IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

IEEE Power & Energy Society Section

Received 19 May 2024, accepted 3 June 2024, date of publication 10 June 2024, date of current version 22 August 2024.

Digital Object Identifier 10.1109/ACCESS.2024.3411601

RESEARCH ARTICLE

A Multi-Stage Resilience Optimization Method for Electricity-Gas Coupled Distribution Networks Based on Islanding Division

TINGJUN LI, (Member, IEEE), HUA BAI, AND XIAOQING HAN, (Senior Member, IEEE)
School of Electrical and Power Engineering, Taiyuan University of Technology, Taiyuan 030024, China

Corresponding author: Xiaoqing Han (hanxiaoqing@tyut.edu.cn)

This work was supported in part by the National Natural Science Foundation of China under Grant U23A20649, and in part by the Science and Technology Project of State Grid Shanxi Electric Power Company under Grant 52051L230103.

ABSTRACT With the increasing penetration of natural gas in power systems, the resilience of electric-gas coupled distribution networks under extreme fault perturbations has received increasing attention. Since the entire phase resilience of an electric-gas coupled distribution network after an extreme event depends on its system function, it is necessary to consider a multi-phase recovery process in order to comprehensively improve the resilience and rapid recovery of electric-gas coupled distribution networks against extreme events. In this paper, a fast fault isolation and service restoration methodology that integrates active islanding effect and RCS is proposed to improve the resilience and fast recovery capability of electric-gas coupled distribution networks. Firstly, an electric-gas coupled distribution network model is constructed, after which the multi-stage recovery process is modeled in detail by combining the dynamic mechanism of the load supply curve of the electric-gas coupled distribution network under the whole process of extreme faults, including the topological constraints and power constraints of each stage and the coupling relationship between each stage. The effectiveness of the proposed multi-stage resilience optimization method is verified using the IEEE33 node power system and the natural gas 7-node distribution system as examples. It is demonstrated that the multi-stage restoration method proposed in this paper can greatly improve the resilience of coupled electric-gas distribution networks.

INDEX TERMS Islanding, electricity-gas coupled distribution networks, resilient optimization, multi-stage, remote control switches.

I. INTRODUCTION

The devastating damage caused by extreme disasters such as ice storms, typhoons and earthquakes to critical energy infrastructure is increasing [1], [2], which seriously threatens the safe and stable operation of energy systems. According to statistics, 80 % of the large-scale blackouts that occurred between 2003 and 2012 were caused by natural disasters, and 90 % of them occurred at the level of dense distribution networks [3]. Enhancing the energy system's resilience and capacity to recover from Low-Probability / High-Damage Contingencies (LPHDC) at the distribution network level has emerged as a critical concern to guarantee the energy system's high-quality and highly resilient functioning.

Resilience is the ability of energy systems to fully prevent, actively resist, effectively adapt and quickly recover in the face of various N-k failure scenarios including extreme natural disasters. It is an effective measure to improve the safety and reliability of modern energy systems. As global natural disasters increase year by year, the construction of "resilient energy systems" with resilience to extreme disturbance events has attracted more and more attention [4]. Specific to the power system, resilience mainly refers to the recovery and support performance of the distribution network under severe natural disasters and other extreme conditions. The existing research also defines resilience as

The associate editor coordinating the review of this manuscript and approving it for publication was Pratyasa Bhui.

the performance of the distribution network to take active measures to ensure that the critical load is continuously powered under extreme conditions, and the power-off load quickly restores power supply [5], [6].

At present, scholars at home and abroad have formed a series of research results around the problem of resilient lifting of traditional power systems, which mainly aim at enhancing disaster adaptability and post-disaster resilience [8], [9], [10], [11], [12], [13], [14], [15]. According to the IEEE1547-2003 standard [7], the distributed power supply should be used to divide the fault outage area into multiple islands for load recovery. In [8], it is proposed to use distributed generation (DG) to quickly restore the power outage area after the power system failure, so as to improve the reliability of the system. In [9], a multi-stage power system restoration process is proposed to maximize the use of distributed generation to restore outage loads. In [10], a method of restoring multi-agent system based on DG island is proposed. In [11], a method based on the combination of fault reconstruction and island operation is proposed to improve the resilience of distribution network without considering the reaction of cascading failure, so as to minimize the loss of load. Reference [12] proposed a method to restore the critical load of power system after natural disasters by using microgrid. In [13], considering the uncertainty of maintenance personnel's time, a two-stage robust optimization model of fault recovery is established to make the optimal fault repair strategy in an uncertain environment. In [14] and [15], the distribution system's maximum recovery capability is achieved by upgrading as many manual switches (MSS) as possible to remote control switches (RCS), which can be quickly switched remotely to achieve rapid recovery.

The above research mainly focuses on the load recovery of the power system, but it should be pointed out that the power system under the requirements of low-carbon structural change has gradually shown the characteristics of extensive interconnection and intelligent interaction. The dependence between heterogeneous energy sources is becoming more and more obvious, forming an integrated energy system that is deeply coupled from energy supply, transmission, distribution and utilization. How to improve the resistance and load recovery ability of heterogeneous energy systems under extreme natural disasters at the distribution network level has become a key issue to maintain the high resilience and stable operation of energy systems.

In recent years, due to the operational flexibility and low carbon of natural gas system, the permeability of natural gas in power system is increasing, which enhances the coupling between power system and natural gas system [16]. The electrical coupling system distribution network can realize the coordinated conversion and risk support of different energy sources, and greatly improve the anti-risk ability of the energy system while improving the energy utilization efficiency. Although it provides a deep coupling energy supply mode of heterogeneous energy, it also brings the problem of cross-energy flow fault propagation under extreme natural disasters [17], [18]. Therefore, the load recovery method for electric-gas coupling system should be studied. Reference [19] studied the optimal energy flow planning method for the interdependence of IDGS. In order to realize the location and capacity of generator sets and energy storage devices, [20] proposed a source-end capacity planning model considering multi-objective (i.e., reliability and cost) coordination. A short-term stochastic scheduling model was presented in [21] to examine the coordination of power and natural gas systems. By coordinating the time of maintenance personnel, A technique for coordinating the repair sequence was presented in [22], which decreased the cost of load loss and repair load length. In [23], for the deeply coupled electricity-gas integrated energy system, the resilience of the integrated energy system is improved by strengthening the line and establishing a three-layer framework of defense-attack-defense to optimize the resilience of the distribution network. In [22] proposes a collaborative maintenance model for electric-gas regional distribution networks by using distribution network reconfiguration and active islanding operation as key measures to enhance resilience. Most of the above studies have considered only a single phase when the electric-apparatus coupled system fails, and there is a lack of research on the full phase.

The above research gives a resilient enhancement method from the perspective of energy supply service recovery. However, there are three stages to the fault recovery procedure for an electricity-gas coupled distribution network: load drop stage, fault isolation stage and service recovery stage. This multi-level process [24] must be effectively considered in the resilient enhancement method to coordinate the regulation behavior of the electricity-gas coupled distribution network against extreme events and improve the resilience of the system.

Considering the multi-stage recovery process after a fault in an electric-gas coupled distribution network, a new approach to enhance the resilience of the distribution system is proposed. The main contributions of this paper are as follows:

(1) An integrated resilience enhancement approach to improve the ability of electric-gas coupled distribution networks to withstand and quickly recover from extreme events is proposed based on a multi-stage recovery process. In it, an active islanding approach is used to divide the distribution system into a number of autonomous islands prior to the occurrence of an extreme event to mitigate the impact of degradation phase faults. And the allocation of RCS in the pre-event phase and the switching operation of RCS in the fault isolation phase and the service recovery phase are optimally determined to achieve fast fault isolation and service recovery.

(2) The topology constraints and operation constraints of each stage in the multi-stage recovery process, as well as the coupling relationship between the stages, are modeled

in detail. The model is suitable for scenarios with variable network topology. In addition, the entire model is formulated as a mixed integer linear programming (MILP) problem that can be easily solved by commercial solvers.

The rest of the paper is organized as follows: Section II constructs the coupled electric-gas system distribution network. Section III describes the model formulation in detail. Section IV provides arithmetic examples for proof. Finally, Section V briefly summarizes the work.

II. MULTI-STAGE DYNAMIC RESTORATION MECHANISM OF ELECTRICITY-GAS COUPLING DISTRIBUTION NETWORK

A. ELECTRICITY-GAS COUPLING DISTRIBUTION NETWORK STRUCTURE

The electricity-gas coupled distribution network (EGCDN) consists of a distribution network and a gas distribution network [26]. The typical structure is shown in Fig. 1. The specific working principle is as follows: Firstly, the power distribution station and the gas distribution station purchase electric energy and natural gas from the superior energy network according to the load demand, and the energy transmission module composed of the distribution network frame and the gas distribution pipeline transports the energy to the energy conversion module or the user side load. In addition to the transmission network, remote control switching elements are also widely present in the energy transmission module to achieve mutual adjustment of the power system and the gas system under abnormal conditions. The energy conversion module is an energy conversion device that connects the distribution network and the gas distribution network, including the Gas-Burning Generator (GBG) and the Power to Gas (P2G), which can realize the flexible conversion of electric energy and natural gas.

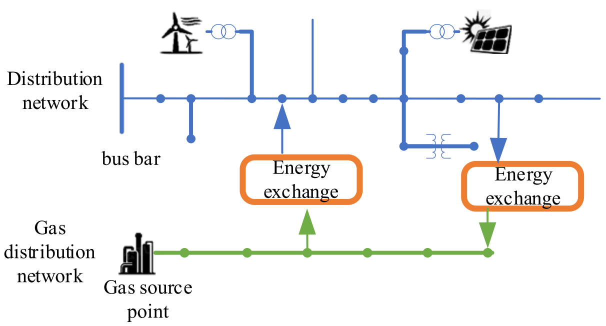

FIGURE 1. Schematic diagram of EGCDN typical structure.

B. RESILIENCE TRIANGLE

The resilience of the electricity-gas coupled distribution network can be expressed by "resilient triangle", which is used to capture the recovery process of the electricity-gas coupling distribution network after the occurrence of extreme events, as shown in Fig.2. Among them, the black solid line represents the entire multi-stage recovery process of the traditional system after the electricity-gas coupled distribution network suffers from extreme events, and the blue portion of the figure, S, reflects the impact of extreme events on the electric-gas coupled distribution network; and the level of resilience of the electric-gas coupled distribution network. The area of S depends on two factors: degradation of the system functionality and the time required for recovery. Therefore, in order to reduce the area of the shaded portion (to increase resilience), two measures can be taken. One is to reduce the degradation of the system function, which requires improving the ability of the coupled electric-gas distribution network to withstand extreme events, and the other is to reduce the time required for recovery, which requires that the system be able to recover quickly from extreme events. When effective resilience measures are implemented, the area of the blue portion S is made to decrease, i.e., the portion Sr with stripes is shown. The multistage recovery process of the resilient electric-gas coupled distribution network after a fault is shown as the red dashed line in Fig. 3.

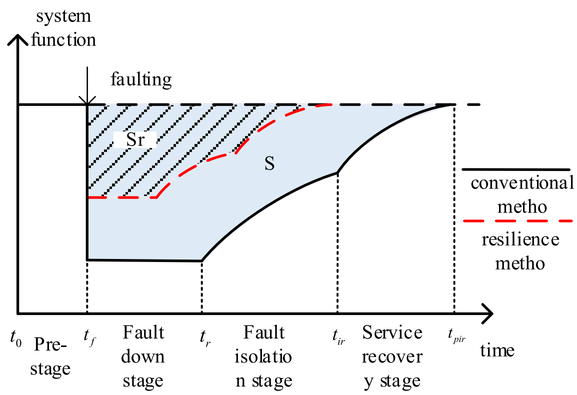

FIGURE 2. Multi-stage recovery process after a failure of an electricity-gas coupled distribution network.

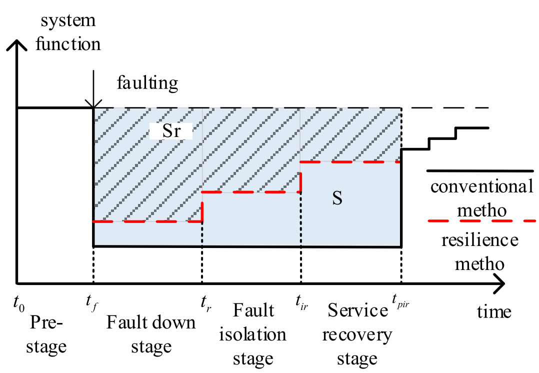

FIGURE 3. Multi-stage recovery process after a failure of an electricity-gas coupled distribution network.

Based on the above analysis, in order to comprehensively improve the ability of electric-gas coupled distribution networks to withstand and quickly recover from extreme events, it is necessary to consider the entire multi-stage recovery process when designing resilience enhancement methods. Therefore, this paper integrates the active islanding effect, which aims to reduce the degradation of system functions during the load shedding phase, and the RCS-based rapid fault isolation and service restoration, which aims to reduce the time required for recovery during the isolation and service restoration phases. Fig. 3 (red dashed curve) represents the multi-stage recovery process of the electric-gas coupled distribution network under the proposed approach.

Considering that faults must be isolated before restoring faults in non-faulty areas, and that RCS involves switching operation time [25], the recovery process of the electricity-gas coupled distribution network can be divided into three stages: load drop, fault isolation and service recovery:

1. Load drop stage: Before the fault is isolated, the electricity-gas coupled distribution network will experience the load drop stage, and the fault condition will greatly affect the system function. This stage involves identifying the fault area, which is defined by the island division's location and the pre-stage topology of the distribution network for the electricity-gas connection.

2. Fault isolation stage: At this stage, by operating the remote-control switch, the fault is isolated and the area of the fault area is reduced.

3. Service recovery stage: At this stage, the Recloser Control System (RCS) is activated, and the network is reconfigured to restore the affected load in the non-fault area. It is crucial to make sure that the fault zone created during the fault isolation step is not linked with the non-fault zone at this point because the network topology may change throughout this procedure.

According to the aforementioned study, when building the resilience enhancement approach, it is essential to take into account the complete multi-stage recovery process in order to significantly improve the electricity-gas coupled distribution network's capacity to withstand extreme events and recover swiftly. Thus, in order to reduce system function attenuation during the load drop stage, the active island effect is examined in detail in this work, as is the RCS-based rapid fault isolation and service recovery, which attempts to shorten the recovery time during the fault isolation and service recovery stages.

III. COMPOSITION AND MODELING OF EGCDN

In this paper, the electricity-gas coupled distribution network system is divided into three parts: distribution network subsystem model, gas distribution subsystem model and energy conversion subsystem model.

A. DISTRIBUTION NETWORK SUBSYSTEM MODEL

The power system includes power lines and grid structures. It is also necessary to consider the withstand power, voltage, and power flow conditions in the power lines. In addition, there are GBG equipment and P2G equipment.

1) NODAL EQUILIBRIUM EQUATIONS

$$\sum P_{GT,i} + \sum P_{DG,i} + \sum P_{GBG,i} = P_{\mathrm{i}} + \sum P_{ij} + \sum P_{P2G,i}, \forall (i,j) \in E_P \tag{1}$$

$$\sum Q_{GT,i} + \sum Q_{DG,i} = Q_{\mathrm{i}} + \sum Q_{ij}, \forall (i,j,k) \in E_P \tag{2}$$

where, $P_{DG,i}, Q_{DG,i}$ are the distributed power supply's generation powers, both active and reactive, connected to the i node; $P_{GBG,i}$ is the active power generated by the GBG unit connected to the i-node, $P_{P2G,i}$ is the active power consumed by the P2G connected to the i-node; P_i, Q_i are the active and reactive power generation power consumed by the load node; $P_{s,ij}, Q_{s,ij}$ are the active and reactive power generation power consumed by each line; E_P is the set of all distribution electronic system nodes; the subscripts i and j are the node numbers of the distribution electronic system.

2) AVAILABLE TRANSFER CAPABILITY LIMITATION OF LINES

$$-M(1-z_{ij}) \leq u_i - u_j - 2\left(r_{ij}P_{ij} + x_{ij}Q_{ij}\right) - \left(r_{ij}^2 + x_{ij}^2\right) i_{ij} \leq M(1-z_{ij}), \forall (i,j) \in E_P \tag{3}$$

$$\frac{P_{ij}^2 + Q_{ij}^2}{i_{ij}} = u_i, \forall (i,j) \in E_P \tag{4}$$

$$\begin{cases} -z_{ij}P_{ij}^{\max} \leq P_{ij} \leq z_{ij}P_{ij}^{\max} \\ -z_{ij}Q_{ij}^{\max} \leq Q_{ij} \leq z_{ij}Q_{ij}^{\max} \end{cases} \tag{5}$$

where, P_{ij} and Q_{ij} represent the active power and reactive power transmitted between the lines ij; r_{ij} and x_{ij} are the resistance and reactance of line ij. M is a sufficiently large positive number; u_i is the voltage of node i; z_{ij} is a binary 01 variable, the line ij is closed to 1, otherwise it is 0.

3) DG OUTPUT CONSTRAINT

$$P_{DG,i}^{\min}(1-a_i) \leq P_{DG,i} \leq P_{DG,i}^{\max}(1-a_i) \tag{6}$$

$$Q_{DG,i}^{\min}(1-a_i) \leq Q_{DG,i} \leq Q_{DG,i}^{\max}(1-a_i) \tag{7}$$

where, $P_{DG,i}$ and $Q_{DG,i}$ are the actual values of the active and reactive power of the ith DG; $P_{DG,i}^{\max}, P_{DG,i}^{\min}, Q_{DG,i}^{\min}, Q_{DG,i}^{\max}$ are the upper and lower limits of the active and reactive power of the ith DG;a_i is a binary 01 variable, and the fault of distribution network node i is 1, otherwise it is 0.

B. GAS DISTRIBUTION NETWORK SUBSYSTEM MODEL

The gas distribution subsystem takes the node pressure and the gas flow through the branch as the state variables, and the relationship between the state variables is constructed based on the Weymouth equation.

$$\sum W_W + \sum W_{P2G,m} + \sum W_{pm} = \sum W_{GBG,m} + \sum W_{L,m}, \forall (p,m) \in G_P \tag{8}$$

$$W_{PL} = \left(C_{pm}\pi_p\right)^2 - \left(C_{pm}\pi_m\right)^2, \forall (m) \in G_P \tag{9}$$

$$\pi_m^{\min} \leq \pi_m \leq \pi_m^{\max} \tag{10}$$

$$W_{L,m}^{\min} \leq W_{L,m} \leq W_{L,m}^{\max} \tag{11}$$

where, the subscripts p and m are the node numbers of the gas distribution subsystem; W_W represents the output of natural gas source; G_P denotes the set of all gas pipelines; C_{pm} denotes the Weymouth coefficient; π_m represents the air pressure value of node m; $W_{P2G,m}$ refers to the amount of natural gas emitted by the P2G unit connected to the m node; $W_{GBG,m}$ refers to the amount of natural gas consumed by the GBG unit connected to the m node; $W_{L,m}$ represents the gas consumption of gas node m.

C. ENERGY CONVERSION SUBSYSTEM MODEL

Different energy supply systems are mainly coupled by various coupling elements. For example, P2G units and GBG units tightly couple them together. The mutual conversion between electricity and gas can be realized.

The relevant constraints of the coupled unit are as follows:

$$W_{P2G,m} = \eta_{P2G} P_{P2G,i}, i \in E_P, m \in G_P \tag{12}$$
$$W_{P2G}^{\min} \le W_{P2G,m} \le W_{P2G}^{\max}, m \in G_P \tag{13}$$
$$P_{GBG,i} = \eta_{GBG} W_{GBG,m}, i \in E_P, m \in G_P \tag{14}$$
$$P_{GBG}^{\min} \le P_{GBG,i} \le P_{GBG}^{\max}, i \in E_P \tag{15}$$

where, $W_{P2G,m}$ refers to the natural gas output of the P2G unit connected to the m node; η_{P2G} refers to the gas production efficiency of P2G; $P_{P2G,i}$ represents the electric power consumed by the P2G connected to the i node; $W_{P2G}^{\max}$ and $W_{P2G}^{\min}$ refer to the upper and lower limits of P2G gas production; $P_{GBG,i}$ refers to the output power of the GBG unit connected to the i node; η_{GBG} refers to the power generation efficiency of GBG unit; $W_{GBG,m}$ refers to the natural gas power consumed by the GBG connected to the m node; $P_{GBG}^{\max}$ and $P_{GBG}^{\min}$ refer to the maximum and minimum constraints of the power generation output of the GBG unit.

IV. MULTI-STAGE OPTIMIZATION MODEL OF ELECTRICITY-GAS COUPLED DISTRIBUTION NETWORK

The model can be divided into four parts: pre-stage model, load drop stage model, fault isolation stage model and service recovery stage model (the formula part is abbreviated as 0, 1, 2 and 3).

A. OBJECTIVE FUNCTION

In this paper, the objective function is to minimize the total amount of load loss in each stage, that is:

$$\min[\int_0^{t_f} (P_{s,j,c,0} + W_{s,n,c,0}) + \int_{t_f}^{t_r} (P_{s,j,c,1} + W_{s,n,c,1}) + \int_{t_r}^{t_{ir}} (P_{s,j,c,2} + W_{s,n,c,2}) + \int_{t_{ir}}^{t_{pir}} (P_{s,j,c,3} + W_{s,n,c,3})] \tag{16}$$

where, $P_{s,j,c,0}, P_{s,j,c,1}, P_{s,j,c,2}, P_{s,j,c,3}$ represent the load loss of distribution network in 0,1,2 and 3 stages respectively; $W_{s,n,c,1}, W_{s,n,c,2}, W_{s,n,c,3}, W_{s,n,c,4}$ represent the load loss of the gas network in stages 0, 1, 2, and 3, respectively.

B. RESTRICTIVE CONDITION

1) PRE-STAGE MODEL

- topological constraint

$$X_{ij,0} + X_{ji,0} = z_{ij,0}, \forall (i,j) \in E_P \tag{17}$$

where, $X_{ij,0}$ is the current direction from i to j.

- power constraint

$$a_{j,0} P_{L,j} \le P_{S,j,c,0} \le P_{L,j}, j \in E_P, \forall c \in C \tag{18}$$
$$a_{j,0} Q_{L,j} \le Q_{S,j,c,0} \le Q_{L,j}, j \in E_P, \forall c \in C \tag{19}$$
$$b_{n,0} W_{L,j} \le W_{S,n,c,0} \le W_{L,n}, n \in G_P, \forall c \in C \tag{20}$$

where, $P_{L,j}$, $Q_{L,j}$ are the active power and reactive power of the electrical node j; $P_{S,j,c,0}$, $Q_{S,j,c,0}$ are the active power and reactive power lost by the electrical node j in the pre-stage; $W_{L,n}$ is the gas consumption of gas node n; $W_{S,n,c,0}$ is the load loss of gas node n in the load drop stage.

2) LOAD DROP STAGE MODEL

Extreme occurrences lead to the formation of the fault zone. In the load drop stage model, the following constraints should be taken into account.

- topological constraint

The distribution network constraints (21) - (24) indicate that if the closed line fails, the two lines at both ends of the line will be divided into fault areas. The constraints (21) and (22) indicate that the buses at both ends of the closed line will be simultaneously located in either the fault zone or the non-fault zone. The constraints (23) - (24) indicates that the fault will propagate through the closed line in the network and will be interrupted upon encountering the disconnected line. The gas distribution network constraints (25) - (28) are the same.

$$a_{i,1} \ge f_{ij,c} z_{ij,0}, \forall (i,j) \in E_P, \forall c \in C \tag{21}$$
$$a_{j,1} \ge f_{ij,c} z_{ij,0}, \forall (i,j) \in E_P, \forall c \in C \tag{22}$$
$$a_{i,1} + z_{ij,1} - 1 \le a_{j,1}, \forall (i,j) \in E_P \tag{23}$$
$$a_{j,1} + z_{ij,1} - 1 \le a_{i,1}, \forall (i,j) \in E_P \tag{24}$$
$$b_{m,1} \ge f_{mn,c} \mu_{mn,0}, \forall (m,n) \in G_P, \forall c \in C \tag{25}$$
$$b_{n,1} \ge f_{mn,c} \mu_{mn,0}, \forall (m,n) \in G_P, \forall c \in C \tag{26}$$
$$b_{m,1} + \mu_{mn,1} - 1 \le b_{n,1}, \forall (m,n) \in G_P \tag{27}$$
$$b_{n,1} + \mu_{mn,1} - 1 \le b_{m,1}, \forall (m,n) \in G_P \tag{28}$$

where, a, b are binary 01 variables, indicate that the fault of distribution network node and gas node is 1, otherwise it is 0; z_{ij} and μ_{mn} are binary 01 variables, indicating that the distribution network line and the gas pipeline are closed to 1 and disconnected to 0; $f_{ij,c}, f_{mn,c}$ are binary 01 variables, indicating that the fault of distribution network line and gas pipeline is 1, otherwise 0; C represents the fault scenario.

The coupling relationship between the load drop stage and the pre-fault stage is also indicated by the constraint criteria. The network topology and fault prior to the occurrence determine the fault zone.

- power constraint

$$a_{j,1}P_{L,j} \leq P_{S,j,c,1} \leq P_{L,j}, j \in E_P, \forall c \in C \quad (29)$$
$$a_{j,1}Q_{L,j} \leq Q_{S,j,c,1} \leq Q_{L,j}, j \in E_P, \forall c \in C \quad (30)$$
$$b_{n,1}W_{L,j} \leq W_{S,n,c,1} \leq W_{L,n}, n \in G_P, \forall c \in C \quad (31)$$

where, $P_{S,j,c,1}$, $Q_{S,j,c,1}$ are the active power and reactive power lost by the electric node j in the load drop stage; $W_{S,n,c,1}$ is the load loss of gas node n in the descending stage.

3) FAULT ISOLATION STAGE MODEL

After the load drop stage, the RCS are switched remotely to isolate the fault to reduce the area of the fault zone determined during the load drop stage. Based on the idea similar to the load drop stage model, this paper proposes a fault isolation model.

- topological constraint

The distribution network constraint (32) show that a line is disconnected upon occurrence of a failure. Only RCS-equipped lines may be opened for quick fault isolation during the fault isolation phase. The constraints (33) and (34) show that both buses at both ends of the line will be impacted within the fault area in the event of a problem on a closed line without RCS. Conversely, these two buses will be part of the non-fault area if the line has RCS installed or was opened during the pre-event period. The buses at both ends of the closed route will be situated in either the same non-fault zone or the same fault zone, according to constraints (35) and (36). The gas distribution network constraints (37) - (41) are the same.

$$\left(1-f_{ij,c}\right)\left(z_{ij,0}-\Psi_{ij}\right) \leq z_{ij,2} \leq \left(1-f_{ij,c}\right) z_{ij,0}, \quad \forall (i,j) \in E_P, \forall c \in C \quad (32)$$
$$a_{i,2} \geq f_{ij,c}\left(1-\Psi_{ij}\right)+z_{ij,0}-1, \forall (i,j) \in E_P, \forall c \in C \quad (33)$$
$$a_{j,2} \geq f_{ij,c}\left(1-\Psi_{ij}\right)+z_{ij,0}-1, \forall (i,j) \in E_P, \forall c \in C \quad (34)$$
$$a_{i,2}+z_{ij,2}-1 \leq a_{j,2}, \forall (i,j) \in E_P \quad (35)$$
$$a_{j,2}+z_{ij,2}-1 \leq a_{i,2}, \forall (i,j) \in E_P \quad (36)$$
$$\left(1-f_{mn,c}\right)\left(\mu_{mn,0}-\Omega_{mn}\right) \leq \mu_{mn,2} \leq \left(1-f_{mn,c}\right) \mu_{mn,0}, \quad \forall (m,n) \in G_P, \forall c \in C \quad (37)$$
$$b_{m,2} \geq f_{mn,c}\left(1-\Omega_{mn}\right)+\mu_{mn,0}-1, \quad \forall (m,n) \in G_P, \forall c \in C \quad (38)$$
$$b_{n,2} \geq f_{mn,c}\left(1-\Omega_{mn}\right)+\mu_{mn,0}-1, \quad \forall (m,n) \in G_P, \forall c \in C \quad (39)$$
$$b_{m,2}+\mu_{mn,2}-1 \leq b_{n,2}, \forall (m,n) \in G_P \quad (40)$$
$$b_{n,2}+\mu_{mn,2}-1 \leq b_{m,2}, \forall (m,n) \in G_P \quad (41)$$

where, Ψ_{ij}, Ω_{mn} are the binary 01 variable, respectively, that the distribution network and the gas distribution network is a RCS is 1, otherwise it is 0.

- power constraint

$$a_{j,2}P_{L,j} \leq P_{S,j,c,2} \leq P_{L,j}, j \in E_P, \forall c \in C \quad (42)$$
$$a_{j,2}Q_{L,j} \leq Q_{S,j,c,2} \leq Q_{L,j}, j \in E_P, \forall c \in C \quad (43)$$
$$b_{n,2}W_{L,j} \leq W_{S,n,c,2} \leq W_{L,n}, n \in G_P, \forall c \in C \quad (44)$$

where, $P_{S,j,c,2}$, $Q_{S,j,c,2}$ are the active power and reactive power lost by the electrical node j in the fault isolation stage. $W_{S,n,c,2}$ is the load loss of gas node n in the fault isolation stage.

4) SERVICE RECOVERY PHASE MODEL

After fault isolation, fast service recovery will be performed based on RCS to recover the affected load outside the fault area. The fault zone should be isolated from the non-fault zone.

- topological constraint

According to the distribution network constraint (45), only lines with RCS can be switched to promptly restore service when a line fails. Other lines will be opened. The purpose of (46) and (47) is to guarantee that the fault area is not reconnected to the non-fault area. The gas distribution network constraints (49) - (51) are the same.

$$\left(1-f_{ij,c}\right)\left(z_{ij,2}-\Psi_{ij}\right) \leq z_{ij,3} \leq \left(1-f_{ij,c}\right)\left(z_{ij,2}+\Psi_{ij}\right), \quad \forall (i,j) \in E_P, \forall c \in C \quad (45)$$
$$a_{i,2}+z_{ij,3}-1 \leq a_{j,2}, \forall (i,j) \in E_P, \forall c \in C \quad (46)$$
$$a_{j,2}+z_{ij,3}-1 \leq a_{i,2}, \forall (i,j) \in E_P, \forall c \in C \quad (47)$$
$$X_{ij,3}+X_{ji,3}=z_{ij,3} \quad (48)$$
$$\left(1-f_{mn,c}\right)\left(\mu_{mn,2}-\Omega_{mn}\right) \leq \mu_{mn,3} \leq \left(1-f_{mn,c}\right) * \left(\mu_{mn,2}+\Omega_{mn}\right), \forall (m,n) \in G_P, \forall c \in C \quad (49)$$
$$b_{m,2}+\mu_{mn,3}-1 \leq b_{n,2}, \forall (m,n) \in G_P, \forall c \in C \quad (50)$$
$$b_{n,2}+\mu_{mn,3}-1 \leq b_{m,2}, \forall (m,n) \in G_P, \forall c \in C \quad (51)$$

- power constraint

$$a_{j,2}P_{L,j} \leq P_{S,j,c,3} \leq P_{L,j}, j \in E_P, \forall c \in C \quad (52)$$
$$a_{j,2}Q_{L,j} \leq Q_{S,j,c,3} \leq Q_{L,j}, j \in E_P, \forall c \in C \quad (53)$$
$$b_{n,3}W_{L,j} \leq W_{S,n,c,3} \leq W_{L,n}, n \in G_P, \forall c \in C \quad (54)$$

where, $P_{S,j,c,3}$, $Q_{S,j,c,3}$ service recovery phase electrical node j lost active power and reactive power. $W_{S,n,c,3}$ is the load loss of gas node n in the service recovery stage.

C. MODEL SOLVING

The influence of extreme events on the electricity-gas coupled distribution network is uncertain. In this paper, a stochastic optimization based on scenario is adopted, and to address the uncertainty of faults resulting from extreme events, ten sets of fault scenarios are chosen. The resilience level and the influence of extreme events on the distribution network of electricity-gas coupled are reflected in the blue part of Fig. 2, which is minimised to determine the optimal resilience scheme. The provided load is employed as a system function in this study, and the area of the blue region, as indicated in (15), is calculated using the expected and duration of load loss in all fault scenarios.

The proposed model is expressed as a MILP problem, and its general form is shown in (55) - (57).

$$\min b^T x + d^T y \tag{55}$$
$$s.t. \quad Ax + Dy > e \tag{56}$$
$$Fx + Gy = f \tag{57}$$

where, A, D, F, G, b, d, e and f, are coefficient matrices.

Therefore, (1) - (15) match the constraint on inequality (56); (17), (21) - (28), (32) - (41), (45) - (51) match the constraint on inequality (57); and (16) match the constraint on inequality (55).

The MILP problem can now be solved by commercial solvers such as GUROBI.

V. EXAMPLE ANALYSIS

A. BASIC DATA

In this paper, the IEEE33-NGS7 electricity-gas coupled distribution network is constructed based on the IEEE33 node power system and the natural gas 7 node system, as shown in Fig.4.

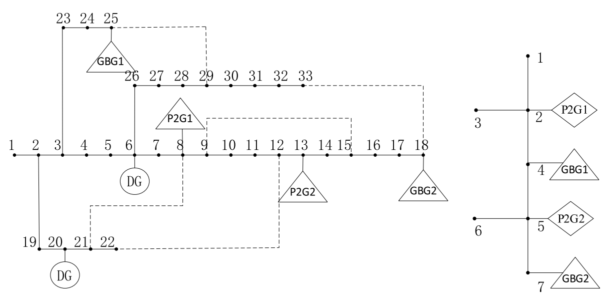

FIGURE 4. Schematic diagram of IEEE33-NGS7 EGCDN arithmetic example.

A closed line is indicated by a solid line, and a disconnected line is indicated by a dotted line. There are 37 lines in the electrical system, node 1 is connected to the power supply, and L33-L37 is the contact line. The voltage amplitude is limited to [0.95,1.05] p.u., and the line capacity is limited to 5MVA. The total load of the system is 3.715 MW + 2.300Mvar. There are six gas pipelines in the gas system, and gas node 1 is connected to the gas supply source. Two P2G units and two GBG units are set up. The number of remote switches is set to 12. The time was set to 0.1h, 0.5h, 0.8h, 1.1h. Ten sets of fault scenarios are randomly generated, including four line faults in the power system and one pipeline fault in the natural gas system, as shown in Fig.5.

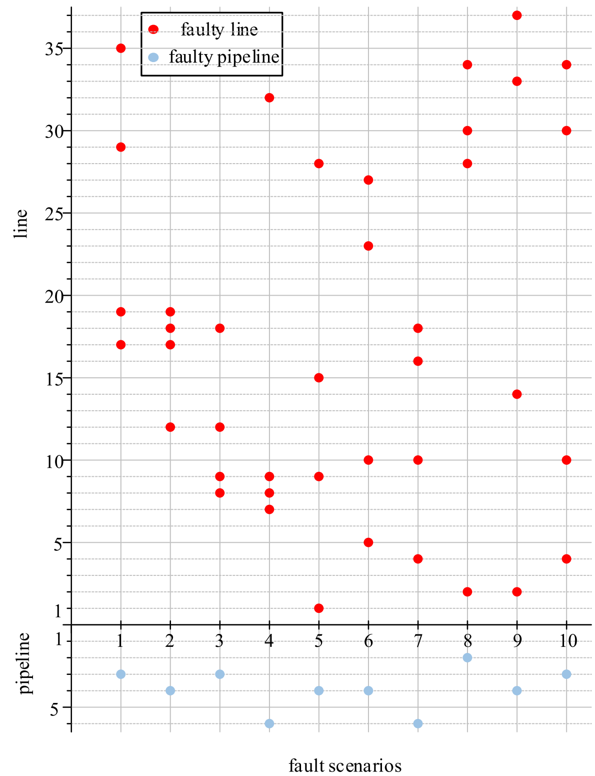

FIGURE 5. IEEE33-NGS7 EGCDN failure scenario.

B. ANALYSIS OF SIMULATION RESULTS

1) THIS PAPER RECOVERY STRATEGY

Fig.6 shows the optimal resilient scheme of active islanding and RCS allocation. The distribution and gas distribution lines are outfitted with RCS, as indicated by the red line. It is evident that two DG islands are formed by the division of the distribution network into four parts. Ensure that each island is

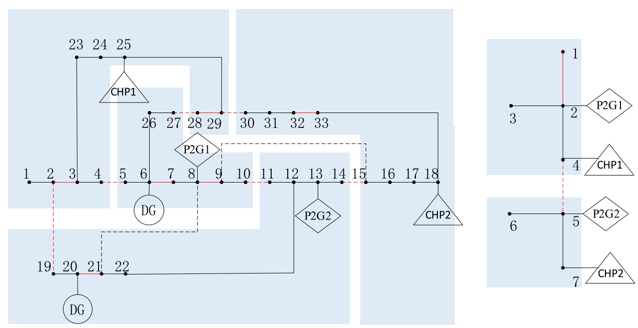

FIGURE 6. An optimal resilient scheme for active islands and RCS allocation in IEEE33-NGS7 EGCDN.

a radial topology. Each region has at least one DG or coupled power supply unit; the gas distribution network is divided into two parts, and each area has at least one gas source point or coupling gas supply unit to ensure that all loads in all areas are serviced.

The fault scenario 5 is selected for detailed analysis, and the network topology corresponding to the recovery process in the fault scenario is shown in Fig. 7. The line marked 'x' indicates that there is a fault in the distribution line or the gas supply pipeline. Obviously, a fault zone forms during the load drop stage, shrinks during the fault isolation stage, and restores the non-fault area during the service recovery phase. The suggested approach is effective in locating fault locations and isolating faults, despite the fact that the network architecture is altered during the recovery process.

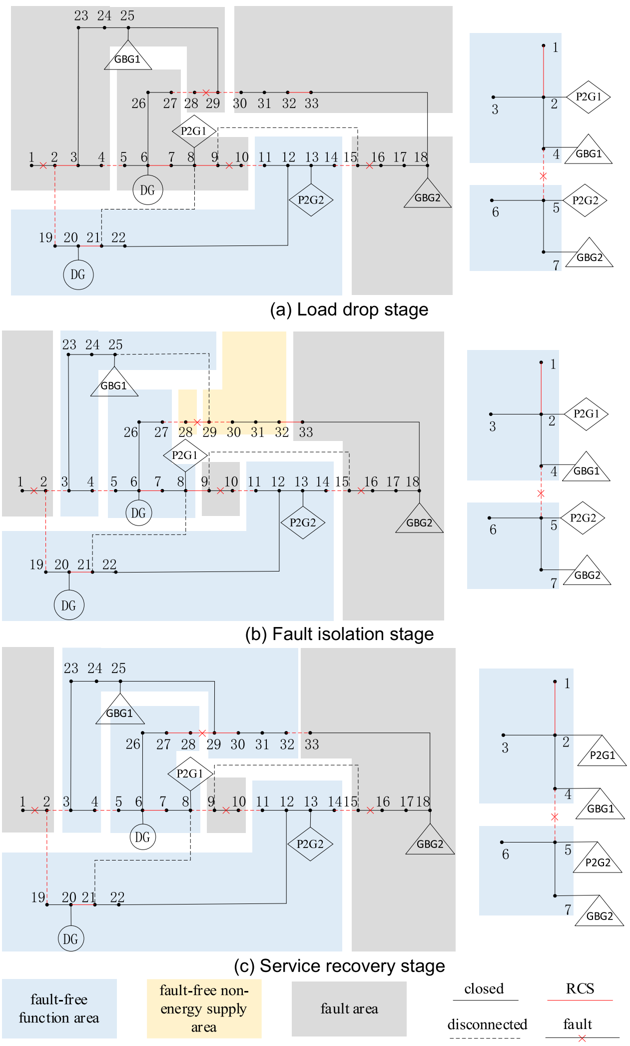

FIGURE 7. Network topology of the IEEE33-NGS7 EGCDN corresponding to the recovery process in a failure scenario 5.

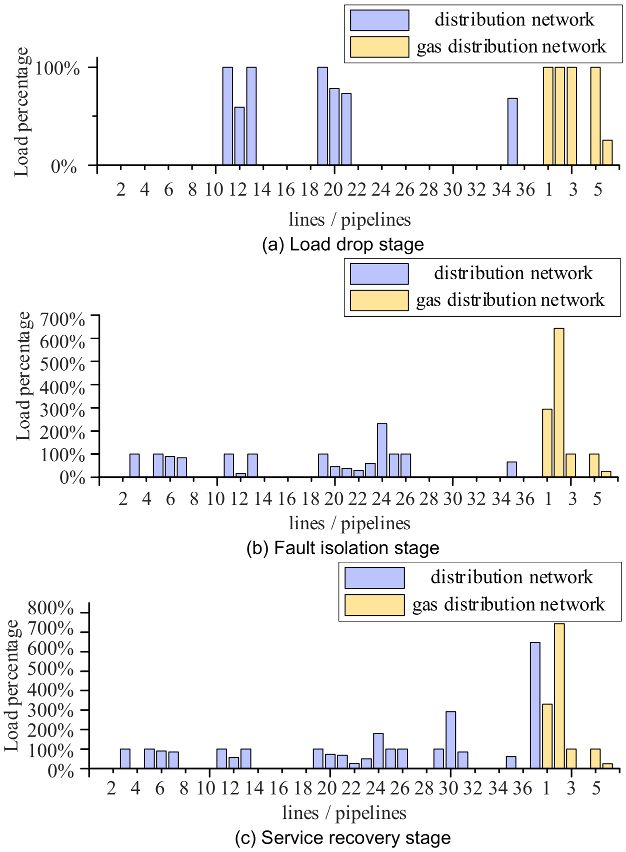

FIGURE 8. Percentage load of the IEEE33-NGS7 EGCDN in each phase of the line/gas pipeline compared to normal conditions under fault scenarios 5.

Due to the active islanding effect, some loads will survive from extreme events during the load drop phase, as shown in Fig. 7 (a). When a fault occurs, all loads on the island will stop running, and the load on the island without fault will not be affected. Active islanding will therefore strengthen the electricity-gas linked distribution network's resistance to extreme occurrences. As seen in Fig. 7 (b), the area of the fault zone is reduced in the fault isolation stage compared to the load drop stage. This is because the RCS switching operation in the fault area isolates some bus faults. As shown in Fig. 7 (c), in the service recovery phase, the non-fault area is reconfigured to recover the load, while the fault area is isolated. This further demonstrates the service recovery model's efficacy.

For further analysis, Fig. 8 shows the load percentage of the line and gas supply pipeline in different stages of the fault scenario compared with the normal situation, and the results are consistent with the topology change in Fig. 7. From the diagram, it is found that some load percentages exceed 100 % in the fault isolation and service recovery stage, which is caused by line reconstruction or coupling unit energy supply. For example, the natural gas pipeline 2 in Fig. 8 (b) is caused by the power supply of the GBG unit connected to the natural gas node 4 to the power system.

Fig. 9 displays the percentage of normal operating load under various fault scenarios. The findings demonstrate

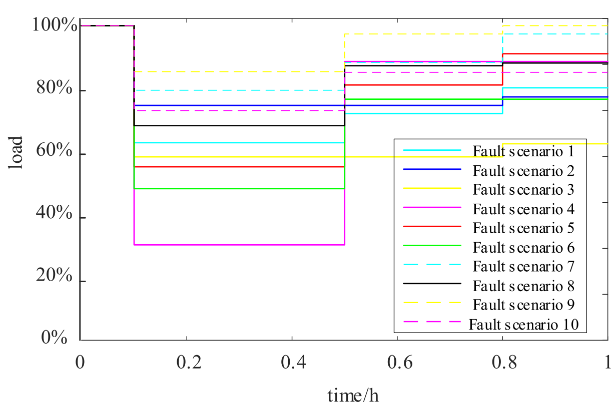

FIGURE 9. Percentage of post-failure loads of the IEEE33-NGS7 EGCDN under different failure scenarios.

that, in the majority of scenarios, the optimal resilience scheme—which combines islanding and RCS—proposed in this research may increase the resilience of electricity-gas coupled distribution networks.

2) COMPARISON OF DIFFERENT RECOVERY STRATEGIES

In order to illustrate the effectiveness and rationality of the above-mentioned solution strategy and the collaborative optimization model with RCS and distributed power supply, this paper analyzes the following three typical operating scenarios:

Scenario 1: The cooperative multi-stage recovery strategy of RCS and distributed power supply is adopted in fault scenario 5.

Scenario 2: Only fast fault isolation and service recovery based on RCS are considered in fault scenario 5.

Scenario 3: Only the distributed power recovery strategy is considered in fault scenario 5.

As can be seen from Fig. 10, in Scenario 2, although quick fault isolation and service recovery are assured, the load drop stage seriously impairs system functionality. In contrast to Scenario 2, Scenario 3 allows for the maintenance of system functionality during the declining phase. However, quick fault isolation and service recovery are not possible in the system since RCS is not present. In scenario 1, the method proposed in this paper improves the ability of the electricity-gas coupled distribution network to resist extreme events and the ability of rapid recovery. The proposed method, scenario 1, comprehensively improves the above two capabilities of the electricity-gas coupled distribution network on the basis of considering the whole multi-stage recovery stage, which is more effective in enhancing resilience. On the contrary, in the existing research, neglecting the multi-stage recovery procedure prevents the system from being totally resilient.

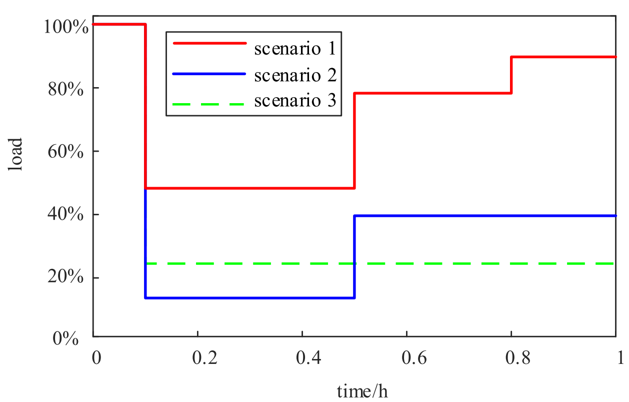

FIGURE 10. Percentage load after failure of the IEEE33-NGS7 EGCDN under different scenarios.

3) IMPACT OF THE MULTI-STAGE RECOVERY PROCESS

Traditional fault recovery approaches usually assume that the fault has been accurately isolated and then only consider the impact of the service recovery process while ignoring the entire multi-phase. In order to highlight the difference between considering multiple phases and not considering them, as well as the advantages of the proposed approach, the following methodology is used to highlight the comparison.

The single-phase approach considers a combination of active siloing and RCS-based fast fault isolation and service recovery. However, it is assumed that faults are isolated immediately after their occurrence and only the service recovery phase is considered.

Objective:

$$\begin{aligned} &\min \int_{t_{ir}}^{t_{pir}} (P_{s,j,c,3} + W_{s,n,c,3}) \\ &\text{s.t.} \quad (1) - (15), (45) - (54) \end{aligned} \tag{58}$$

This approach has been widely used in existing studies, e.g., in literature [27], where the idea is mainly focused on the service recovery phase, and the parameter settings are kept the same as above. The optimal scheme for active islanding + RCS allocation is shown in Figure 11.

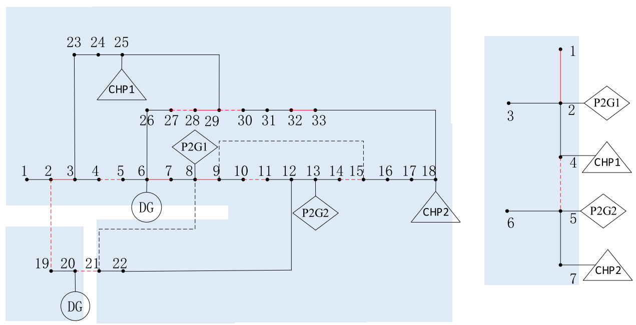

FIGURE 11. IEEE33-NGS7 optimization of active siloing + RCS allocation.

This approach has been widely used in existing studies, e.g., in literature [27], where the idea is mainly focused on the service recovery phase, and the parameter settings are kept the same as above. The optimal scheme for active islanding and RCS allocation is shown in Figure 11.

As shown in Fig. 12, due to ignoring the load shedding phase and load segregation phase and considering only the service recovery phase, the resilience is poorer when considering the actual entire recovery process. Compared to the traditional approach which only considers a single phase when designing the resilience enhancement method, this approach has a higher resilience enhancement efficiency by considering the entire multi-phase process. This also shows the importance of considering the entire multi-stage process.

4) RESTORATION OF ELECTRICITY-GAS UNCOUPLED DISTRIBUTION NETWORK

The optimal resilient allocation and active islanding method for the electro-pneumatic system when it is decoupled is depicted in Figure 13. The distribution and gas distribution lines are outfitted with RCS, as indicated by the red line. It is evident that two DG islands are formed by the division of the

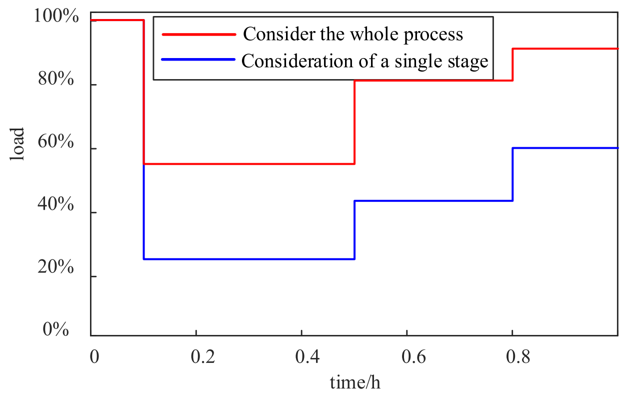

FIGURE 12. Percentage load after failure of the IEEE33-NGS7 EGCDN whether to consider the whole process.

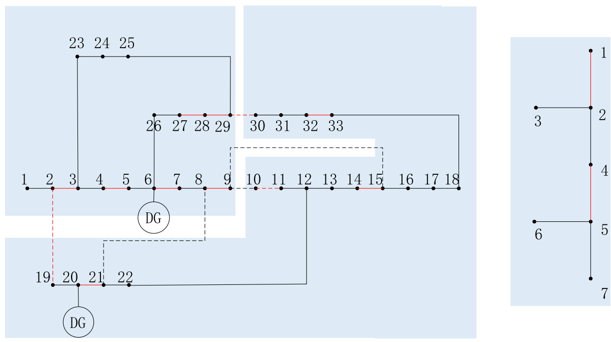

FIGURE 13. IEEE33-NGS7 optimal resilience schemes for active siloing and RCS allocation in EGCDN.

distribution network into two parts. Make sure every island has a radial topology. Each region has at least one DG or coupled power supply unit.

The corresponding topology of the recovery process in the fault scenario is shown in Fig. 15. In the load drop stage, due to the small number of islands formed, all loads are powered off. Furthermore, because there is no gas supply source or coupling unit during the fault isolation and service recovery stages, the gas node 5,6,7 load has been unable to restore gas supply. Fig. 14 shows the percentage of load recovery in the

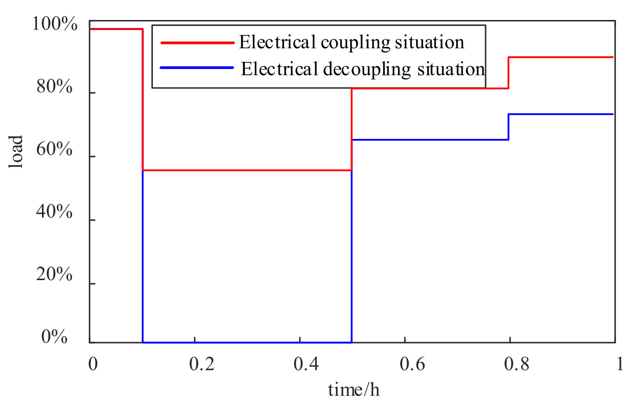

FIGURE 14. Percentage of load after failure of IEEE33-NGS7 EGCDN with or without electricity-gas distribution network coupling.

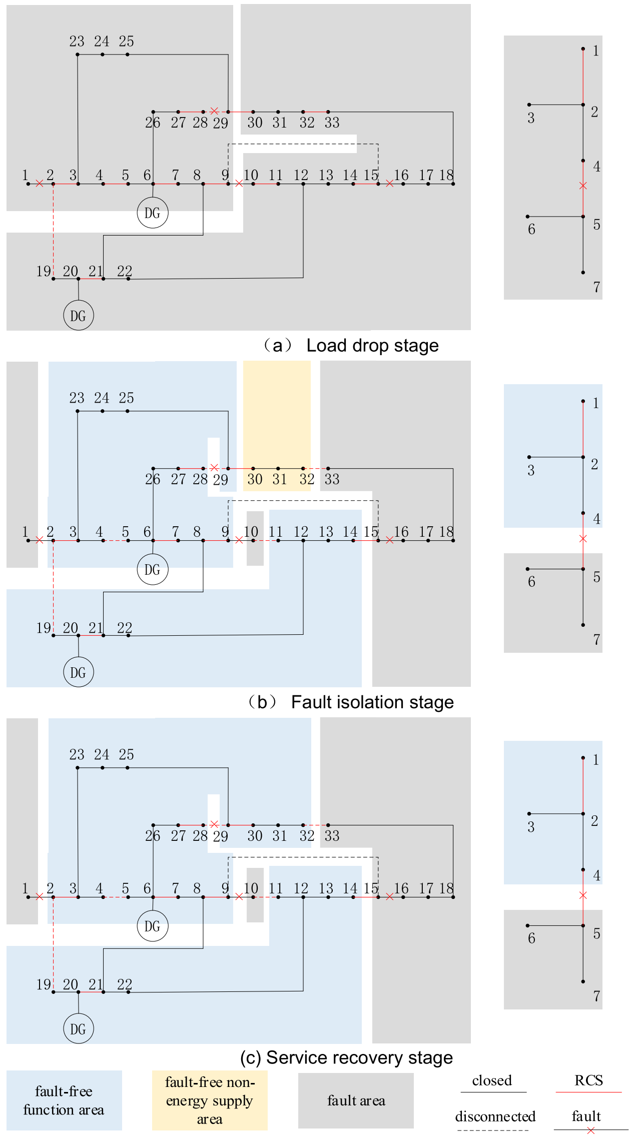

FIGURE 15. Network topology of the IEEE33-NGS7 EGCDN corresponding to the recovery process under failure scenarios.

electricity-gas coupled distribution network scenario and the uncoupled scenario when fault scenario 5 occurs.

5) COMPARISON OF DIFFERENT ISLAND CAPACITY

In order to verify the influence of island capacity on the above solution model, the following two scenarios are set.

Scenario 1: The cooperative multi-stage recovery strategy of RCS and distributed power supply is adopted in fault scenario 5.

Scenario 2: In fault scenario 5, the rated capacity of DG is changed to 3.5 MVA by using the cooperative multi-stage recovery strategy of RCS and distributed power supply.

The load recovery of scenario 1 and scenario 2 is shown in Fig. 16. Fig. 17 shows the proportion of load recovery of nodes in different stages in this scenario.

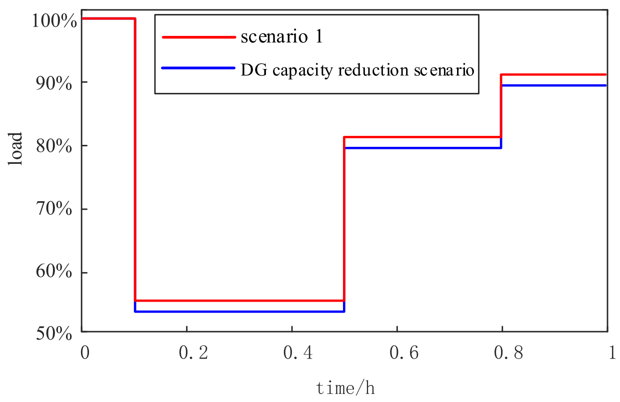

FIGURE 16. Percentage loading of lines/gas lines in each phase of the IEEE33-NGS7 EGCDN at different DG capacities compared to normal conditions.

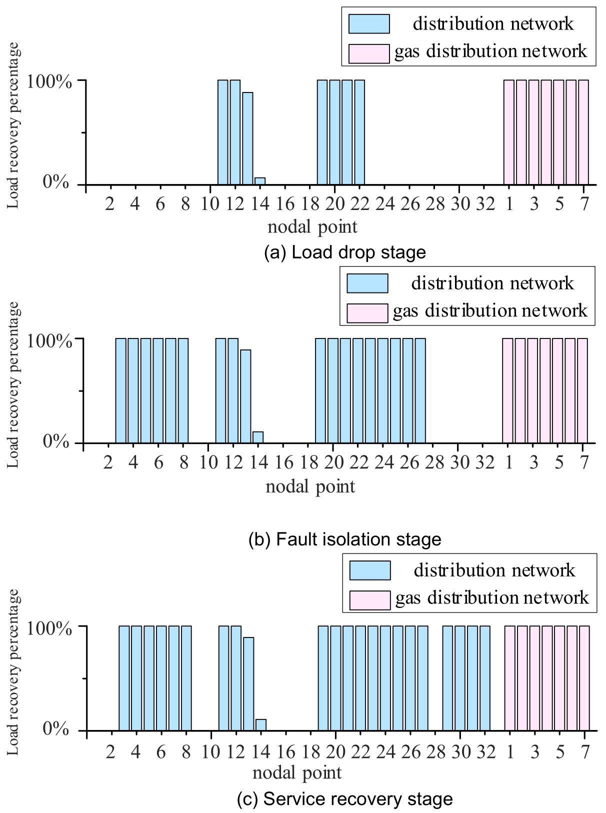

FIGURE 17. Percentage of load recovery at each node in each phase of the IEEE33-NGS7 EGCDN under different DG capacities.

Note that the load on the 14-15 nodes does not fully recover during the load drop phase. This is because the DG capacity on node 20 is limited and cannot meet all the loads on the active island. Similar to this, the load on the active island can only be partially restored during the fault isolation and service recovery phases due to DG's restricted capacity. Thus, it can be said that even though the load is located in the power supply's non-fault zone, it might not be completely serviced or restored. The system's functionality during the load drop, fault isolation, and service recovery stages will all be directly impacted by the DG's capacity.

VI. CONCLUSION

Aiming at the multistage recovery process after a fault in an electric-gas coupled distribution network, this paper proposes a multistage resilience improvement optimization method for electric-gas coupled distribution networks, which quantifies both the active islanding effect and the fast action of RCS. The main conclusions are as follows:

- Compared with the existing resilience improvement methods that only consider a single stage, the ex-ante prevention, ex-ante confrontation, and ex-post recovery process proposed in this paper comprehensively improves the ability of electric-gas coupled distribution networks to withstand extreme events and recover quickly. Compared with the traditional methods, the overall resilience enhancement of the method is 165%, which has a great impact on the resilience of the electric-gas coupled distribution network.
- As an effective measure to improve the resilience of electric-gas coupled distribution grids, the strategy combining active islanding and RCS fast action is able to withstand extreme events and recover from faults quickly. The proposed model effectively reduces load loss through preventive flexibility improvement measures and achieves global optimization of post-fault operation schemes.

In this paper, it is found that distributed generation and coupled units have a significant impact on system flexibility. Therefore, future work focuses on more accurately determining the capacity and location of distributed generation and coupled units while considering a multi-stage recovery process. Considering that larger scale extreme disasters can lead to more line failures, the ex-ante prevention, ex-ante countermeasures and ex-post restoration of power-coupled distribution networks are considered in order to improve the flexibility of the whole process and to reduce the loss of loads.

REFERENCES

[1] *Assembly U N G. Integrated and Coordinated Implementation of and Follow-up to the Outcomes of the Major United Nations Conferences and Summits in the Economic, Social and Related Fields*, 2010.
[2] M. Nazemi, M. Moeini-Aghtaie, M. Fotuhi-Firuzabad, and P. Dehghanian, "Energy storage planning for enhanced resilience of power distribution networks against earthquakes," *IEEE Trans. Sustain. Energy*, vol. 11, no. 2, pp. 795–806, Apr. 2020.
[3] Executive Office of the President, *Economic Benefits of Increasing Electric Grid Resilience to Weather Outages*. IEEE USA Books & eBooks, 2013.
[4] C. Biyun, C. Haoying, and Li Bin, "Optimized configuration of automatic switches for resilient distribution networks in response to extreme disasters," *Power Automat. Equip.*, vol. 39, no. 11, pp. 71–77, 2019.
[5] X. Yin, H. Jinghan, and W. Ying, "A review and outlook of distribution network fault recovery research in the context of resilience," *J. Electrotechnol.*, vol. 34, no. 16, pp. 3416–3429, 2019.
[6] L. Jia, C. Hao, and K. Weihong, "Optimization and resilience enhancement method of core backbone network framework under ex-treme weather," *High Voltage Eng.*, vol. 49, no. 4, pp. 1591–1599, 2023.
[7] T. S. Basso and R. DeBlasio, "IEEE 1547 series of standards: Interconnection issues," *IEEE Trans. Power Electron.*, vol. 19, no. 5, pp. 1159–1162, Sep. 2004.
[8] Y. Xu, C.-C. Liu, K. P. Schneider, F. K. Tuffner, and D. T. Ton, "Microgrids for service restoration to critical load in a resilient distribution system," *IEEE Trans. Smart Grid*, vol. 9, no. 1, pp. 426–437, Jan. 2018.

[9] W. Zhi, L. Yafei, and G. Wei, "A modified decomposition method for multistage planning of energy storage, distributed generation and distribution network," *Proc. CSEE*, vol. 39, no. 16, pp. 4705–4715, 2019.
[10] A. Sharma, D. Srinivasan, and A. Trivedi, "A decentralized multiagent system approach for service restoration using DG islanding," *IEEE Trans. Smart Grid*, vol. 6, no. 6, pp. 2784–2793, Nov. 2015.
[11] Z. Xiang, X. Huili, and Z. Bolin, "Hybrid algorithm based coordination between distribution network fault reconfiguration and islanding operation," *Power System Technol.*, vol. 39, no. 1, pp. 136–142, 2015.
[12] H. Gao, Y. Chen, Y. Xu, and C.-C. Liu, "Resilience-oriented critical load restoration using microgrids in distribution systems," *IEEE Trans. Smart Grid*, vol. 7, no. 6, pp. 2837–2848, Nov. 2016.
[13] Z. Yachao and X. Shiwei, "Coordinated optimization framework of multitimescale restoration strategies for resilience enhancement of distribution networks," *Automat. Electr. Power Syst.*, vol. 45, no. 18, pp. 28–34, 2021.
[14] Y. Xu, C.-C. Liu, K. P. Schneider, and D. T. Ton, "Placement of remote-controlled switches to enhance distribution system restoration capability," *IEEE Trans. Power Syst.*, vol. 31, no. 2, pp. 1139–1150, Mar. 2016.
[15] S. Lei, J. Wang, and Y. Hou, "Remote-controlled switch allocation enabling prompt restoration of distribution systems," *IEEE Trans. Power Syst.*, vol. 33, no. 3, pp. 3129–3142, May 2018.
[16] Q. Shi, F. Li, M. Olama, J. Dong, Y. Xue, M. Starke, C. Winstead, and T. Kuruganti, "Network reconfiguration and distributed energy resource scheduling for improved distribution system resilience," *Int. J. Electr. Power Energy Syst.*, vol. 124, Jan. 2021, Art. no. 106355.
[17] M. Bao, Y. Ding, C. Shao, Y. Yang, and P. Wang, "Nodal reliability evaluation of interdependent gas and power systems considering cascading effects," *IEEE Trans. Smart Grid*, vol. 11, no. 5, pp. 4090–4104, Sep. 2020.
[18] Li Gengfeng, H. Yuxiong, and B. Zhaohong, "A review and outlook of operational reliability assessment of integrated energy systems," *Power Automat. Equip.*, vol. 39, no. 8, pp. 12–21, 2019.
[19] S. Chen, Z. Wei, G. Sun, K. W. Cheung, and D. Wang, "Identifying optimal energy flow solvability in electricity-gas integrated energy systems," *IEEE Trans. Sustain. Energy*, vol. 8, no. 2, pp. 846–854, Apr. 2017.
[20] M. Bao, Y. Ding, and M. Sang, "Research on energy capacity planning of electricity-gas systems considering multi-objective coordination," *Proc. SPIE*, vol. 41, no. 22, pp. 7551–7563, 2021.
[21] A. Alabdulwahab, A. Abusorrah, X. Zhang, and M. Shahidehpour, "Coordination of interdependent natural gas and electricity infrastructures for firming the variability of wind energy in stochastic day-ahead scheduling," *IEEE Trans. Sustain. Energy*, vol. 6, no. 2, pp. 606–615, Apr. 2015.
[22] Y. Lin, B. Chen, J. Wang, and Z. Bie, "A combined repair crew dispatch problem for resilient electric and natural gas system considering reconfiguration and DG islanding," *IEEE Trans. Power Syst.*, vol. 34, no. 4, pp. 2755–2767, Jul. 2019.
[23] Z. Yachao, Y. Yang, and H. Zhipeng, "Resilience enhancement strategy of electricity-gas integrated energy system based on distributionally robust optimization," *Automat. Electr. Power Syst., Automat. Electr. Power Syst.*, vol. 45, no. 13, pp. 76–84, 2021.
[24] M. Panteli, D. N. Trakas, P. Mancarella, and N. D. Hatziargyriou, "Power systems resilience assessment: Hardening and smart operational enhancement strategies," *Proc. IEEE*, vol. 105, no. 7, pp. 1202–1213, Jul. 2017.
[25] L. S. de Assis, J. F. V. González, F. L. Usberti, C. Lyra, C. Cavellucci, and F. J. Von Zuben, "Switch allocation problems in power distribution systems," *IEEE Trans. Power Syst.*, vol. 30, no. 1, pp. 246–253, Jan. 2015.
[26] C. Zexing, Z. Yongjun, and H. Yu, "Research on optimal reconfiguration method of integrated energy distribution network based on conditional value-at-risk," *Global Energy Internet*, vol. 3, no. 6, pp. 590–599, 2020.
[27] Z. Bie, Y. Lin, G. Li, and F. Li, "Battling the extreme: A study on the power system resilience," *Proc. IEEE*, vol. 105, no. 7, pp. 1253–1266, Jul. 2017.

TINGJUN LI (Member, IEEE) received the B.S. degree from the School of Electrical Engineering and Automation, Wuhan University, Wuhan, China, in 2016, and the M.Sc. and Ph.D. degrees from Taiyuan University of Technology, Taiyuan, China, in 2019 and 2023, respectively.

He is currently a Lecturer with Taiyuan University of Technology. His research interests include energy internet and power system scheduling.

HUA BAI received the B.S. degree from the College of Electrical and Power Engineering, Taiyuan University of Technology, Taiyuan, China, in 2017, where she is currently pursuing the M.Sc. degree with the Department of Electrical Engineering.

Her current research interests include power system operation optimization and integrated energy systems.

XIAOQING HAN (Senior Member, IEEE) received the B.Sc., M.Sc., and Ph.D. degrees from the College of Electrical and Power Engineering, Taiyuan University of Technology, Taiyuan, China.

She is currently a Professor with Taiyuan University of Technology. Her research interests include power system simulation, stability analysis, and integration of renewable sources.