Fault recovery strategy of distribution networks with multiple EHs for reliability improvement

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Abstract. It has become a trend that user-side electricity/heat/gas energy supplies and loads are connected to the distribution network with energy hubs (EHs). The integrations of EHs bring new opportunities for the improvement of power supply reliability of distribution networks. For the distribution network with multiple EHs, a fault recovery strategy for the improvement of power supply reliability is proposed in this paper. Combining the models of EHs and radial distribution network, the typical structure of distribution network with multiple EHs is analyzed. Considering the scope of the fault and EH optimal dispatching, a failure recovery strategy for reliability improvement of distribution network with multiple EHs is proposed. With the objective of minimum power outage losses and operating costs, an optimal scheduling model for multiple EHs island operation is established. The analysis of the calculation example shows that the grid-connected operation of EH can improve the reliability of distribution network, and the optimal dispatch of the EH can effectively reduce the loss of power outage during the failure.

1. Introduction

The distribution network with multiple energy hubs (EHs) is one of the future development trends of distribution system. The EH is the hub that realizes the conversion between various energy sources, which can realize the mutual benefit of energy flow through the optimization of the operation between different internal devices [1]. Energy coupling components such as the cogeneration unit in the EH can convert the redundant energy in the gas network into electrical energy and transfer to distribution networks. Distributed generations and energy storage devices can directly supply power to the electric load in the event of a distribution network failure. Through optimized dispatch of energy and equipment, existing resources will be fully utilized to ensure the power supply of electric load to the greatest extent. Therefore, the distribution network with multiple EHs can provide support for the load of the distribution network in the event of a fault, and improve the reliability of power supply. Researches on the failure recovery strategy of the distribution network with multiple EHs under fault conditions and the optimal dispatch of EHs are of great significance to improve the reliability of power supply.
Various methods have been proposed focused on the fault recovery and reliability improvement of active distribution network with a large number of distributed sources and energy storage devices started early and has achieved certain results. In reference to the problem of active distribution network failure recovery, ref. [2] proposed a rapid generation method of network reconfiguration scheme, in order to improve the probability of reliable power supply in the distribution network under fault conditions. Ref. [3] proposed an active distribution network fault recovery method considering the high penetration rate of renewable energy, in order to ensuring the reliability of power supply for important users. Considering the randomness of distributed power outputs, ref. [4] established an active distribution network fault islanding strategy based on the distributed power period output model. The first stage of the fault recovery model is to optimize the load recovery, and the second stage is to optimize the number of switching operations. At present, the fault recovery strategy of active distribution network is mostly relied on network reconstruction, adjusting transformer taps, and using distributed power sources to form islands to achieve load energy supply during fault repair.

In recent years, more and more user-side electricity/heat/gas supplies and loads are connected to the distribution network through EHs. Compared with distributed power sources and energy storage devices, the optimal scheduling of EHs is more complex and more flexible. In the event of a fault, it has a greater potential to improve power supply reliability through optimized dispatch of the EH. Ref. [5] established a double-layer fault recovery optimization model for the distribution network with electrical-gas coupling components. This model takes the optimal failure recovery index and the economy of the natural gas network as the upper and lower model goals. Through the application of this model, the continuous power supply time of the electric load can be extended. Ref. [6] designed a fault recovery strategy suitable for permanent faults in electricity-gas-heat and transportation energy interconnected distribution networks. This strategy is divided into a network reconstruction strategy that takes the power grid switch state as the main player, and an operation optimization strategy that takes the optimized operation of each energy sub-network as the slave player. This strategy improves the reliability of power supply during the recovery period of the energy interconnection distribution network. Ref. [7] established an optimized operation strategy under the failure state of the integrated energy system on the user side. This strategy takes into account the thermal inertia and energy storage capacity elasticity of cold storage/heat storage equipment, takes the shortest dynamic response time as the optimization goal, and realizes the hour-level extension of the power supply time of the electric load. In summary, the access of multiple EHs will change the fault handling mode of the distribution network, which will have a great impact on the formulation of fault recovery strategies for the distribution network. At present, relevant research is insufficient.

In response to the above problems, this paper proposes a failure recovery strategy for a distribution network with multiple EHs for reliability improvement. First, according to the location and impact of the distribution network failure, a partitioning method based on failure consequences for the distribution network with multiple EHs is proposed. Second, considering the locations of different areas and whether the load point is connected to EHs, a fault recovery strategy for each area of the distribution network with multiple EHs is established. Third, an optimal scheduling model for island operation of EHs is established, considering the minimum loss of power outage and operating costs. Finally, the effectiveness of the proposed strategy and model is verified by a simulation example.

2. Reliability evaluation method of distribution network containing EH

2.1. Distribution network structure with EHs
The distribution network studied in this paper is not only interconnected with traditional electricity loads, but also EHs. The distribution network structure with EHs is shown in figure 1.
Seven energy supply areas named P1, P2..., P7 are connected to the distribution network. The inputs of the three energy supply areas P3, P5 and P7 are power electricity (Pe) and power gas (Pg), and the outputs are load electricity (Le) and load heat (Lh). The remaining four energy supply areas P1, P2, P4 and P6 are only for electrical energy input and electrical load demand. For energy supply areas P3, P5 and P7, the efficient and reliable operation can be achieved by multi-energy coupling and optimal scheduling. Therefore, energy supply areas P3, P5 and P7 are also called EH3, EH5, EH7.

The structure of the EH is shown in figure 2. In figure 2, the EH includes production, conversion, storage equipment of electric and heat energies, and electric and heat buses. The production equipment includes combined heating and power (CHP), gas boiler (GB), wind turbine (WT), photovoltaic panel (PV); the conversion equipment includes distribution transformer (T), electric boiler (EB); the energy storage equipment includes electric energy storage (ES) and heat energy storage (HS). The mathematical models of all the above equipment of the EH can be found in ref. [8].

2.2. Reliability evaluation method of distribution network with multiple EHS
This paper adopts Expectation of Energy Not Supply (EENS) [9] and Average Reduction Duration Index (ARDI) [9] as the reliability evaluation indicators for various load points of distribution networks. Considering the time sequence characteristics of wind and solar power generation and energy storage components, the sequential Monte Carlo simulation method is conducted to calculate the reliability indices [10].
The calculation of the reliability indices of the load point served by EH needs to obtain the reduction of the electric and heating load, and the reduction of the electric and heating load can be obtained by solving the optimal scheduling model proposed in this paper.

The calculation of the reliability indices of the load point not served by EH can be divided into three types: the first type of the load point does not lose connection with the main power supply and does not cause energy loss; the second type of the load point loses connection with main power supply and cannot obtain electric power from EH after a component fails, and the load reduction can be directly calculated; the third type of the load point loses connection with main power supply but can obtain power from the EH, and the amount of load reduction is obtained from the optimal scheduling of the grid island.

3. Failure recovery strategy of distribution networks with multiple EHs

For the distribution network with multiple EHs, when the power network fails, the distribution network is divided into the fault upstream area, the fault isolation area and the fault downstream area based on the fault location. Each partition adopts different failure recovery strategies to ensure power supply.

Taking the distribution network with multiple EHs as shown in figure 1 as an example, the fault recovery strategy of each partition will be explained. In figure 1, CB is the circuit breaker at the substation outlet, S1, S2 and S3 are section switches, and there is a simulated fault point on the feeder. Assuming that the distribution network has a high level of Feeder Automation (FA), the time spent on fault location and isolation is negligible compared to the time spent on fault repair. After the feeder 5 fails, the CB is tripped, and then the section switches S1 and S2 on both sides of the fault point are disconnected, and finally the CB is closed again, and the system enters the fault recovery stage. The partitions of the distribution network during the failure recovery stage are shown in figure 1.

The fault upstream area is the area connected to the main power supply during the fault recovery stage. The two energy supply areas P1 and P2 in figure 1 are in the fault upstream area. During the failure recovery period, the EH in the fault upstream area adopts optimal scheduling model under normal condition, and each load point is normally supplied with energy.

The fault isolation area is the area where the fault point is located. In figure 1, the energy supply area P3 is in the fault isolation area. The power network in the fault isolation area is topologically disconnected due to the fault. Therefore, all load points not served by EH in the fault isolation area are interrupted. The EH adopts the optimal scheduling model for island operation, and the reduction of the load point served by EH is solved by the optimal scheduling model for island operation.

The fault downstream area is behind the fault isolation area and is disconnected from the main power supply during the failure recovery period. In figure 1, the energy supply area P4, P6 and EH5, EH7 are in the fault downstream area. If there is no EH in the fault downstream area, the electric load will be reduced. If the fault downstream area contains some EHs, the EHs and load points will form an island together, and the optimal scheduling model for island operation will be adopted. The load reduction in the island is solved by the optimal scheduling model under island mode.

4. A fault recovery model for a distribution network with multiple EHs

During the failure recovery period, the fault upstream area adopts the optimization scheduling under normal operation, while the fault isolation area and the fault downstream area with EH operate in the island mode.

4.1. Optimal scheduling method for EH in the fault upstream area

The optimal scheduling of the EH in the fault upstream area mainly considers the economics of the system operation, and minimizes the cost of purchasing electricity and gas from the external electric grid and the external gas grid. When the electric power generated by EH is greater than load demand, the surplus power will feed back to external electric grid, and the power purchase cost is negative. Based on the optimization model in ref. [8], the operation of the fault upstream area is optimized.
4.2. Optimal scheduling model for fault isolation area and fault downstream area

When the power network fails, multiple EHs in the fault isolation area or the downstream area will form islands. Although disconnected to the main power supply, the EH is still connected to the external gas grid, and the EH contains distributed generations and storage. By scheduling the outputs of the EHs in the island, the electric load reduction is minimized and the operation economy is optimized.

(1) Objective function

The optimal scheduling model under island mode needs to meet the requirements of load demand as much as possible, and at the same time to meet the operating economy. Therefore, the objective function includes the comprehensive operating cost of the EHs and the reduction cost of load points not served by EH in the island.

\[ \min F_{\text{opt}_{\text{island}}} = \left[ \sum_{i=1}^{n} C_{\text{EH}_i}(t) + \sum_{j=1}^{m} C_{\text{NL}_\text{island}}(t) \right] \cdot \Delta t \]  

Among them:

\[ C_{\text{EH}_i}(t) = K_{\text{cost}_i} \cdot c_{\text{elec}} \cdot L_{\text{cut}_i}(t) + K_{\text{heat}_i} \cdot c_{\text{heat}} \cdot L_{\text{cut}_i}(t) + c_{\text{elec}} \cdot P_{\text{dis}_i}(t) + c_{\text{gas}} \cdot P_{\text{gas}_i}(t) \]  

\[ C_{\text{NL}_\text{island}}(t) = K_{\text{cost}_\text{NL}} \cdot c_{\text{elec}} \cdot L_{\text{cut}_\text{NL}_\text{island}}(t) \]

where \( n \) and \( m \) are the number of energy hubs and load points not served by EH in the island respectively; \( C_{\text{EH}_i}(t) \) is the comprehensive operating cost of the \( i^{th} \) EH in the island; \( C_{\text{NL}_\text{island}}(t) \) is the electric load reduction cost of the \( i^{th} \) load point not served by EH in the island; \( K_{\text{cost}_i} \) and \( K_{\text{heat}_i} \) are respectively the reduction cost coefficient of electric load and heating load; \( c_{\text{elec}}, c_{\text{heat}}, c_{\text{gas}} \) are the unit prices of electric energy, natural gas energy, and heat energy respectively; \( L_{\text{cut}_i}(t) \) and \( L_{\text{cut}_\text{NL}_i}(t) \) are respectively the reduction of electric load and heating load of the \( i^{th} \) EH in the island; \( P_{\text{dis}_i}(t) \) and \( P_{\text{gas}_i}(t) \) are respectively the interaction power of the \( i^{th} \) EH with the external power grid and the interaction power of the \( i^{th} \) EH with the external gas grid; \( K_{\text{cost}_\text{NL}} \) and \( L_{\text{cut}_\text{NL}_\text{island}}(t) \) are respectively the electric load reduction cost coefficient and the electric load reduction amount of the load points not served by EH in the island.

(2) Constraints

1) System power balance constraints

a. Electric balance

\[ L_e(t) = P_{\text{MT}_t}(t) + P_i(t) + P_{\text{pm}_t}(t) + P_{\text{wt}_t}(t) - P_{\text{EB}_t}(t) + P_{\text{ES}_\text{elec}}(t) - P_{\text{ES}_\text{dis}}(t) \]  

\[ P_i(t) = P_{\text{dis}_i}(t) \]  

where \( L_e(t), P_{\text{MT}_t}(t), P_{\text{pm}_t}(t), P_{\text{wt}_t}(t), P_{\text{EB}_t}(t) \) are respectively the electric load demand of the EH, the output power of the transformer, the photovoltaic output, the wind generator output and the power consumption of the electric boiler at time \( t \); \( P_{\text{ES}_\text{elec}}(t) \) and \( P_{\text{ES}_\text{dis}}(t) \) are the charge and discharge power of the energy storage device respectively.

b. Thermal balance

\[ L_h(t) = Q_{\text{MT}_t}(t) + Q_{\text{pm}_t}(t) + Q_{\text{wt}_t}(t) + Q_{\text{ES}_\text{dis}}(t) - Q_{\text{ES}_\text{elec}}(t) \]  

where \( L_h(t), Q_{\text{MT}_t}(t), Q_{\text{pm}_t}(t) \) and \( Q_{\text{wt}_t}(t) \) are respectively the heat load demand of the EH, the heat output power of the gas turbine and the heat output power of the electric boiler at time \( t \).

2) Tie line constraint

The EH is connected to the distribution network and the natural gas network, the input power and the input natural gas volume of the EH are limited by the maximum transmission power of the tie line.

\[ P_{\text{elec}_{\text{max}}} \leq P_{\text{dis}_i}(t) \leq P_{\text{elec}_{\text{max}}} \]  

\[ 0 \leq F_{\text{gas}_i}(t) \leq F_{\text{gas}_{\text{max}}} \]

where \( P_{\text{elec}_{\text{max}}} \) and \( P_{\text{elec}_{\text{max}}} \) are the maximum power delivered to the external electric grid and the maximum power absorbed from the external electric grid by the EH; \( F_{\text{gas}_i}(t) \) and \( F_{\text{gas}_{\text{max}}} \) are respectively the amount of natural gas absorbed from the external gas grid and the maximum amount limit of natural gas absorbed from the external gas grid by the EH during the \( t \) period.

3) Energy storage constraints
\[ \begin{align*}
    P_{SE_{-}ch}(t) & \leq P_{SE_{-}ch_{\max}} \\
    P_{SE_{-}dis}(t) & \leq P_{SE_{-}dis_{\max}} \\
    P_{SE_{-}ch}(t) \cdot P_{SE_{-}dis}(t) & = 0 \\
    P_{min} & \leq P_{SE} \leq P_{max}
\end{align*} \]

where \( P_{SE_{-}ch}(t) \), \( P_{SE_{-}dis}(t) \), \( P_{SE}(t) \) are respectively the charging power, discharging power and storage capacity in \( t \) period;

4) Energy conversion device constraints

\[ \begin{align*}
    P_{MT_{-}min} & \leq P_{MT}(t) \leq P_{MT_{-}max} \\
    P_{EB_{-}min} & \leq P_{EB}(t) \leq P_{EB_{-}max} \\
    Q_{CB_{-}min} & \leq Q_{CB}(t) \leq Q_{CB_{-}max}
\end{align*} \]

where \( P_{MT_{-}min} \) and \( P_{MT_{-}max} \) are the minimum output electric power and maximum output electric power of the gas turbine respectively; \( P_{EB_{-}min} \) and \( P_{EB_{-}max} \) are the minimum power and maximum power of electric boiler; \( Q_{CB_{-}min} \) and \( Q_{CB_{-}max} \) are the minimum power and maximum power of the gas boiler respectively.

5) Island constraints

The electric energy on the power tie line in the island needs to meet the balance of supply and demand, that is, the sum of the interactive power of EHs in the island is equal to the sum of the electric power absorbed by the load points not served by EH. Therefore, the constraints in the island are:

\[ \sum_{i=1}^{n} P_{elec}(t) + \sum_{j=1}^{n} L_{NLe}(t) + \sum_{j=1}^{n} L_{NLena} = 0 \]

\[ 0 \leq L_{NLena}(t) \leq L_{NLena}(t), j = 1,2,...,m \]

where \( P_{elec}(t) \) is the interactive power between the \( i^{th} \) EH in the island and the grid, when \( P_{elec}(t) \) is positive, the EH absorbs power from the island, and when \( P_{elec}(t) \) is negative, the EH delivers power to the island; \( L_{NLe}(t) \) is the electric load demand of the \( j^{th} \) load point not served by EH in the island. When there is only one EH and without load point not served by EH in the island, the transmission power of the tie line between the EH and the grid is zero.

In this paper, after linearization of the nonlinear constraints, the constructed model is transformed into a 0-1 mixed integer linear programming problem, which is solved by the commercial software CPLEX on the YALMIP platform under the MATLAB environment.

5. Simulation result

5.1. Parameter setting

The distribution network with multiple EHs shown in figure 1 is employed to verify the effectiveness of the fault recovery strategy proposed in this paper. The annual hourly electric heating load demand, annual wind speed, and sunlight data of the system are detailed in ref. [11]. The operating parameters and reliability parameters of the internal components of the EH are detailed in the ref. [12-13]. The length of feeders 1, 5, 7, 8, 12, and 13 is 0.6 km, the length of feeders 2, 3, 10, 11, and 14 is 0.75 km, and the length of feeders 4, 6, 9 is 0.8 km. The length of each pipeline in the natural gas network is the same as that of the power network. The failure rate of the power line is 0.065 times/km/year, and the mean time to repair the fault is 5 hours; the failure rate of the natural gas network is 0.012 times/km/year, and the mean time to repair the fault is 5 hours; the failure rate of the energy storage system is 0.03 times/year, and the mean time to repair the fault is 20 hours. The sequential Monte Carlo simulation method is used to evaluate the reliability of the distribution network with multiple EHs, and the maximum simulation period is 5000 years.

5.2. Reliability calculation results of distribution network with multiple EHs

This paper designs the following three scenarios for the reliability calculation: Scenario 1 is the distribution network operating without EH;
Scenario 2 is the distribution network operating under single EH island mode; Scenario 3 is the distribution network operating under multiple EHs island mode. Among them, scenario 1 is that the distribution network is not connected to the EH, that is, the traditional distribution network operation mode; scenario 2 is that each EH operates independently during the failure recovery period, that is, there is only one EH in the island; Scenario 3 is that the EH participates in supporting the power supply of the distribution network load during the failure recovery period, that is, the island contains one or more EHs and load points not served by EH. The reliability calculation results in the three scenarios are shown in Table 1.

| Scenario | P1      | P2      | P3      | P4      | P5      | P6      | P7      |
|----------|---------|---------|---------|---------|---------|---------|---------|
| Scenario 1 | EENS 171.7 | 171.7  | 248.1  | 339.3  | 414.2  | 487.3  | 487.3  |
|           | ARDI 1.035 | 1.035  | 1.398  | 2.045  | 2.291  | 2.354  | 2.354  |
| Scenario 2 | EENS 171.7 | 171.7  | 18.37 | 339.3  | 21.67  | 487.3  | 23.89  |
|           | ARDI 1.035 | 1.035  | 0.4021 | 2.045  | 0.4026 | 2.354  | 0.4131 |
| Scenario 3 | EENS 171.7 | 171.7  | 16.87 | 211.7  | 18.24  | 356.26 | 20.38  |
|           | ARDI 1.035 | 1.035  | 0.3851 | 1.879  | 0.3874 | 2.143  | 0.3934 |

In the three operation modes of distribution network operation alone, single EH operation, and multiple EHs operation, the electrical load reliability indices of load points P1 and P2 have not changed. By analyzing the positions of P1 and P2 in the distribution network, it can be known that P1 and P2 are not the load points of the EH and do not participate in the island operation mode of the EH. Therefore, the three operation modes do not affect the electrical load reliability indices of P1 and P2.

In the two operating modes of a single EH and multiple EHs, the reliability indices of load points P3–P7 have been significantly improved compared with the independent operation mode of the distribution network. In the case of a power distribution network failure, the EH with a small power load can be optimized and dispatched, and the rich electrical energy can be restored to the load points not served by EH through the power network, so the electrical load reliability indices of the load point P3–P7 are significantly reduced.

In the two operation modes of single EH operation and multiple EHs operation, the changes of the electrical load reliability indices of load points P3–P7 can be concluded that the EH operates independently when the distribution network fails, and the rich power generation capacity is wasted. The island operation mode of scenario 3 can make full use of the power generation capacity of the EH and restore more load points not served by EH.

6. Conclusion
Aiming at the current status of insufficient research on fault recovery of multiple EHs connected to the distribution network, this paper proposes a reliability improvement-oriented fault recovery strategy for distribution networks with multiple EHs, and draws the following conclusions:

1. The proposed fault recovery strategy takes into account the fault-affected partition and the optimal scheduling of the EH, which simplifies the reliability calculation and can obtain more realistic calculation results of the reliability indices.

2. This paper establishes an optimal scheduling model that considers power outage losses and minimum operating costs. During the fault recovery period of the power distribution network with EHs, the power of the internal components of the EH can be adjusted to greatly improve the reliability of the distribution network.

3. During the restoration of the distribution network fault, multiple EHs form an island operation compared with a single EH island operation, the reliability of the load node is higher.

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