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Collaborative Service Restoration with Network Reconfiguration for Resilience Enhancement in Integrated Electric and Heating Systems

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Abstract: Coordinated fault recovery is essential for the resilience enhancement of integrated electric and heating systems (IEHS) following natural catastrophes as the linkage of the power distribution system (PDS) and district heating system becomes tighter. DHS reconfiguration is a viable method for service restoration because it could adjust the energy between energy sources and achieve uninterrupted energy supplies. In this paper, a collaborative service restoration model considering DHS reconfiguration is proposed to achieve better recovery after natural disasters. DHS reconfiguration could guarantee interrupted power supply in non-fault regions by shifting electric loads between power sources and accomplish optimal service restoration by adjusting the power output of combined heat and power units. Numerous case studies are undertaken to demonstrate the performance of coordinated reconfiguration on resilience enhancement and to confirm the efficacy of the proposed paradigm.

Keywords: integrated electric and heating system; collaborative service restoration; DHS reconfiguration; resilience enhancement

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1. Introduction

In recent years, frequent natural disasters damaged extensive energy infrastructures and caused massive energy outages [1,2]. In 2012, the superstorm Sandy destroyed the natural gas and power transmission systems in the US [3–5], where more than 4.8 million people suffered natural gas and power outages [6]. In 2020, the ice disaster damaged the power transmission lines. It caused 300 million people to experience energy shortages and forced the unit to shut down at Changchun thermal power plant in Jilin, China.

The resilience of the integrated energy system has garnered a lot of attention as people are becoming more aware of these dangers. The service restoration methods of integrated energy systems have been extensively researched to enhance the integrated energy system resilience after disasters [7,8]. For the purpose of boosting resilience, a technique of service restoration that takes into account the coordinated operation of district and regional integrated energy systems has been proposed [9–12]. A service recovery model was developed for the electric and gas system, which considers subsystem coordination [13]. A repair crew dispatch strategy considering the power distribution system reconfiguration was proposed to enhance the electric and gas system resilience [14].

With the introduction of various coupling elements, such as combined heat and power (CHP) units and heating boilers, the electric and heating systems are now closely related [15,16]. The complicated coupling characteristics between the power distribution system (PDS) and district heating system (DHS) would induce two practical problems: (i) Through coupling components, the defects in PDS/DHS could spread to the other system. (ii) The operation flexibility of CHP units cannot be completely utilized during the fault recovery process when subsystems function independently, according to Khatibi and Liu et al.'s analysis and demonstration of the fault propagation among subsystems [17,18]. Therefore, the joint service restoration approach is required for improving resilience.

DHS reconfiguration is an imperative tool for PDS resilience enhancement [19,20]; nonetheless, it has not been considered in the collaborative recovery process of integrated electric and heating systems (IEHSs) for enhancing the overall system resilience. PDS reconfiguration could achieve uninterruptible power supplies in non-faulted regions and adjust the power generation of CHP units after natural disasters to accomplish better service restoration, which has great potential for resilience enhancement of IEHSs.

This paper presents a collaborative service restoration approach that takes into account the reconfiguration of PDS to enhance the resilience of IEHSs. The proposed method offers several contributions, including the development of a comprehensive framework for service restoration, the consideration of PDS reconfiguration as a means of enhancing IEHS resilience, and the incorporation of collaboration among different stakeholders in the restoration process. Overall, this paper offers a valuable contribution to the field of IEHS resilience and provides a practical approach for enhancing the resilience of these critical systems:

(1) A model for collaborative service restoration is presented, which considers the interaction between the fault isolation and restoration stages. It emphasizes the complex coupling characteristics between PDS and DHS to enhance resilience in park-level IEHSs.
(2) Coordinated reconfiguration is a key focus in the collaborative recovery process of park-level IEHSs. This approach can improve overall system resilience by shifting electric loads between power sources and optimally adjusting power generation of CHP units in PDS to ensure better energy supply during fault recovery progress.

In Section 2, an overview of a park-level IEHS is provided. In Section 3, a comprehensive fault recovery model is presented, which addresses the coordinated reconfiguration during the recovery process. The results of testing on the P33H14 system are presented in Section 4—concludes the paper and discusses future work.

2. A Collaborative Service Restoration Model for Park-Level IEHS

The park-level IEHS consists of two closely linked subsystems: the power distribution system and the district heating system. These two subsystems are connected through coupling components (e.g., CHP units). The CHP units serve as the primary energy source for the DHS and PDS, further strengthening the relationship between the two subsystems.

The process of fault recovery in IEHSs can be broken down into two stages: fault isolation and service restoration. In the fault isolation stage, it has been discovered that IEHS fault isolations cannot be achieved by PDS or DHS operators. Coordinated operation of DHS and PDS can shift partial abnormal nodes/buses to non-faulted regions, reducing initial faulted regions. In the fault restoration stage, reconfigurations of DHN and PDS can be coordinated to recover load shedding in normal regions. It is important to note that flexibility resources are not exploited to enhance park-level IEHS resilience unless they are coordinated together. Coordinated operation of DHS valves and PDS switches is essential for fault isolation and service restoration in IEHSs after disasters to enhance IEHS resilience.

In this section, we present a collaborative service restoration model that takes into account the reconfiguration of the power distribution system. The model comprises fault isolation and restoration models. During the fault isolation stage, the PDS reconfiguration enables uninterrupted power supply in non-faulted regions. In the service restoration stage, the PDS reconfiguration enhances fault recovery by leveraging the operational flexibility of combined heat and power units. This approach offers a promising solution for improving the reliability and resilience of IEHS.

2.1. Topological Constraints

2.1.1. Fault Isolation Model

The fault isolation model is a crucial tool in network management, as it allows for the accurate identification of faulted regions and the description of fault propagation throughout the network. This model is designed to provide network administrators with a comprehensive understanding of the network's behavior in the event of a fault, allowing them to quickly and effectively address any issues that arise [21]. The fault isolation model identifies the faulted regions accurately and describes fault propagation in the network, which is shown as follows:

$$\left(1-f_{ij,c}\right)\left(z_{ij,0}-s_{ij,0}\right) \leq z_{ij,c,t} \leq \left(1-f_{ij,c}\right)z_{ij,0}, \forall (i,j) \in k^{pipe} \cup k^{line}, \forall t \in T_i, \forall c \in C, \tag{1}$$

$$m_{i,c,t} - z_{ij,0} + 1 \geq f_{ij,c}\left(1-s_{ij,0}\right), \forall (i,j) \in k^{pipe} \cup k^{line}, \forall t \in T_i, \forall c \in C, \tag{2}$$

$$m_{j,c,t} - z_{ij,0} + 1 \geq f_{ij,c}\left(1-s_{ij,0}\right), \forall (i,j) \in k^{pipe} \cup k^{line}, \forall t \in T_i, \forall c \in C, \tag{3}$$

$$m_{j,c,t} - z_{ij,c,t} + 1 \geq m_{i,c,t}, \forall (i,j) \in k^{pipe} \cup k^{line}, \forall t \in T_i, \forall c \in C, \tag{4}$$

$$m_{i,c,t} - z_{ij,c,t} + 1 \geq m_{j,c,t}, \forall (i,j) \in k^{pipe} \cup k^{line}, \forall t \in T_i, \forall c \in C, \tag{5}$$

$$m_{g,c,t} = m_{h,c,t}, \forall g \in k_{i,h}^{CHP}, h \in k_{i,e}^{CHP}, \forall t \in T_i, \forall c \in C. \tag{6}$$

where k^{pipe} and k^{line} are the set of lines and pipes, $k_{i,h}^{CHP}$ and $k_{i,e}^{CHP}$ are the set of CHP units i in DHS and PDS, T_i represents the fault isolation period, $z_{ij,0}$ is a binary variable that represents whether the line/pipe (i,j) is closed in the pre-event stage, $s_{ij,0}$ is a binary variable that represents whether the line/pipe (i,j) is equipped with a switch in the pre-event stage, $z_{ij,c,t}$ is a binary variable that represents whether the line/pipe (i,j) is connected in the fault isolation stage during period t, $f_{ij,c}$ is a binary variable that represents whether there is a fault on line/pipe (i,j), and $m_{i,c,t}$ is a binary variable that represents whether bus i is divided into faulted regions.

Constraint (1) implies that the switches/valves in non-faulted regions could be operated for fast fault isolation. Constraints (2) and (3) indicate that when there is a fault occurring on a pipe/line, the nodes/buses of the pipe/line will be involved in the faulted/non-faulted region according to switch/valve configuration. Constraints (4) and (5) indicate that the two nodes/buses of a closed pipe/line will be involved in the same region. Constraint (6) illustrates that if CHP units are faulted in DHS/PDS, they are also faulted in the other subsystem. Overall, the abovementioned constraints provide valuable insights into fault isolation in pipeline systems and can be used to develop effective strategies for identifying and addressing faults quickly and efficiently.

2.1.2. Service Restoration Model

After identifying the fault location, switches and valves will be utilized to restore the lost loads in the unaffected regions. The topological constraints will also be taken into consideration during this process. These constraints are formulated based on the information gathered during the fault isolation stage [22].

$$\left(1-f_{ij,c}\right)\left(z_{ij,t-1}-s_{ij,0}\right) \leq z_{ij,c,t} \leq \left(1-f_{ij,c}\right)\left(z_{ij,t-1}+s_{ij,0}\right), \forall (i,j) \in k^{pipe} \cup k^{line}, \forall t \in T_r, \forall c \in C, \tag{7}$$

$$a_{ij,c,t} + a_{ji,c,t} = z_{ij,c,t}, \forall (i,j) \in k^{pipe} \cup k^{line}, \forall t \in T_r, \forall c \in C, \tag{8}$$

$$\sum_{i \in \pi(j)} a_{ij,c,t} \leq 1, \forall j \in k^{nd}, \forall t \in T_r, \forall c \in C, \tag{9}$$

$$\sum_{s \in \sigma(j)} a_{js,c,t} = 0, \forall j \in k^{nd}, \forall t \in T_r, \forall c \in C, \tag{10}$$

$$z_{ij,c,t} = N_{ij} - N_s, \forall (i,j) \in k^{pipe} \cup k^{line}, \forall t \in T_r, \forall c \in C, \tag{11}$$

$$m_{j,c,t-1} - z_{ij,c,t} + 1 \geq m_{i,c,t-1}, \forall (i,j) \in k^{pipe} \cup k^{line}, \forall t \in T_r, \forall c \in C, \tag{12}$$

$$m_{i,c,t-1} - z_{ij,c,t} + 1 \geq m_{j,c,t-1}, \forall (i,j) \in k^{pipe} \cup k^{line}, \forall t \in T_r, \forall c \in C, \tag{13}$$

where T_r represents the service restoration period, and $a_{ij,c,t}$ and $a_{ji,c,t}$ are binary variables that represent the virtual power flow between buses i and j. When $a_{ij,c,t}$ is one, bus i is the parent of bus j in the spanning tree. N_{ij} is the number of pipes/lines, and N_s is the number of heat/electric sources.

The power distribution network is a critical infrastructure that requires constant monitoring and maintenance to ensure uninterrupted power supply to consumers. In the event of a fault, it is essential to isolate the affected area to prevent further damage and restore power to the non-faulted regions as quickly as possible. Constraint (7) illustrates that the pipes/lines equipped with the switches in non-faulted regions could be switched for network reconfiguration. The topology should be radial, as shown in Constraints (8)–(10). This ensures that there is only one path for power flow, which simplifies fault detection and isolation. In the fault isolation stage, the switches in the non-faulted regions can be used to reconfigure the network and restore power to the affected areas. Constraints (12)–(13) illustrate that the faulted areas will not be reconnected to the non-faulted zones in the fault isolation stage. It is important to ensure that the restoration process is carried out in a safe and efficient manner, while also adhering to the relevant regulations and standards. The use of advanced technologies and tools can help to streamline the restoration process and minimize the impact of the fault on the power system. Additionally, ongoing monitoring and maintenance of the power system can help to prevent future faults and ensure the reliability and stability of the system. Overall, a comprehensive approach to fault management and power system restoration is essential for ensuring the continued operation and success of the power grid.

2.2. Operation Constraints

2.2.1. PDS Operation Constraints

A mixed-integer second-order cone programming model is formulated for solving the collaborative service restoration problem in [23–27]. It contains power balance constraints in (14)–(18), transmission capacity constraints in (19) and (20), voltage drop constraints in (21)–(23), unit output constraints in (24)–(27), and load shedding constraints in (28) and (29).

1. Power Balance Constraints

$$p_{j,c,t} = \sum_{s \in \delta(j)} p_{js,c,t} - \sum_{i \in \pi(j)} \left(p_{ij,c,t} - r_{ij} l_{ij,c,t}\right), \forall j \in k^{bus}, \forall t \in T, \forall c \in C, \tag{14}$$

$$q_{j,c,t} = \sum_{s \in \delta(j)} q_{js,c,t} - \sum_{i \in \pi(j)} \left(q_{ij,c,t} - x_{ij} l_{ij,c,t}\right), \forall j \in k^{bus}, \forall t \in T, \forall c \in C, \tag{15}$$

$$p_{j,c,t} = p^{DG}_{j,c,t} + p^{CHP}_{j,c,t} + \sigma p^{SNOP}_{j,c,t} - \left(p^{L}_{j,c,t} - p^{Loss}_{j,c,t}\right), \forall j \in k^{bus}, \forall t \in T, \forall c \in C, \tag{16}$$

$$q_{j,c,t} = q^{DG}_{j,c,t} + q^{CHP}_{j,c,t} + \sigma q^{SNOP}_{j,c,t} - \left(q^{L}_{j,c,t} - q^{Loss}_{j,c,t}\right), \forall j \in k^{bus}, \forall t \in T, \forall c \in C, \tag{17}$$

$$\left\| 2p_{ij,c,t}\ 2q_{ij,c,t}\ l_{ij,c,t} - u_{i,c,t} \right\|_2 \leq l_{ij,c,t} + u_{i,c,t}, \forall j \in k^{bus}, \forall t \in T, \forall c \in C, \tag{18}$$

where k^{bus} is the set of buses; $\pi(j)$ and $\delta(j)$ are the parent and child buses of bus j; $p_{j,c,t}$ and $q_{j,c,t}$ are the power injections of bus j; $p_{ij,c,t}$ and $q_{ij,c,t}$ are the power flow from bus i to bus j; r_{ij} and x_{ij} are resistance and reactance of the line (i,j); l_{ij} is the square current of the line (i,j); $p^{DG}_{j,c,t}$, $p^{CHP}_{j,c,t}$, and $p^{SNOP}_{j,c,t}$ are the power generation of distributed generation (DG), CHP unit, and SNOP; $q^{L}_{j,c,t}$ and $q^{Loss}_{j,c,t}$ are the electric demand and load shedding of bus j; and $u_{i,c,t}$ is the square voltage of bus j.

2. Transmission Capacity Constraints

$$-z_{ij,c,t}\overline{S}_{ij} \le p_{ij,c,t} \le z_{ij,c,t}\overline{S}_{ij}, \forall (i,j) \in k^{line}, \forall t \in T, \forall c \in C, \tag{19}$$

$$-z_{ij,c,t}\overline{S}_{ij} \le q_{ij,c,t} \le z_{ij,c,t}\overline{S}_{ij}, \forall (i,j) \in k^{line}, \forall t \in T, \forall c \in C, \tag{20}$$

where $\overline{S}_{ij}$ is the transmission capacity of the line (i,j).

3. Voltage Drop Constraints

$$u_{i,c,t} - u_{j,c,t} - 2\left(r_{ij}p_{ij,c,t} + x_{ij}q_{ij,c,t}\right) + \left(r_{ij}^2 + x_{ij}^2\right)l_{ij,c,t} \le \left(1 - z_{ij,c,t}\right)M, \forall (i,j) \in k^{line}, \forall t \in T, \forall c \in C, \tag{21}$$

$$u_{i,c,t} - u_{j,c,t} - 2\left(r_{ij}p_{ij,c,t} + x_{ij}q_{ij,c,t}\right) + \left(r_{ij}^2 + x_{ij}^2\right)l_{ij,c,t} \ge \left(1 - z_{ij,c,t}\right)M, \forall (i,j) \in k^{line}, \forall t \in T, \forall c \in C, \tag{22}$$

$$\underline{u}_j \le u_{j,c,t} \le \overline{u}_j, \forall j \in k^{bus}, \forall t \in T, \forall c \in C, \tag{23}$$

where $\underline{u}_j$ and $\overline{u}_j$ are the minimum and maximum square voltage magnitude of bus j.

4. Unit Output Constraints

$$\left(1 - m_{j,c,t}\right)\underline{p}_j^{CHP} \le p_{j,c,t}^{CHP} \le \left(1 - m_{j,c,t}\right)\overline{p}_j^{CHP}, \forall j \in k^{CHP}, \forall t \in T, \forall c \in C \tag{24}$$

$$\left(1 - m_{j,c,t}\right)\underline{q}_j^{CHP} \le q_{j,c,t}^{CHP} \le \left(1 - m_{j,c,t}\right)\overline{q}_j^{CHP}, \forall j \in k^{CHP}, \forall t \in T, \forall c \in C, \tag{25}$$

$$\left(1 - m_{j,c,t}\right)\underline{p}_j^{DG} \le p_{j,c,t}^{DG} \le \left(1 - m_{j,c,t}\right)\overline{p}_j^{DG}, \forall j \in k^{DG}, \forall t \in T, \forall c \in C, \tag{26}$$

$$\left(1 - m_{j,c,t}\right)\underline{q}_j^{DG} \le q_{j,c,t}^{DG} \le \left(1 - m_{j,c,t}\right)\overline{q}_j^{DG}, \forall j \in k^{DG}, \forall t \in T, \forall c \in C, \tag{27}$$

where $\underline{p}_j^{CHP}$, $\underline{q}_j^{CHP}$ and $\overline{p}_j^{CHP}$, $\overline{p}_j^{CHP}$ are the limited power generation of CHP unit j; $\underline{p}_j^{DG}$, $\underline{q}_j^{DG}$ and $\overline{p}_j^{DG}$, $\overline{p}_j^{DG}$ are the limited power generation of DG j; Constraints (24)–(27) illustrate that when unit shutdown occurs in the faulted regions, CHP units/DG would not provide the power supply.

5. Load Shedding Constraints

$$m_{j,c,t}p_j^{L} \le p_{j,c,t}^{Loss} \le p_j^{L}, \forall j \in k^{bus}, \forall t \in T, \forall c \in C, \tag{28}$$

$$m_{j,c,t}q_j^{L} \le q_{j,c,t}^{Loss} \le q_j^{L}, \forall j \in k^{bus}, \forall t \in T, \forall c \in C. \tag{29}$$

Constraints (28) and (29) illustrate that the electric loads would be fully shed in faulted regions because the unit shutdown and the partial loads in non-faulted regions would be lost for energy balance. It is evident that in the event of a fault in a particular region, the electric loads in that region would be completely shed. This is due to the fact that the unit would shut down, resulting in a loss of partial loads in non-faulted regions, which would disrupt the energy balance of the system.

2.2.2. DHS Operation Constraints

The available heat quantity in the energy flow model is introduced as an auxiliary variable, i.e., $h_{ij} = cm_{ij}\left(\tau_{ij}^{S} - \tau_{ij}^{R}\right)$, and the energy flow model is applied to the service restoration model [28–31]. It contains heat station constraints in (30)–(32), heat transmission constraints in (33)–(35), energy balance constraints in (36), unit output constraints in (37), and load shedding constraints in (38).

1. Heat Station Constraints

CHP units are the main heating sources in industrial parks in China and commonly operate in the mode of determining electricity by heat [20–24]. Thus, the relationship between power and heat generation of CHP units is expressed as

$$\underline{\nu}_j h_{j,c,t}^{CHP} \le p_{j,c,t}^{CHP} \le \overline{\nu}_j h_{j,c,t}^{CHP}, \forall\, j \in k^{CHP}, \forall t \in T, \forall c \in C, \tag{30}$$

$$h_{j,c,t}^{HB} = \gamma_j f_{j,c,t}^{HB}, \forall\, j \in k^{HB}, \forall t \in T, \forall c \in C, \tag{31}$$

$$\sum_{j \in k_k^{CHP}} h_{j,c,t}^{CHP} + \sum_{j \in k_k^{HB}} h_{j,c,t}^{HB} = h_{k,c,t}^{HS}, \forall k \in k^{HS}, \forall t \in T, \forall c \in C, \tag{32}$$

where k^{CHP}, k^{HB}, and k^{HS} are the set of CHP units, heating boilers, and heat stations; $h_{j,c,t}^{CHP}$ is the heat generation of CHP unit j; $\underline{\nu}_j$ and $\overline{\nu}_j$ are the minimum and maximum coefficient of power and heat generation of CHP unit j; $h_{j,c,t}^{HB}$ and $f_{j,c,t}^{HB}$ are the heat generation and fuel consumption of heating boiler j; γ_j is the coefficient between heat generation and fuel consumption of heating boiler j; and $h_{k,c,t}^{HS}$ is the heat generation of heat station k.

2. Heat Transmission Constraints

$$h_{ij,c,t}^{P,out} = h_{ij,c,t}^{P,in} - h_{ij,c,t}^{loss}, \forall (i,j) \in k^{pipe}, \forall t \in T, \forall c \in C, \tag{33}$$

$$-z_{ij,c,t}\overline{h}_{ij}^{P} \le h_{ij,c,t}^{P,in} \le z_{ij,c,t}\overline{h}_{ij}^{P}, \forall (i,j) \in k^{pipe}, \forall t \in T, \forall c \in C, \tag{34}$$

$$-z_{ij,c,t}\overline{h}_{ij}^{P} \le h_{ij,c,t}^{P,out} \le z_{ij,c,t}\overline{h}_{ij}^{P}, \forall (i,j) \in k^{pipe}, \forall t \in T, \forall c \in C, \tag{35}$$

where $h_{ij,c,t}^{P,out}$, $h_{ij,c,t}^{P,in}$, and $h_{ij,c,t}^{loss}$ are the outlet heat quantity, inlet heat quantity, and lost heat quantity of the pipe (i,j), and $\overline{h}_{ij}^{P}$ is the limited transmission of the pipe (i,j).

3. Energy Balance Constraints

$$\sum_{(j,s) \in S_j^{pipe-}} h_{js,c,t}^{P,out} + \sum_{k \in k_j^{HS}} h_{k,c,t}^{HS} = h_{j,c}^{L} - h_{j,c,t}^{Loss} + \sum_{(i,j) \in S_j^{pipe+}} h_{ij,c,t}^{P,in}, \forall j \in k^{nd}, \forall t \in T, \forall c \in C, \tag{36}$$

where S_j^{pipe-} and S_j^{pipe+} are the set of pipes flowing from/to node j.

4. Unit Output Constraints

$$\left(1 - m_{j,c,t}\right)\underline{h}_j^{CHP} \le h_{j,t}^{CHP} \le \left(1 - m_{j,c,t}\right)\overline{h}_j^{CHP}, \forall j \in k^{CHP}, \forall t \in T, \forall c \in C, \tag{37}$$

Constraint (37) illustrates that when unit shutdown occurs in the faulted regions, CHP units would not provide the heat supply.

5. Load Shedding Constraints

$$m_{j,c,t} h_j^{L} \le h_{j,c,t}^{Loss} \le h_j^{L}, \forall j \in k^{nd}, \forall t \in T, \forall c \in C \tag{38}$$

Constraint (38) illustrates that the heat loads would be fully shed in the faulted regions and partial loads in the non-faulted regions would be lost.

2.2.3. Objective and Resilience Metrics

The objective and resilience metrics are proposed in (39) and (40) in order to reduce the loss of electric and heat loads during the fault recovery process and evaluate the park-level IEHS resilience [32–35].

$$\min \sum_{c \in C} p_c \left\{ T_i \left(\sum_{j \in k^{bus}} a_j p_{j,c,t}^{Loss} + \sum_{j \in k^{nd}} b_j h_{j,c,t}^{Loss} \right) + T_r \left(\sum_{j \in k^{bus}} a_j p_{j,c,t}^{Loss} + \sum_{j \in k^{nd}} b_j h_{j,c,t}^{Loss} \right) \right\}, \quad (39)$$

$$R_c = 1 - \frac{T_i \left(\sum\limits_{j \in k^{bus}} a_j p_{j,c,t}^{Loss} + \sum\limits_{j \in k^{nd}} b_j h_{j,c,t}^{Loss} \right) + T_r \left(\sum\limits_{j \in k^{bus}} a_j p_{j,c,t}^{Loss} + \sum\limits_{j \in k^{nd}} b_j h_{j,c,t}^{Loss} \right)}{T \left(\sum\limits_{j \in k^{bus}} a_j p_{j,c,t}^{Loss} + \sum\limits_{j \in k^{nd}} b_j h_{j,c,t}^{Loss} \right)}, \forall c \in C. \quad (40)$$

where a_j and b_j are the weight of the electric and heat loads.

3. Case Studies

3.1. Case Description

The proposed strategy is evaluated using a modified P33H14 system (Figure 1) with three heat stations (HS1, HS2, and HS3) that utilize extraction-condensing CHP units and a heating boiler to supply DHS heat loads. During the pre-event phase, specific valves are typically open. The tests were conducted using Matlab R2020a on a computer with an i7-1165G7 CPU and 16 GB of memory.

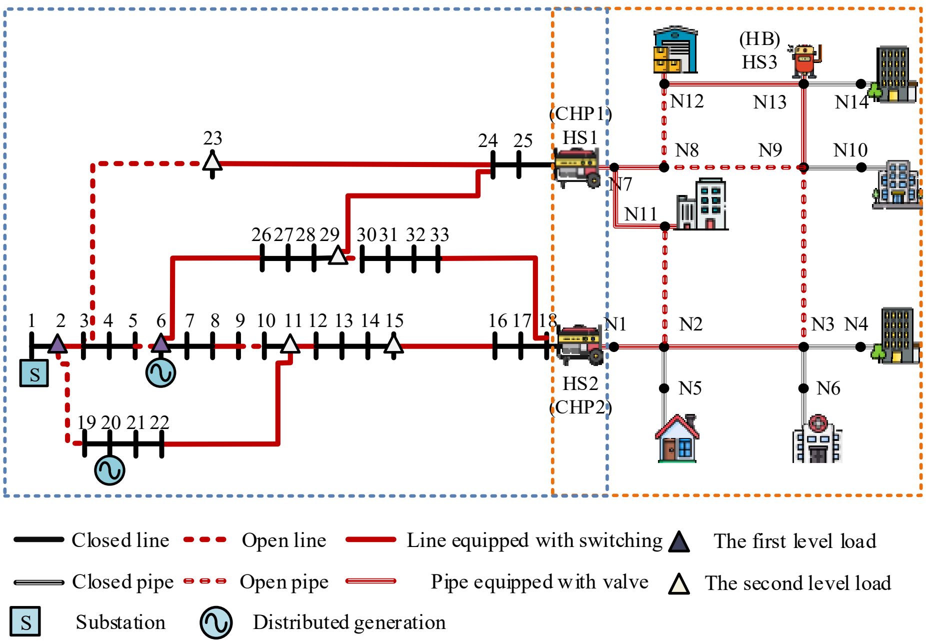

Figure 1. Structure of P33H14 system. Number represents node number, blue frame represents boundary of PDS and orange frame represents boundary of DHS.

3.2. Case Analysis

To demonstrate how the coordinated reconfiguration of PDS and DHS can improve resilience, two cases are conducted:

Case 1: Only consider PDS reconfiguration for restoration.

Case 2: Coordinated reconfiguration is considered to restore services.

3.2.1. PDS Fault Scenario

During the recovery process, several power and heat lines in the park-level Integrated Energy and Heating System (IEHS) were destroyed by natural disasters, including lines 6-26, 8-9, 11-12, and 23-24. As a result, there were major power and heat outages in the IEHS. The impact of these events is summarized in Figure 2 and Table 1 and the following conclusions can be drawn.

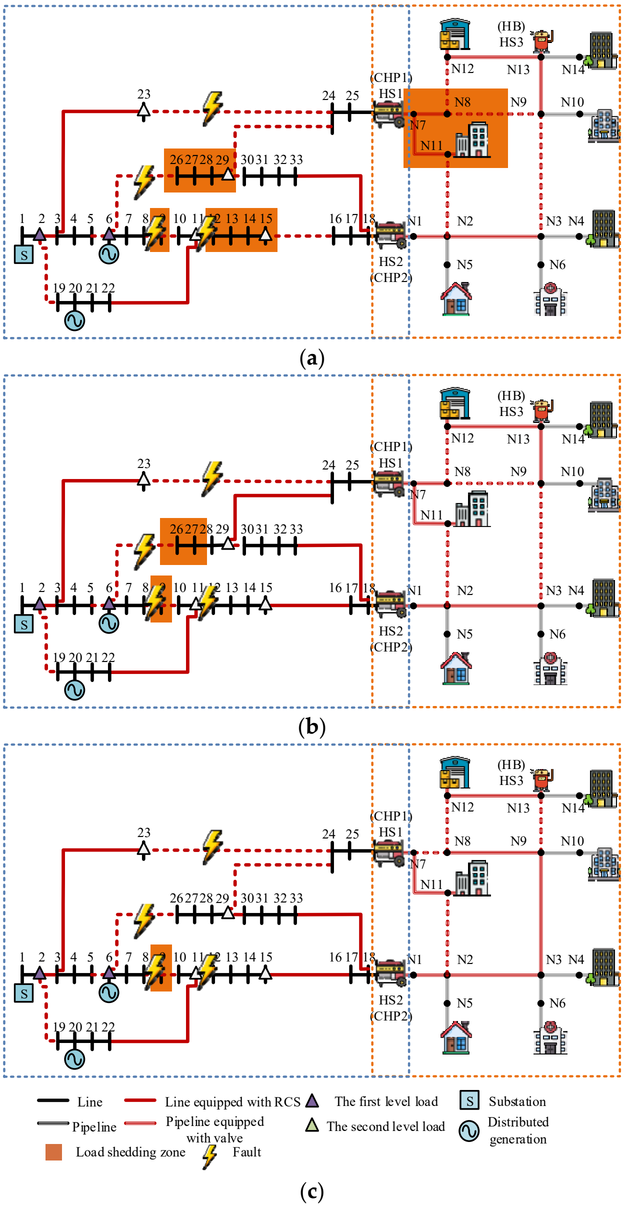

Figure 2. Topology of P33H14 during fault recovery. (**a**) Fault isolation stage; (**b**) fault restoration stage (Case 1); (**c**) fault restoration stage (Case 2). Number represents node number, blue frame represents boundary of PDS and orange frame represents boundary of DHS.

Table 1. Load curtailment and resilience metric.

Scenario	Case	Total Load Curtailment (MW)	Load Curtailment (MW) Electric	Heat	Resilience Metric
PDS fault scenario	Case 1	90.7	104.6	77.6	0.85
	Case 2	72.6	41.6	30	0.96
DHS fault scenario	Case 1	113.9	45.7	68.2	0.89
	Case 2	96.8	31.6	25.2	0.92

Firstly, the faults in the PDS propagated to DHS through CHP units, which led to the power production of CHP1 being limited during the fault isolation stage. Specifically, the load at bus 26–29 was completely lost, and the heat loads at nodes 7, 8, and 11 were partially lost.

Secondly, to improve fault repair and increase the DHS capability in natural catastrophes, the District Heating Network (DHN) reconfiguration was implemented by remotely scheduling valves and dispersing loads across heat sources. In Case 2, tie valve operation was performed on pipelines N3-N9, N7-N8, N8-N9, and N8-N12, which shifted the heat loads to CHP2. This strategy aimed to minimize DHS load shedding, and as a result, CHP1 was fully utilized.

Finally, the coordinated reconfiguration approach proved to be more effective than only PDS reconfiguration in enhancing the park-level IEHS resilience. The load curtailment decreased by 19.9%, and the value of the resilience metric increased by 12.9% in Case 2 compared to Case 1. This demonstrates the importance of a coordinated approach in improving the resilience of energy systems in the face of natural disasters.

3.2.2. DHS Fault Scenario

Table 1 displays the switch operations required for the recovery progress of the district heating system (DHS) after pipes N2-3, N2-11, and N12-13 were damaged by disasters. The results of these operations are summarized in Table 1, which leads to several conclusions.

Firstly, faults in PDS can cause simultaneous power and heat outages in DHS. During the fault isolation stage, electric load reductions at buses 30 and 31 result in partially disappearing heat loads at nodes 3, 4, and 6 and limit the power generation of CHP2.

Secondly, reconfiguring the district heating network (DHN) can improve PDS resilience and increase availability by optimally changing the topology of the heating network. Case 1 reveals that the critical heat source, CHP1′s heat output, is constrained during the isolation stage, leading to a challenging energy balance with incomplete DHS heat outage recovery despite PDS reconfiguration. In Case 2, redistributing the heat load at node 8 through valve operations in pipes N3-N9 and N8-N9 enables CHP2 operation flexibility.

Thirdly, overall load curtailment reduces by 15.0% with coordinated operation in Case 2 (Table 2).

Table 2. Switch operation during the recovery progress.

Line/Pipe	Pre-Event	Fault Isolation Case 1	Fault Isolation Case 2	Restoration Case 1	Restoration Case 2
L3-23	0	0	0	1	1
L9-10	0	0	0	1	1
L18-33	1	1	1	0	0
L29-30	0	0	0	1	1
N3-9	0	0	1	0	1
N8-9	0	0	1	0	1

4. Conclusions

In this paper, we propose a collaborative service restoration strategy that incorporates coordinated network reconfiguration. Our approach takes into account the interaction between fault isolation and service restoration stages and emphasizes the complex coupling characteristics between the primary distribution system (PDS) and the district heating system (DHS). Through comprehensive case studies, we confirm that faults in the PDS can propagate to the DHS via coupling units. We also demonstrate that DHS reconfiguration can help expand the scope of energy supply by shifting loads among power sources. Furthermore, coordinated reconfiguration can reduce load curtailments when faults propagate between subsystems and significantly enhance the resilience of the integrated energy and heating system (IEHS) by adjusting the power production of combined heat and power (CHP) units.

For future research, we plan to consider more uncertainties, such as load fluctuations and random failures. We will also explore different ways to express similar viewpoints while ensuring the originality of the content. Overall, our study highlights the importance of coordinated network reconfiguration in enhancing the resilience of IEHSs and provides insights for future research in this area.

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Nomenclature

Abbreviations

T	Index of fault recovery periods
C	Index of fault scenarios
T_i/T_r	Index of fault isolation and service restoration periods
$k_{i,h}^{CHP}/k_{i,e}^{CHP}$	Index of CHP units i in DHS and PDS
k^{pipe}/k^{line}	Set of lines/pipes
k^{bus}/k^{bus}	Set of buses/nodes
$\pi(j)/\delta(j)$	Set of parent and child buses of bus j
$k^{CHP}/k^{HB}/k^{HS}$	Set of CHP units, heating boilers, and heat stations
S_j^{pipe-}/S_j^{pipe+}	Set of pipes flowing from/to node j

Parameters and Functions

A_i	Power loss coefficient of SOP at bus i.
$\underline{q}_{i,c,t}^{SNOP}/\overline{q}_{i,c,t}^{SNOP}$	Minimum/maximum reactive power injections of SOP at bus i
$S_{i,c,t}^{SNOP}$	Capacity of SOP at bus i
$z_{ij,0}$	Binary variable that represents whether the line/pipe (i,j) is closed in the pre-event stage
$s_{ij,0}$	Binary variable that represents whether the line/pipe (i,j) is equipped with a switch in pre-event stage
$f_{ij,c}$	Binary variable that represents whether there is a fault on the line/pipe (i,j),
N_s	Number of heat/electric sources
N_{SOP}	Number of SOPs
N_{ij}	Number of pipes/lines
r_{ij}/x_{ij}	Binary variable that represents whether there is a fault on the line/pipe (i,j)
l_{ij}	Binary variable that represents whether there is a fault on the line/pipe (i,j)
$\overline{S}_{ij}$	ransmission capacity of the line (i,j)
$\underline{u}_j/\overline{u}_j$	Minimum/maximum square voltage magnitude of bus j.

$\underline{p}_j^{DG}/\overline{p}_j^{DG}$	Minimum/maximum power generation of DG j
$\underline{p}_j^{CHP}/\overline{p}_j^{CHP}$	Minimum/maximum power generation of CHP unit j
$\underline{v}_j/\overline{v}_j$	Minimum/maximum coefficient of power and heat generation of CHP unit j
γ_j	Coefficient between heat generation and fuel consumption of heating boiler j
$\overline{h}_{ij}^{P}$	Maximum transmission limit of the pipe (i,j)
a_j/b_j	Weight of electric and heat load j
Variables	
$p_{i,c,t}^{SNOP}/q_{i,c,t}^{SNOP}$	Active/Reactive power injection of bus i that is associated with SOP
$p_{i,c,t}^{SNOP,Loss}/q_{i,c,t}^{SNOP,Loss}$	Active/Reactive Power loss of bus i that is associated with SOP
$z_{ij,c,t}$	Binary variable that represents whether the line/pipe (i,j) is connected in the fault isolation stage during period t
$m_{i,c,t}$	Binary variable that represents whether bus i is divided into faulted regions.
$a_{ij,c,t}$	Binary variables that represent the virtual power flow between buses i and j
σ	Binary variable that represents whether SOP is in operation
$m_{i,c,t}$	Binary variable that represents whether bus i is divided into faulted regions.
$p_{j,c,t}/q_{j,c,t}$	Active/Reactive power injection of bus i that is associated with SOP
$p_{ij,c,t}/q_{ij,c,t}$	Active/Reactive power flow from bus i to bus j
$p_{j,c,t}^{DG}/q_{j,c,t}^{DG}$	Active/Reactive power generation of DG at bus i
$p_{j,c,t}^{CHP}/q_{j,c,t}^{CHP}$	Active/Reactive power generation of CHP unit at bus i
$p_{j,c,t}^{L}/q_{j,c,t}^{L}$	Electric demand of bus j
$p_{j,c,t}^{Loss}/q_{j,c,t}^{Loss}$	Load shedding of bus j
$u_{i,c,t}$	Square voltage of bus j
$h_{j,c,t}^{CHP}$	Heat generation of CHP unit j
$h_{j,c,t}^{HB}/f_{j,c,t}^{HB}$	Heat generation and fuel consumption of heating boiler j
$h_{k,c,t}^{HS}$	Heat generation of heat station k
$h_{ij,c,t}^{P,out}/h_{ij,c,t}^{P,in}/h_{ij,c,t}^{loss}$	Outlet, inlet, and loss heat quantity of pipe (i,j)

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