \forall i \in E, t \in T$$  

$$P_{i,t}^{DG} - P_{i,t}^{L} + P_{i,t}^{S} = \sum_{j \in j \in E} P_{i,j,t} - \sum_{m \in m, i \in E} \left( P_{m,i,t} - R_{m,i,t}^2 \right) \forall i \in N, t \in T$$  

$$Q_{i,t}^{DG} - Q_{i,t}^{L} + Q_{i,t}^{S} = \sum_{j \in j \in E} Q_{i,j,t} - \sum_{m \in m, i \in E} \left( Q_{m,i,t} - X_{m,i,t}^2 \right) \forall i \in N, t \in T$$  

$$U_{i,j,t}^2 - U_{i,t}^2 \geq 2(R_{ij}P_{i,j,t} + X_{ij}Q_{i,j,t}) + \left( R_{ij}^2 + X_{ij}^2 \right) P_{i,j,t}^2 - M_v(1 - y_{ij,t}) \forall i \in E, t \in T$$  

$$U_{i,j,t}^2 - U_{i,t}^2 \leq 2(R_{ij}P_{i,j,t} + X_{ij}Q_{i,j,t}) + \left( R_{ij}^2 + X_{ij}^2 \right) P_{i,j,t}^2 + M_v(1 - y_{ij,t}) \forall i \in E, t \in T$$  

where $M_v$ is a sufficiently large constant that can relax the constraints of Equations (19) and (20) when the line is in a disconnected state. To make the above constraints more compact, its value can be taken as the square of the maximum allowable voltage amplitude $U_{\text{max}}$.

Equations (17) and (18), respectively, represent the balance of active and reactive power at nodes in the distribution system. Equation (16) is an expression for the relationship between the power flow, current amplitude square, and voltage amplitude square of the distribution line in the form of second-order cone relaxation, which is accurate in radial distribution networks.

The DG in the distribution network of this paper considers diesel generators, energy storage, wind, solar power plants, etc.

The adjustment range and speed of the active power output of diesel generators are shown in Equations (21) and (23), respectively. Specifically, the active power of diesel generators cannot exceed the allowable upper and lower limits, and the adjusted range of active power between adjacent scheduling periods should be within the range that can be reached by the climbing rate. The active power output regulation range and speed of the diesel generator are shown in Equations (22) and (24), respectively.
where $\beta^\text{dis}_{i,t}$ and $\beta^\text{ch}_{i,t}$ are 0–1 variables that represent the discharge and charging states of the energy storage system $i$, with values of 1 indicating that the energy storage system is in the discharge and charging states during the scheduling period $t$, respectively. These two variables are mutually exclusive, meaning that only one can be taken as 1 within the same scheduling period $t$. It is worth noting that Equation (32) shows the energy relationship of the energy storage system between adjacent scheduling periods; Equation (34) indicates that the energy stored by the energy storage system at the beginning and end of the scheduling period is the same.

The output of wind and solar power plants has uncertainty, and its model and uncertainty handling methods will be explained in Section 4.

3. Distribution Network Fault Recovery Model

3.1. Objective Function

After the failure of the distribution network and the superior power grid, the distribution system may not be able to utilize the superior power grid for fault recovery and it is necessary to divide and operate islands according to the methods in Section 2. If the main network resumes power supply, the power loss load can be further connected to the main network through distribution lines to achieve distribution network fault recovery.

One of the goals of distribution network fault recovery is to maximize load recovery, followed by optimizing network operation losses after fault recovery, and finally minimiz-
ing the number of switches as much as possible. This paper will weight three objectives in the form of (35) [26].

\[
max F = \sum_{i \in N} \sum_{t \in T} \beta_{i,k} \phi_{i,j}^H - \theta_{\text{loss}} \sum_{i \in E} \sum_{t \in T} R_{ij} \delta_{ij,t}^2 \\
- \theta_{\text{switch}} \left[ \sum_{d \in E} (1 - z_d) + \sum_{d \in E} z_d \right]
\]

(35)

when the value of \( w_i \) is 1, it indicates that the load has been restored, and the value of \( w_i \) being 0 indicates that the load has not been restored. When the value of \( z_d \) is 1, it indicates that the switch is closed, and a value of 0 indicates that the switch is open.

During the island operation phase, the power grid will undergo troubleshooting. Due to the fact that the troubleshooting time is not fixed, it is difficult to accurately determine the autonomous operation time of the distribution island. During the operation of the island, there may be large-scale changes in new energy and load, resulting in changes in the island division plan and affecting user satisfaction with electricity consumption. This paper considers the impact of changes in island partition schemes on load during the fault recovery phase and sets the load weight value of node \( i \) in island \( k \) to \( \beta_{i,k} \) designed as (36).

\[
\beta_{i,k} = \alpha_{i,k} + \xi_1 \sum_{t \in T_{\text{is}}} \left| y_{i,k,t} - y_{i,k,t-1} \right| + \xi_2 \sum_{t \in T_{\text{is}}} \left| y_{i,k,t} - 1 \right| \quad \forall i \in N
\]

(36)

In Equation (36), the first item \( \alpha_{i,k} \) represents the load weight value during the islanding division stage. The second item \( \xi_1 \sum_{t \in T_{\text{is}}} \left| y_{i,k,t} - y_{i,k,t-1} \right| \) represents the impact of changes in the islanding scheme on the load. If the power supply status of node \( i \)'s load changes during adjacent scheduling periods, \( \left| y_{i,k,t} - y_{i,k,t-1} \right| \) will be 1, providing the weight value of node \( i \)'s load during the fault recovery phase. The third item \( \xi_2 \sum_{t \in T_{\text{is}}} \left| y_{i,k,t} - 1 \right| \) represents the impact of node \( i \)'s load not receiving power during the island operation phase. If the load is not receiving power, \( y_{i,k,t} = 0 \), then \( \left| y_{i,k,t} - 1 \right| \) will be 1, providing the weight value of node \( i \)'s load during the fault recovery phase.

The distribution network fault recovery also adopts the rolling optimization method to gradually determine the distribution island operation plan for each scheduling period. The actual duration of the scheduling period \( \Delta T \) is taken as 15 min. The operation strategies of adjacent scheduling periods need to be connected and coordinated. The scheduling plan for the \( t \)-th scheduling period is obtained by solving a joint optimization model within time periods \( T = \{ t, t + \Delta T, \ldots, t + T_f \Delta T \} \).

3.2. Constraint Condition

In the process of fault recovery in the distribution network, it is still necessary to ensure the radial topology structure of the distribution network, namely Equations (6), (7) and (10)–(12). Due to the existing power supply capacity of the main network, power exchange can be carried out between the distribution network and the main network. Therefore, Equations (8) and (9) should be replaced with the following Equation (37).

\[
\phi_{i,j,t} \geq 0 \quad \forall i \in N, t \in T
\]

(37)

The power flow of the line and the amplitude of node voltage cannot exceed the limit, i.e., Equations (14)–(20). In addition, diesel generators, energy storage, and other DGs need to meet their own operational constraints, namely Equations (21)–(34). The wind and solar power plant model and uncertainty handling methods will also be explained in Section 4.

In addition to the above constraints, during the fault recovery process, loads that were not previously cut off during island operation should not be cut off during this process. This constraint can ensure that the power supply of important loads is not affected during the fault recovery process, which can be expressed by Equation (38).
\[ w_i = 1 \quad \forall i \in N_k, k \in \Omega \]  

The interaction power between the distribution network and the main network should meet capacity constraints, which can be expressed by Equation (39).

\[-S_{ij}y_{ij} \leq P_{ij,t} \leq S_{ij}y_{ij} \quad \forall ij \in E, t \in T \]  

4. Modeling and Solving Methods for Uncertainty in Distribution Networks

In response to the impact of wind and solar power uncertainty on the proposed islanding and operation methods of the distribution network, this section establishes an uncertainty model for wind and solar power plants at nodes, and simulates wind and solar fluctuations using scenario generation and restoration methods. Subsequently, based on the second-order cone programming method, a distribution network islanding and operation model and a distribution network fault recovery model considering new energy uncertainty are established.

4.1. Uncertainty Modeling of Wind and Solar Power Plants

Wind energy, as a clean and renewable energy source, has randomness, intermittency, and volatility. Wind speed is the main factor determining the output of wind farms. The existing literature mostly uses Weibull distribution to describe wind speed [27], and its probability density function can be expressed as (40).

\[ g_i(v) = \frac{k_i}{c_i} \left( \frac{v}{c_i} \right)^{k_i - 1} \exp \left( - \left( \frac{v}{c_i} \right)^{k_i} \right) \]  

In stability analysis for large wind farms with multiple wind turbines operating in parallel, one or more equivalent turbines are often considered. For a single wind turbine, the wind speed determines its active output, and its corresponding relationship is (41).

\[ p_{\text{wind}}^{i,t} = \begin{cases} 0 & v_i \leq v_c, v_i \geq v_d \\ \frac{v_i - v_c}{v_d - v_c} & v_c < v_i \leq v_r \\ \frac{v_r - v_i}{v_d - v_c} & v_r < v_i < v_d \end{cases} \]  

There are errors in photovoltaic prediction. In this paper, the photovoltaic prediction error is considered to follow a normal distribution, and the probability density function of photovoltaic active output can be expressed as (42).

\[ f\left( p_{\text{pv}}^{i,t} \right) = \frac{1}{\sqrt{2\pi}\sigma_{i,t}^{\text{pv}}} \exp \left( - \left( \frac{p_{\text{pv}}^{i,t} - \mu_{i,t}^{\text{pv}}}{\sqrt{2}\sigma_{i,t}^{\text{pv}}} \right)^2 \right) \]  

4.2. Model Solving Methods

Without taking into account the output uncertainty of wind and solar power plants, the aforementioned models for distribution network islanding, operation, and fault recovery can all be formulated as a standard second-order cone programming problem. Assuming the dimension with solving variables is \( n \), the standard form of the \( n \)-dimensional second-order cone can be expressed as (43).

\[ C = \{ (u, t) \mid u \leq t, t \geq 0 \} \]  

where \( u \in R^{n-1}; t \in R \). The feasible region of the second-order cone composed of constraints is (44).

\[ \| Ax + b \|_2 \leq c'x + d \]
where \( x \in \mathbb{R}^n; b \in \mathbb{R}^m; c \in \mathbb{R}^m; d \in \mathbb{R}; A \in \mathbb{R}^{m \times n}; c' \) is the transposition of vector \( c \). Combining the general model of second-order cone programming, deterministic islanding and operation models of distribution networks, as well as distribution network fault recovery models, can be expressed as (45).

\[
\begin{aligned}
\min f(x) \\
\text{s.t.} \quad & \| Ax + b \|_2 \leq c'x + d \\
& g(x) = 0 \\
& h(x) \leq 0
\end{aligned}
\]

To solve the optimization model that includes uncertainty in the output of wind and solar power plants, this paper uses the scenario generation and restoration method to simulate wind and solar fluctuations. The scenario generation and restoration method includes two sub-processes: scenario generation and scenario restoration. In the process of scenario generation, based on the uncertainty model of wind and solar power plants, the power fluctuations of each node of the wind and solar power plant are randomly simulated and combined into a set of simulation scenarios. By repeating the process multiple times, a comprehensive description of various fluctuations can be obtained. Scenario restoration refers to the clustering analysis of a large number of generated scenarios to obtain a few scenarios with stronger representativeness and significant differences between them.

In the process of scenario generation, this paper uses Latin hypercube sampling to generate a large number of wind and solar power plant output scenarios, with a sampling scale of \( N \).

The process of scene restoration can be described as the following steps:

1. Based on the generated output scenarios of \( N \) wind and solar power plants, set the clustering number to \( K \) and randomly select \( K \) clustering centers \( C_i \). Using the Formula (46), calculate the Euclidean distance between each pair of scenarios and the cluster center.

\[
d(X, C_i) = \sqrt{\sum_{j=1}^{M} (X_j - C_{ij})^2}
\]

2. Divide each scenario into the nearest cluster center.
3. Calculate the average value of each cluster center data as the new cluster center and proceed to the next iteration.
4. Repeat steps 2–3, and when the set number of iterations is reached or the clustering center no longer changes, the clustering is completed and the scenario is restored to \( K \).
5. Count the number of scenarios in each cluster center as its weight value \( \rho_i \).

Record the typical output scenarios of \( K \) wind and solar power plants obtained by the scene generation and restoration method as \( \Psi_{typ} \), while ensuring good resilience of fault recovery strategies to fluctuations in typical scenario sets \( \Psi_{typ} \). Add two extreme scenarios in \( \Psi_{typ} \), namely the “maximum wind power output minimum photovoltaic output” scenario and the “minimum wind power output maximum photovoltaic output” scenario, and the expanded scenario set \( \Psi_{com} \) can be expressed as (47).

\[
\Psi_{com} = \Psi_{typ} \cup \left\{ \left( \frac{p_{\text{wind}}}{i_{\text{max}}}, \frac{p_{\text{pv}}}{i_{\text{min}}} \right), \left( \frac{p_{\text{wind}}}{i_{\text{min}}}, \frac{p_{\text{pv}}}{i_{\text{max}}} \right) \right\}
\]

After adding extreme conditions, according to the summary form of the deterministic optimization problem in Equation (45), the distribution network islanding and operation model considering the uncertainty of new energy, as well as the distribution network fault recovery model, can be expressed as (48).
The optimization model in Equation (48) can be solved using mature commercial software CPLEX 12.10.

5. Example Analysis

5.1. Example System

This paper uses an improved IEEE-33 node distribution network with DG configuration to verify the feasibility and effectiveness of the proposed islanding operation and fault recovery strategy for the distribution network. The IEEE-33 node distribution system is a standard and widely recognized test system in the field of distribution network studies. Its structure and characteristics make it an ideal model for numerous analyses related to the distribution network, and, as such, it is frequently used as a benchmark in academic research [28]. The improved IEEE-33 node distribution network is shown in Figure 1. In Figure 1, the numbers indicate the individual nodes and the arrows indicate the power flow. This paper improves the IEEE-33 node distribution network to include 4 DGs. Among them, DG1 is wind power or photovoltaic, connected to 6 nodes; DG2 is energy storage, connected to 13 nodes; DG3 and DG4 are both diesel generators, connected to 24 nodes and 31 nodes, respectively. The DG parameters in the example in this paper are shown in Table 1 [29–31].

The topology diagram of the distribution network is shown in Figure 1. In Figure 1, the numbers indicate the individual nodes and the arrows indicate the power flow. This paper improves the IEEE-33 node distribution network to include 4 DGs. Among them, DG1 is wind power or photovoltaic, connected to 6 nodes; DG2 is energy storage, connected to 13 nodes; DG3 and DG4 are both diesel generators, connected to 24 nodes and 31 nodes, respectively. The DG parameters in the example in this paper are shown in Table 1 [29–31].

![Topology diagram of the distribution network.](image)

**Table 1. Parameters of DGs in case studies.**

<table>
<thead>
<tr>
<th>Node</th>
<th>DG Type</th>
<th>Capacity (kW)</th>
<th>Power Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>Wind or photovoltaic power</td>
<td>500</td>
<td>0.85</td>
</tr>
<tr>
<td>13</td>
<td>Energy storage</td>
<td>700</td>
<td>0.9</td>
</tr>
<tr>
<td>24</td>
<td>Diesel generator</td>
<td>1000</td>
<td>0.8</td>
</tr>
<tr>
<td>31</td>
<td>Diesel generator</td>
<td>1000</td>
<td>0.9</td>
</tr>
</tbody>
</table>
According to the importance of each node load in the distribution network, this paper divides the load into first level load, second level load, and third level load. The weight coefficients of the three types of loads and their corresponding nodes are shown in Table 2.

Table 2. Weight coefficient and located node of the three types of loads.

<table>
<thead>
<tr>
<th>Load Type</th>
<th>Weight Coefficient</th>
<th>Node</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 1</td>
<td>100</td>
<td>5, 6, 12, 13, 23, 24, 29, 31</td>
</tr>
<tr>
<td>Level 2</td>
<td>10</td>
<td>7, 11, 15, 22, 26, 30, 32</td>
</tr>
<tr>
<td>Level 3</td>
<td>1</td>
<td>1, 2, 3, 4, 8, 9, 10, 14, 16, 17, 18, 19, 20, 21, 25, 27, 28</td>
</tr>
</tbody>
</table>

In the data collection process, the JZ818 model smart meter from Jinzhi Technology Co., Ltd. (Shenzhen, China) is utilized to measure the power from wind and photovoltaic sources. This smart meter, with a power measurement precision of level 1.0, ensures the measurement error within its operational range does not exceed 1%, upholding the accuracy and reliability of the data gathered. It supports bidirectional energy measurement and various communication modes such as RF, PLC, GPRS, and NB-IoT, further enhancing the robustness of our data collection approach.

This paper describes the uncertainty of both systems through the scenario generation and restoration method in Section 4.2. Taking wind power as an example, the process begins by gathering extensive wind speed data from the microgrid project in Hubei Province over prolonged periods, ensuring a broad understanding of the wind profile. For a distinct typical day, wind speed readings are precisely captured at 15 min intervals, summing up to 96 data points for that day. Subsequently, statistical methods are employed to estimate the Weibull parameters, $k$ and $c$, which portray the probability distribution of wind power across varying wind speeds. Utilizing a typical day’s wind speed data as the foundation, 500 distinct wind speed curves are generated to encapsulate the inherent variability of wind speeds. This procedure is built upon the Weibull distribution. For each of the 500 scenarios, random samples are drawn from the Weibull distribution characterized by our estimated $k$ and $c$ parameters. These samples are then superimposed upon the base wind speed profile of the selected typical day. By doing so, each generated curve mirrors the typical day’s profile but incorporates variations steered by the Weibull-derived randomness.

Further, to ensure computational efficiency in subsequent analyses, these 500 wind speed curves are adeptly condensed into 5 representative curves using the restoration technique delineated in Section 4.2 of the paper. Based on the measured data and the uncertainty model, Figures 2 and 3 show the scenario generation results and scenario restoration results for wind power generation, respectively. Figures 4 and 5 show the scenario generation results and scenario recovery results for PV, respectively.

Figure 2. Scenario generation result of the wind power.
5.2. Analysis of Islanding Division and Operation in Distribution Networks

Assuming that the new energy source at node 6 is wind power, and assuming that the distribution system is in an extreme fault situation, that is, the upstream substation outlet circuit breaker trips, the connection between the distribution system and the higher-level power grid is disconnected and line s28 malfunctions. Taking the output data of wind farms and photovoltaic power plants during a certain period as an example, the proposed island division and operation model is solved and the results of the island division are shown in Figure 6. From the figure, it can be seen that all DGs and important loads are divided into two distribution islands, among which Island 1 contains two DGs and 12 loads, and Island 2 contains two DGs and 11 loads.
The proposed autonomous operation strategy does not require a predetermined total scheduling time, and the operation strategy for each scheduling period is updated in real-time through rolling mode. However, for comparison purposes, five of these periods are selected for analysis below. Island 2 contains uncertain new energy sources, so this paper first selects Island 2 for analysis.

When node 6 in Island 2 is connected to wind power, the voltage of the island at different time periods is shown in Figure 7, and the DG output, load, and network loss within the island are shown in Figure 8. The total load within the island during five periods is 1.58 MW, 1.32 MW, 1.04 MW, 0.96 MW, and 1.295 MW, respectively. In order to achieve a sustainable power supply and optimized operation of important loads in the island, the wind power output during the five periods is 0.5 MW, 0.45 MW, 0.3 MW, 0.25 MW, and 0.43 MW, and the diesel generator output is 1.0849 MW, 0.873 MW, 0.7434 MW, 0.7144 MW, and 0.8693 MW, respectively. The total losses of the lines within the isolated island during operation are 4.9 kW, 3 kW, 3.4 kW, 4.4 kW, and 4.3 kW in five periods, respectively. In
addition, the maximum voltage of all nodes within the five time periods is 1.1 pu, and the
minimum voltage is 1.0884 pu. In this example, the proportion of wind power output is
31.65%, 34.09%, 28.85%, 26.04%, and 33.21%, respectively. This means that the strategy
proposed in this paper can achieve effective islanding and islanding operation without the
voltage exceeding the limit when the proportion of new energy power is 34.09%.

Figure 7. Voltage of isolated island at different times when wind power is connected.

When node 6 in Island 2 is connected to photovoltaic power, the voltage of the island
at different time periods is shown in Figure 9, and the DG output, load, and network
loss within the island are shown in Figure 10. The total load within the island during
the five periods is 1.58 MW, 1.32 MW, 1.04 MW, 0.96 MW, and 1.295 MW, respectively.
In order to achieve a sustainable power supply and optimized operation of important
loads in the island, the photovoltaic output during the five periods is 0.12 MW, 0.25 MW,
0.42 MW, 0.02 MW, and 0.63 MW, and the diesel generator output is 1.4709 MW, 1.0752 MW,
0.6226 MW, 0.9486 MW, and 0.6685 MW, respectively. The total loss of the line within the
isolated island during operation is 10.9 kW, 5.2 kW, 2.6 kW, 8.6 kW, and 3.5 kW in the five
periods, respectively. In addition, the maximum voltage of all nodes during the five time
periods is 1.1 pu, and the minimum voltage is 1.0811 pu. In this example, the proportion of
photovoltaic output is 7.59%, 18.94%, 40.38%, 2.08%, and 48.65%, respectively. This means
that the strategy proposed in this paper can achieve effective islanding and islanding
operation without the voltage exceeding the limit when the proportion of new energy
power is unlikely to be 48.65%.
Figure 7. Voltage of isolated island at different times when wind power is connected.

When node 6 in Island 2 is connected to photovoltaic power, the voltage of the island at different time periods is shown in Figure 9, and the DG output, load, and network loss within the island are shown in Figure 10. The total load within the island during the five periods is 1.58 MW, 1.32 MW, 1.04 MW, 0.96 MW, and 1.295 MW, respectively. In order to achieve a sustainable power supply and optimized operation of important loads in the island, the photovoltaic output during the five periods is 0.12 MW, 0.25 MW, 0.42 MW, 0.02 MW, and 0.63 MW, and the diesel generator output is 1.4709 MW, 1.0752 MW, 0.6226 MW, 0.9486 MW, and 0.6685 MW, respectively. The total loss of the line within the isolated island during operation is 10.9 kW, 5.2 kW, 2.6 kW, 8.6 kW, and 3.5 kW in the five periods, respectively. In addition, the maximum voltage of all nodes during the five time periods is 1.1 pu, and the minimum voltage is 1.0811 pu. In this example, the proportion of photovoltaic output is 7.59%, 18.94%, 40.38%, 2.08%, and 48.65%, respectively. This means that the strategy proposed in this paper can achieve effective islanding and islanding operation without the voltage exceeding the limit when the proportion of new energy power is unlikely to be 48.65%.

Figure 8. DG output, load, and network loss in isolated island when wind power is connected.

Figure 9. Voltage of isolated island at different times when photovoltaic power is connected.
Compared to the situation where node 6 is connected to wind power and photovoltaic power, the fluctuation of photovoltaic power is greater within five time periods. However, the proposed island division and operation strategy can ensure that the load within the island can receive power supply without the voltage exceeding the limit. Therefore, the proposed islanding and operation method can utilize the generation capacity of DGs and islanding to maintain the normal operation of important loads in situations where the distribution system cannot recover from the power grid.

To further analyze the impact of new energy uncertainty on the safe operation of islands, it is assumed that node 6 in Island 2 is connected to wind power and randomly generates 20 wind power scenarios. Figure 11 shows the statistics of island voltage fluctuations in different scenarios during a certain period of time. It can be seen that in the 20 wind power scenarios, the node voltage within the island is between 1.08 pu and 1.1 pu, and there is no voltage exceeding the limit. Therefore, the proposed islanding and operation method can not only maintain the normal operation of important loads but also cope with the impact of new energy uncertainty on the safe operation of the system, effectively avoiding further expansion of faults and causing chain failures.

On this basis, this paper analyzes Island 1 and the initial energy storage capacity is 50% of the rated capacity. During the five time periods, the total load in Island 1 is 1.84 MW, 1.90 MW, 1.96 MW, 2.02 MW, and 2.08 MW, respectively. The total losses of the lines within the island are 4.51 kW, 4.43 kW, 4.55 kW, 4.62 kW, and 4.31 kW, respectively. As shown in Figure 12, the maximum voltage of all nodes during the five time periods is 1.093 pu, and there is no voltage exceeding the limit.

In addition, considering the impact of the initial energy storage capacity on system operation, when the initial energy storage capacity is 80% of the rated capacity, the voltage of Island 1 at different time periods is simulated, as shown in Figure 13. During the five time periods, when the total load in Island 1 is 2.08 MW, 1.98 MW, 2.08 MW, 2.21 MW, and 1.83 MW, the total losses of the lines in Island 1 are 4.51 kW, 4.44 kW, 4.52 kW, 4.55 kW, and 4.52 kW, respectively. The maximum voltage of all nodes in Island 1 is 1.094 pu, and there
is no voltage exceeding the limit. To a certain degree, it indicates that the island division and operation strategy proposed in this paper can be applied to different initial energy storage capacities.

Figure 11. Voltage fluctuation statistics of isolated island under different scenarios.

Figure 12. Voltage of Island 1 at different time periods when the initial energy storage capacity is 50%.

Figure 13. Voltage of Island 1 at different time periods when the initial energy storage capacity is 80%.
Figure 12. Voltage of Island 1 at different time periods when the initial energy storage capacity is 50%.

Figure 13. Voltage of Island 1 at different time periods when the initial energy storage capacity is 80%.

5.3. Analysis of Distribution Network Fault Recovery

If the main network resumes power supply, the power loss load can be further connected to the main network through distribution lines to achieve distribution network fault recovery. This section tests the performance of the proposed power grid fault recovery strategy in different types of fault situations.

5.3.1. The Fault Occurred in S28 and DG3

When the fault branch is set to S28 and DG3, the system isolates the fault point. Based on the power supply capacity of the remaining DGs in the main and distribution networks, network reconstruction is carried out and the network structure shown in Figure 14 is obtained. It can be seen that due to the presence of DG4 in the downstream area, the system turns switch S29 off and DG4 switches to island operation mode. Due to DG3 malfunction, DG3 exits the system, stops supplying power, and switch S22 is reconnected to the main network; DG1 and DG2 are connected to the remaining systems to participate in fault recovery and reconstruction and node 28 is connected to the main network through the interconnection switch S37.

Figure 15 shows the voltage of each node before and after reconstruction during faults in lines S28 and DG3. The minimum/maximum voltage and network loss before and after reconstruction are shown in Table 3. From the table, it can be seen that through network reconstruction, the system network loss is effectively controlled and the minimum voltage of nodes is also improved. Specifically, after fault reconstruction, the overall active power loss of the line is reduced by 5.87 kW, and the minimum node voltage increases by 0.0046 pu. Therefore, the network reconstruction strategy can help improve the stability of the distribution network.
Minimum and maximum voltage of nodes and power loss before and after network reconstruction are shown in Table 3. From the table, it can be seen that through network reconstruction, the system network loss is effectively controlled and the minimum node voltage increases by 0.0046 pu. Therefore, the network reconstruction strategy can help improve the economy and stability of the system.

Table 3. Minimum and maximum voltage of nodes and power loss before and after network reconstruction when the fault occurred in S28 and DG3.

<table>
<thead>
<tr>
<th>Algorithm Category</th>
<th>Active Power Loss</th>
<th>Minimum Voltage</th>
<th>Maximum Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before reconstruction</td>
<td>49.3339</td>
<td>1.0683</td>
<td>1.1</td>
</tr>
<tr>
<td>After GA reconstruction</td>
<td>43.4675</td>
<td>1.0729</td>
<td>1.1</td>
</tr>
</tbody>
</table>

5.3.2. The Fault Occurred in S28

When the faulty branch is set to S28, the system isolates the faulty point. Based on the power supply capacity of the remaining DGs in the main and distribution networks, network reconstruction is carried out and the network structure shown in Figure 16 is obtained. It can be seen that due to the presence of DG4 in the downstream area, the system turns switch S29 off and DG4 switches to island operation mode; DG1 and DG2 are connected to the remaining systems to participate in fault recovery and reconstruction and node 28 is connected to the main network through the interconnection switch S37.
compared to the simultaneous failures of S28 and DG3, the integration of DG3 can significantly improve the economy and stability of the system.

Table 4. Minimum and maximum voltage of nodes and power loss before and after network reconfiguration when the fault occurred in S28.

<table>
<thead>
<tr>
<th>Algorithm Category</th>
<th>Active power Loss</th>
<th>Minimum Voltage</th>
<th>Maximum Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before reconstruction</td>
<td>22.2987</td>
<td>0.9736</td>
<td>1.1</td>
</tr>
<tr>
<td>After GA reconstruction</td>
<td>19.2725</td>
<td>0.9824</td>
<td>1.1</td>
</tr>
</tbody>
</table>

Figure 16. Network reconfiguration result when the fault locates at line S28.

Figure 17 shows the voltage of each node before and after reconstruction during the line S28 fault. The minimum/maximum voltage and network loss before and after reconstruction are shown in Table 4. From the table, it can be seen that network reconstruction helps to reduce system network losses and increase the minimum voltage of nodes. In this example, after fault reconstruction, the overall active power loss of the line is reduced by 3.03 kW, and the minimum voltage of the node increases by 0.0088 pu. Meanwhile, compared to the simultaneous failures of S28 and DG3, the integration of DG3 can significantly reduce network losses in the distribution system and help to increase the minimum voltage of the nodes. Therefore, reasonable allocation of DG in the distribution network will help improve the economy and stability of the system.

Figure 17. Voltage of nodes before and after network reconfiguration when line S28 is faulty.
5.3.3. The Fault Occurred in S9 and S22

When the fault branch is set to S9 and S22, the system isolates the fault point. Based on the power supply capacity of the remaining DGs in the main and distribution networks, the network reconstruction results are shown in Figure 18. It can be seen that there are two isolated islands after network reconstruction. Specifically, the downstream area of branch S9 contains DG2, so S17 is disconnected and DG2 operates in island mode, supplying power to nodes 10–16. The downstream area of branch S22 contains DG3, so the contact switch S3 remains disconnected. DG3 operates in island mode and supplies power to nodes 22–24. DG1 and DG4 are connected to the remaining system to participate in fault recovery and reconstruction. Therefore, switch S29 is closed again and node 17 is connected to the remaining system through contact with switch S36.

Figure 18. Network reconfiguration result when the fault locates at line S9 and S22.

Figure 19 shows the voltage of each node before and after reconstruction during faults in lines S28 and DG3. The minimum/maximum voltage and network loss before and after reconstruction are shown in Table 5. Similar to the above two examples, network reconstruction helps to reduce system network losses and increase the minimum voltage of the nodes. In this example, after fault reconstruction, the overall active power loss of the line is reduced by 5.64 kW and the minimum voltage of the node increases by 0.0046 pu.

Figure 19. Voltage of nodes before and after network reconfiguration when lines S9 and S22 are faulty.
Through analysis of the above three examples, the proposed fault recovery strategy can effectively reduce system network loss and increase the minimum voltage of nodes through network reconstruction, which helps to improve the economy and stability of the system.

5.3.4. The Impact of Island Operation on Fault Recovery

This paper considers the impact of changes in island partitioning schemes on load during the fault recovery phase and the load weight value \( \beta_{i,k} \) is designed in the form of Equation (36). This section compares the impact of island operation on fault recovery and compares the \( \beta_{i,k} \) designed as \( \beta_{i,k} = \alpha_{i,k} \), which only considers the load weight values of the island division stage, ignores the correlation between the island division stage and the island operation stage, and does not consider the impact of changes in the island division scheme on the load, as well as the impact of node 6’s load not receiving power during the island operation stage.

Assuming that the fault occurs in S28 and assuming that the superior power grid resumes power supply within 20 h, that is, the distribution grid has to operate in isolation for 20 h, and assume that the new energy source for node 6 is wind power, in the 20 h rolling optimization, node 28 is initially not classified as an island due to the small wind power output, but is later classified as Island 2 during the wind power surge. Finally, due to the reduced wind power output, it is eliminated by Island 2, implying that node 6 experienced a process of power outage, power supply, and then another power outage after a system failure. The network reconstruction results obtained using the method of islanding operation on fault recovery in this paper are displayed in Figure 16, while the results using the comparative method are presented in Figure 20. It is evident that node 28 in the comparison method did not receive power. This is because the comparison method assigns excessive weight values to switch actions, neglecting the impact of intermittent power supply during islanding operation on user satisfaction with electricity consumption. For the method proposed in this paper, due to the sequence of events experienced by node 6 after a system failure, during the fault recovery process the power supply recovery of node 6 receives a higher weight value, thus ensuring the power supply to the node and achieving high user satisfaction with electricity consumption.

![Figure 20. Network reconfiguration result when the fault locates at line S28 (comparison method).](image-url)
Table 5. Minimum and maximum voltage of nodes and power loss before and after network reconfiguration when the fault occurred in S9 and S22.

<table>
<thead>
<tr>
<th>Algorithm Category</th>
<th>Active Power Loss</th>
<th>Minimum Voltage</th>
<th>Maximum Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before reconstruction</td>
<td>39.5470</td>
<td>0.9650</td>
<td>1.1</td>
</tr>
<tr>
<td>After GA reconstruction</td>
<td>33.9117</td>
<td>0.9696</td>
<td>1.1</td>
</tr>
</tbody>
</table>

6. Experiment

To further verify the viability of the proposed strategy, the present study employs a semi-physical simulation approach. The framework for the semi-physical experiment is visually represented in Figure 21. Within this structured layout, the environment of the distribution network is replaced by the OPAL-RT system, which can provide a robust platform for the experimental validation due to its precision and reliability. The proposed strategy is implemented using a digital signal processing (DSP) controller, which is an integral component ensuring the seamless execution of the strategy. In the operation, the DSP controller gathers comprehensive power information from the OPAL-RT environment of the distribution network. Working in collaboration with the control method delineated in this study, it effectively partitions the distribution network and the separated parts take the islanding strategy for operation. Beyond this, the observation of the voltage at various nodes within the system is conducted using an oscilloscope.

Figure 21. Semi-physical experiment framework.

Given the connection of node 6 to photovoltaic power generation and a fault in line S28, the DSP controller is able to accurately detect the fault and issue corresponding switch signals to isolate the fault area. Consequently, the entire distribution network bifurcates into two islands, as depicted in Figure 6, with each island possessing the capacity for islanding operation. After the islanding, Island 1 and Island 2 utilize the resources within the separated part and dispatch them for operation using the proposed method. The voltage of each node in Island 2 during the islanding operation is exhibited in Figures 22–24, the straight line in the figure indicates no signal access.
It should be noted that these three figures show the voltage waveforms, with node 24 serving as the phase reference node. From the figures, we can observe that after a fault occurs in the distribution network, the islanding system is able to operate stably without exceeding the limits of voltage frequency and voltage magnitude. For example, with Figure 22, the voltages of each node range approximately from 1.082 to 1.099, indicating minimal fluctuation and consistent power distribution throughout the island. The phase angles of the nodes vary between $-10.09$ degrees and 0 degrees, demonstrating a reasonable distribution range without extreme deviations, further emphasizing the stability within the network. Moreover, the voltage frequency nearing 50 Hz is another indicator of the operational stability of Island 2. This standard frequency value reflects efficient and stable energy distribution throughout the island, reducing the likelihood of voltage-related issues. In conclusion, these observations succinctly highlight the robust and stable operational capacity of Island 2. Further, the feasibility and effectiveness of the proposed strategy in the distribution network are effectively verified by using the semi-physical experiment method.

Figure 22. Cont.
Figure 22. Node voltage waveform for time period 1.

Figure 23. Cont.
Figure 23. Node voltage waveform for time period 2.

Figure 24. Cont.
Figure 24. Node voltage waveform for time period 3.

7. Conclusions

This study proposes a distribution network islanding operation and fault recovery strategy which incorporates the inherent uncertainty of new energy sources. This method is particularly applicable to scenarios when the main network fails to recuperate after extreme faults, or in instances where the primary network is restored but certain distribution network faults persist. The results show that the strategic implementation of the rolling optimization method during the islanding operation and fault recovery phases not only ensures the safety and economic efficiency of the system operation but also offers adaptability in real-time planning for each scheduling period. Crucially, the presented islanding and operation approach maximizes the utility of the power generation capacity and the islanding capability of DGs. Delving into the specifics, during the islanding division stage, the node voltage remains within the 1.08 pu to 1.1 pu range, even when new energy contributions surge to 34.09% and 48.65%. Concurrently, line losses, as a proportion of the total load, range from 0.22% to 0.26% and are contingent upon whether initial energy levels
in storage units stand at 50% or 80%. In the fault recovery stage, the proposed method showcases power loss reductions of approximately 11.9%, 13.6%, and 14.2% across three distinct cases, in comparison to traditional approaches bereft of network reconstruction. Future researches will focus on refining the optimization algorithm to further bolster system efficiency. Moreover, further studies should consider how other renewable energy sources, beyond the ones considered in this study, influence islanding and fault recovery.

**Author Contributions:** Conceptualization, Z.Y. and J.H.; Data curation, Y.L.; Formal analysis, W.H.; Methodology, Z.Y., J.H., F.Y., Y.L. and H.M.; Resources, H.M.; Software, J.H., L.L. and Y.D.; Validation, L.S.; Writing—original draft, J.H.; Writing—review and editing, J.H., L.L. and Y.D. All authors have read and agreed to the published version of the manuscript.

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**Nomenclature**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Omega )</td>
<td>the set of islands divided</td>
</tr>
<tr>
<td>( N_k )</td>
<td>the set of nodes in island ( k )</td>
</tr>
<tr>
<td>( N_S )</td>
<td>the set of the node connected to the main network</td>
</tr>
<tr>
<td>( N_{DG} )</td>
<td>the set of DG nodes in the distribution network</td>
</tr>
<tr>
<td>( E )</td>
<td>the set of DG nodes in the distribution network</td>
</tr>
<tr>
<td>( E_k )</td>
<td>the set of lines in island ( k )</td>
</tr>
<tr>
<td>( E_S )</td>
<td>the set of the connection line between the distribution network and the main network.</td>
</tr>
<tr>
<td>( E_F )</td>
<td>the set of the faulty line</td>
</tr>
<tr>
<td>( L )</td>
<td>the set of distribution lines</td>
</tr>
<tr>
<td>( T )</td>
<td>the solution period for rolling optimization</td>
</tr>
<tr>
<td>( t_1 )</td>
<td>scheduling period for a new isolated island scheme</td>
</tr>
<tr>
<td>( \tau_f )</td>
<td>the step size of rolling optimization</td>
</tr>
<tr>
<td>( \Delta T )</td>
<td>the scheduling time window</td>
</tr>
<tr>
<td>( a_{ik} )</td>
<td>the weight value assigned to node ( i ) load in island ( k )</td>
</tr>
<tr>
<td>( p_{L_{i,k,t}} )</td>
<td>the active load that node ( i ) in island ( k ) needs to cut off at time ( t )</td>
</tr>
<tr>
<td>( \mu_{loss} )</td>
<td>the weight of the network loss term</td>
</tr>
<tr>
<td>( S_{ij} )</td>
<td>the maximum apparent power allowed to flow through line ( ij )</td>
</tr>
<tr>
<td>( Q_{i,t}^L )</td>
<td>the load active demand of time period node ( i ) at time ( t )</td>
</tr>
<tr>
<td>( Q_{i,t}^R )</td>
<td>the load reactive demand of time period node ( i ) at time ( t )</td>
</tr>
<tr>
<td>( Q_{L_i}^D )</td>
<td>the reactive output of diesel generator ( i )</td>
</tr>
<tr>
<td>( Q_{max}^{L_i} )</td>
<td>the maximum values of the reactive output of diesel generator ( i )</td>
</tr>
<tr>
<td>( Q_{min}^{L_i} )</td>
<td>the minimum values of the reactive output of diesel generator ( i )</td>
</tr>
<tr>
<td>( R_{p_i}^{l} )</td>
<td>the active ramp rates of diesel generator ( i ).</td>
</tr>
<tr>
<td>( R_{q_i}^{l} )</td>
<td>the reactive ramp rates of diesel generator ( i ).</td>
</tr>
<tr>
<td>( N_{ES} )</td>
<td>the set of energy storage systems</td>
</tr>
<tr>
<td>( p_{dis_{i,j}}^{l} )</td>
<td>the discharge active power of energy storage system ( i ) at time ( t )</td>
</tr>
<tr>
<td>( p_{ch_{i,j}}^{l} )</td>
<td>the charge active power of energy storage system ( i ) at time ( t )</td>
</tr>
<tr>
<td>( p_{dis_{i,j}}^{l_{,min}} )</td>
<td>the minimum discharging active power of the energy storage system ( i )</td>
</tr>
<tr>
<td>( p_{dis_{i,j}}^{l_{,max}} )</td>
<td>the maximum discharging active power of the energy storage system ( i )</td>
</tr>
</tbody>
</table>


\begin{align*}

R_{ij} & \quad \text{the resistance of line } ij \\
X_{ij} & \quad \text{the reactance of line } ij \\
l_{ij,k,t} & \quad \text{the current flowing through line } ij \\
P_{li,k,t}^h & \quad \text{the load active power of node } i \text{ in island } k \text{ at time } t \\
p_{\text{wind}}^{i,j,k,t} & \quad \text{the wind power active power of node } i \text{ in island } k \text{ at time } t \\
p_{PV}^{i,j,k,t} & \quad \text{the photovoltaic active power of node } i \text{ in island } k \text{ at time } t \\
y_{i,k} & \quad \text{the states of node } i \text{ in island } k \\
y_{ij,k} & \quad \text{the states of line } ij \text{ in island } k \\
r_k & \quad \text{the potential root node of island } k \\
M_{\theta} & \quad \text{a sufficiently large parameter} \\
\psi_{i,j,t} & \quad \text{the flow direction of power from node } i \text{ to node } j \text{ at time } t \\
p_{DG}^{i,j,t} & \quad \text{the active power generation capacity of DG in island } k \text{ at time } t \\
Q_{DG}^{i,j,t} & \quad \text{the reactive power generation capacity of DG in island } k \text{ at time } t \\
P_{li,t}^h & \quad \text{the load active power of node } i \text{ at time } t \\
P_{i,j,t}^h & \quad \text{the active power flowing through the line } ij \text{ at time } t \\
Q_{ij,t}^h & \quad \text{the reactive power flowing through the line } ij \text{ at time } t \\
U_{i,t} & \quad \text{the voltage of node } i \text{ at time } t \\
U_{\text{min}} & \quad \text{the allowable minimum voltage amplitude of the node} \\
U_{\text{max}} & \quad \text{the allowable maximum voltage amplitude of the node} \\
\sigma^L & \quad \text{specified threshold for load} \\
\sigma^PV & \quad \text{specified threshold for photovoltaic power} \\
\sigma^{\text{wind}} & \quad \text{specified threshold for wind power} \\
p_{\text{wind}}^{i,j,t} & \quad \text{the active output of node } i \text{'s wind turbine at time } t \\
P_{r,i} & \quad \text{the rated output power of node } i \text{'s fan at time } t \\
v_i & \quad \text{the wind speed at node } i \\
v_c & \quad \text{the cut-in wind speed of node } i \text{'s fan} \\
v_r & \quad \text{the rated wind speed of the fan at node } i \\
v_d & \quad \text{the cut-out wind speed of node } i \text{'s fan} \\
p_{PV}^{i,j,t} & \quad \text{the active output of node } i \text{'s photovoltaic system at time } t \\
p_{L}^{i,j,t} & \quad \text{the expected output of photovoltaic active power at time } t \\
R_{i,\text{min}} & \quad \text{the minimum charging active power of the energy storage system } i \\
R_{i,\text{max}} & \quad \text{the maximum charging active power of the energy storage system } i \\
Q_{\text{dis}}^{i,t} & \quad \text{the discharge reactive power of energy storage system } i \text{ at time } t \\
Q_{\text{h}}^{i,t} & \quad \text{the charge reactive power of energy storage system } i \text{ at time } t \\
P_{\text{dis}}^{i,t} & \quad \text{the discharge states of the energy storage system } i \text{ at time } t \\
P_{\text{h}}^{i,t} & \quad \text{the charge states of the energy storage system } i \text{ at time } t \\
\eta_{i}^{\text{ch}} & \quad \text{the charging efficiency of the energy storage system } i \\
\xi_{i}^{\text{r}} & \quad \text{the opening and closing status of switch } d \\
\psi_{i}^{\text{typ}} & \quad \text{the weight values of the network loss term} \\
\psi_{\text{com}}^{i} & \quad \text{the switching frequency term} \\
\psi_{\text{w}}^{i} & \quad \text{the scheduling period experienced by the operation of isolated islands} \\
\psi_{\text{typ}}^{i} & \quad \text{the weight values assigned to node } i \text{'s load} \\
\psi_{\text{typ}}^{i} & \quad \text{the state of load at node } i \\
\psi_{\text{typ}}^{i} & \quad \text{the load recovery power of node } i \text{ at time } t \\
\psi_{\text{typ}}^{i} & \quad \text{the weight values of the network loss term} \\
\psi_{\text{com}}^{i} & \quad \text{the switching frequency term} \\
\psi_{\text{w}}^{i} & \quad \text{the scheduling period experienced by the operation of isolated islands} \\
\psi_{\text{typ}}^{i} & \quad \text{the weight values assigned to node } i \text{'s load} \\
\psi_{\text{typ}}^{i} & \quad \text{the state of load at node } i \\
\psi_{\text{typ}}^{i} & \quad \text{the load recovery power of node } i \text{ at time } t \\
C_t & \quad \text{the data object} \\
C_i & \quad \text{the i-th clustering center} \\
C_i & \quad \text{the j-th attribute value of } X \text{ and } C_t \\
C_i & \quad \text{the typical output scenarios of } K \text{ wind and solar power plants obtained by the scene generation and restoration} \\
C_i & \quad \text{the expanded scenario set} \\
C_i & \quad \text{the wind speed shape coefficient of node } i \\
C_i & \quad \text{the maximum apparent power allowed to flow through the line } ij \\
C_i & \quad \text{the active power of time period node } i \text{ when cutting off the load at time } t \\
C_i & \quad \text{the standard deviation of photovoltaic active output at time } t
\end{align*}

References


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