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A Coordinated Reconfiguration Strategy for Multi-Stage Resilience Enhancement in Integrated Power Distribution and Heating Networks

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CONTECTS

01 Background

1. Background

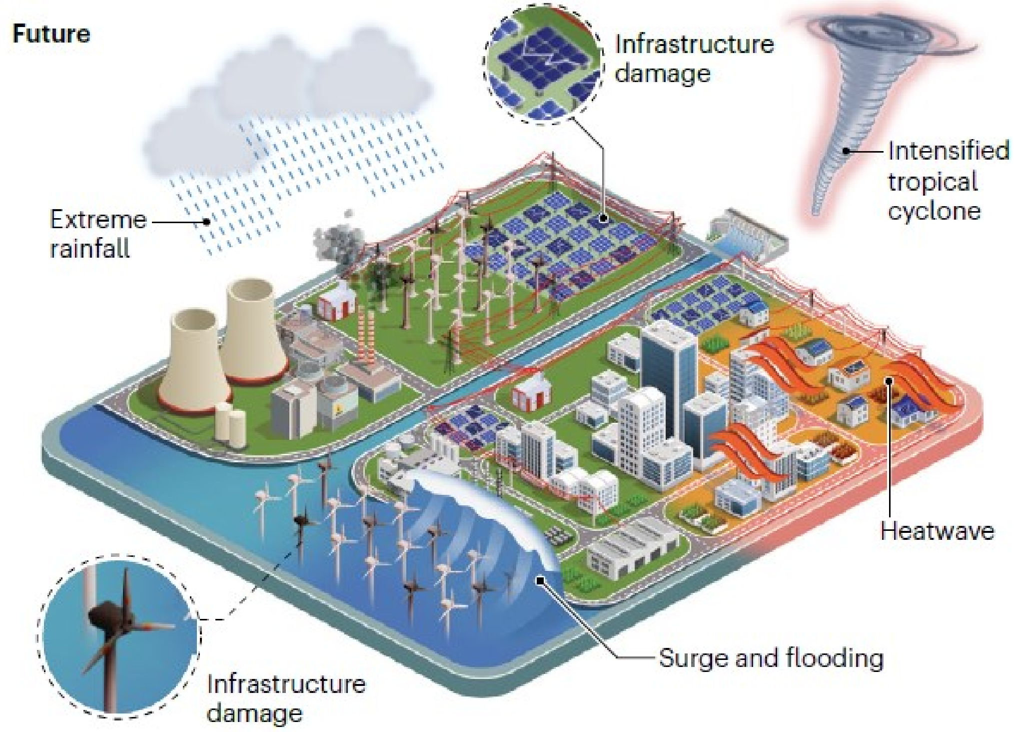
Recently, climate change has brought about more frequent and extensive natural disasters, such as hurricanes, storms, and ice disasters. The resilience of the integrated energy system is prominent under extreme weather.

- Jilin, China, November 2020

  The 2020 ice disaster resulted in the shut-down of chief thermal electric plants owing to line outages, where over 300 million people suffered power and heating shortages.

- Texas, US, Febaurary 2021

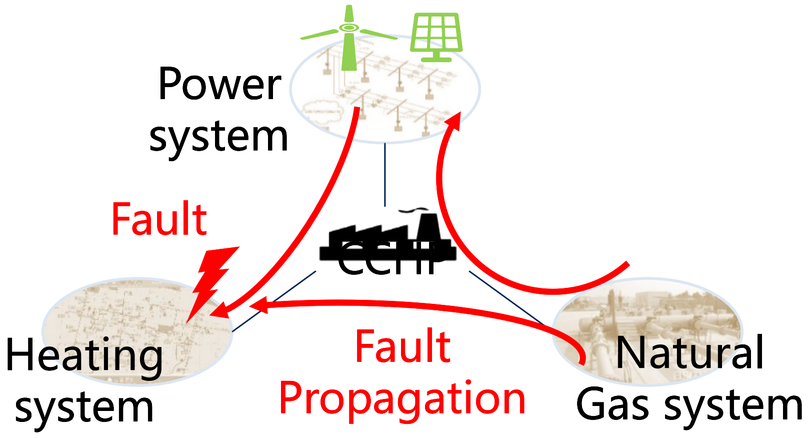
  The onslaught of Winter Storm Uri in 2021 left close to 10 million people without gas and power supplies at peak hours, and its economic toll was estimated to be as high as $295 billion



1. Background

The extensive applications of combined heat and power (CHP) units，provide a tighter linkage between power systems and district heating systems (DHS)，this raises major practical problems.

- ➢ Any power distribution systems (PDS) or DHS failures can propagate into other subsystem in integrated electric and heating system (IEHS).
- ➢ Flexibility resources for devising the IEHS emergency control cannot be fully exploited during service restoration stage.



The coordinated resilience enhancement method is highly desirable!

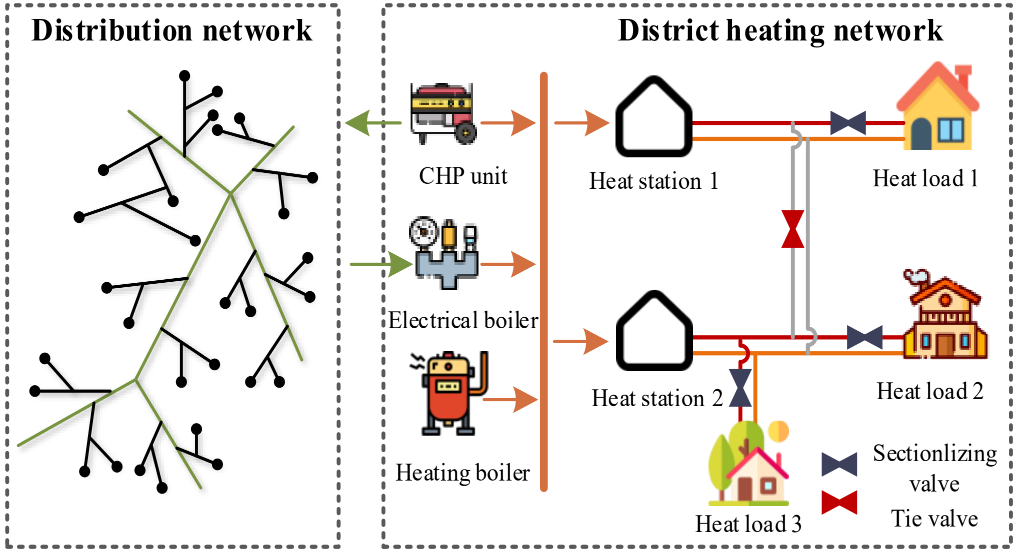
1. Background

The necessity of DHS reconfiguration

The PDS reconfiguration is regarded as the primary measure for resilience enhancement. Similar to that of PDS, the DHS reconfiguration can be realized by remote switching of tie and sectionalizing valves.

DHN reconfiguration

- DHS reconfiguration can redistribute heating loads among heat sources for DHS resilience enhancement
- Heating supply structure can be readjusted to match line switching to prevent wider fault propagations and enhance the resilience in IEHS



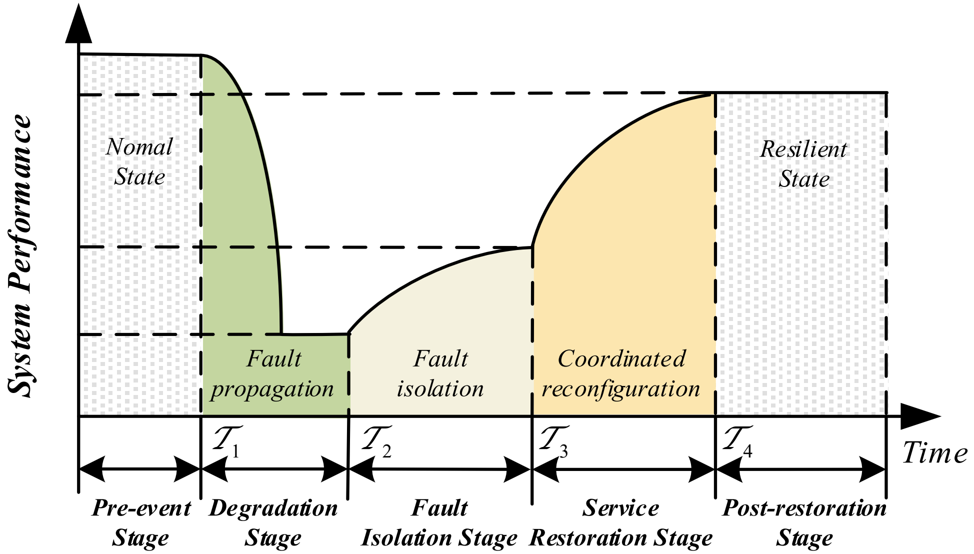
The DHS reconfiguration is necessary for collaborative restoration in IEHS

1. Problem description

Research object：A **park-level integrated electric and heating system** **consisting** of power distribution system and district heating system.

Restoration Stages：

- ➢ **Degradation stages**：PDS or DHS faults can **propagate into the other subsystem** through closed pipes/lines and coupling components.
- ➢ **Fault isolation stages**：The initial faulted regions would be reduced.
- ➢ **Service restoration stages**：the **reconfigurations of DHN and PDS** could be coordinated to recover the load shedding in normal regions.



The multi-stage coordinated recovery model of park-level IEHSs is formulated

1. Contribution

- **A multi-stage fault recovery model of park-level IEHS is proposed for IEHS countering natural disasters and achieving fast restoration.** The proposed model formulates fault propagations among subsystems and defines service restoration stages with topological constraints to address the coordinated fault recovery of PDS and DHS.
- **The reconfigurations of DHN and PDS are coordinated to provide additional flexibility for short-time fault recovery.** To our knowledge, this is the first work that focuses on the DHN reconfiguration for resilience enhancement by optimally rescheduling the heating supply topology in DHS to match the PDS line switching strategy after natural disasters.
- **A current-oriented linearized Distflow (CLD) model for PDS is proposed** to reformulate the original intractable mixed-integer nonlinear problem (MINLP) into a solvable mixed-integer linear problem (MILP), which introduces a current-oriented auxiliary variable and approximates the differences of branch current projection along with bus voltages.

02

Multi-stage coordinated recovery model

2. Multi-stage coordinated recovery model

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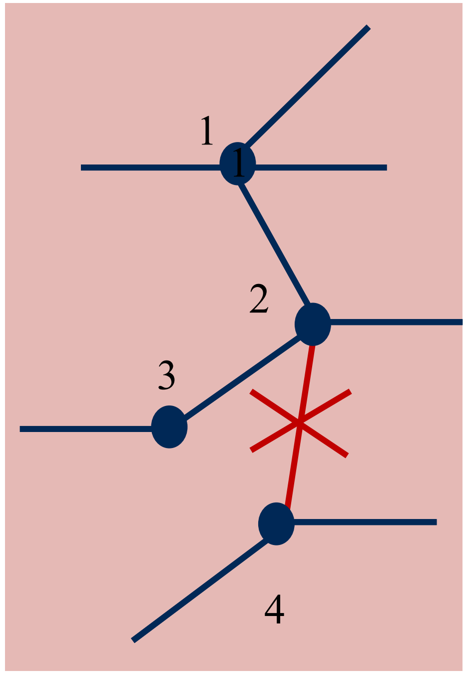
Network topology constraints

Degradation Stage



Model Building

$$
\begin{aligned}
& n_{i,c,t} \ge f_{ij,c}\mu_{ij,0}, \\
& \forall (i,j) \in k^{pipe} \cup k^{line}, t=1, \forall c \in C, \\
& n_{j,c,t} \ge f_{ij,c}\mu_{ij,0}, \\
& \forall (i,j) \in k^{pipe} \cup k^{line}, t=1, \forall c \in C, \\
& n_{i,c,t} + \mu_{ij,0} - 1 \le n_{j,c,t}, \\
& \forall (i,j) \in k^{pipe} \cup k^{line}, t=1, \forall c \in C, \\
& n_{j,c,t} + \mu_{ij,0} - 1 \le n_{i,c,t}, \\
& \forall (i,j) \in k^{pipe} \cup k^{line}, t=1, \forall c \in C, \\
& n_{m,c,t} = n_{n,c,t}, \\
& \forall m \in k_{i,n}^{CHP}, n \in k_{i,b}^{CHP}, t=1, \forall c \in C.
\end{aligned}
$$

Operation Constraints

When a fault occurs on a closed pipe/line, connected nodes/buses will be comprised in the faulted regions.

Nodes/buses connected to a closed pipe/line will be divided into the same region

CHP units in DHS faulted region will participate in PDS analyses

2. Multi-stage coordinated recovery model

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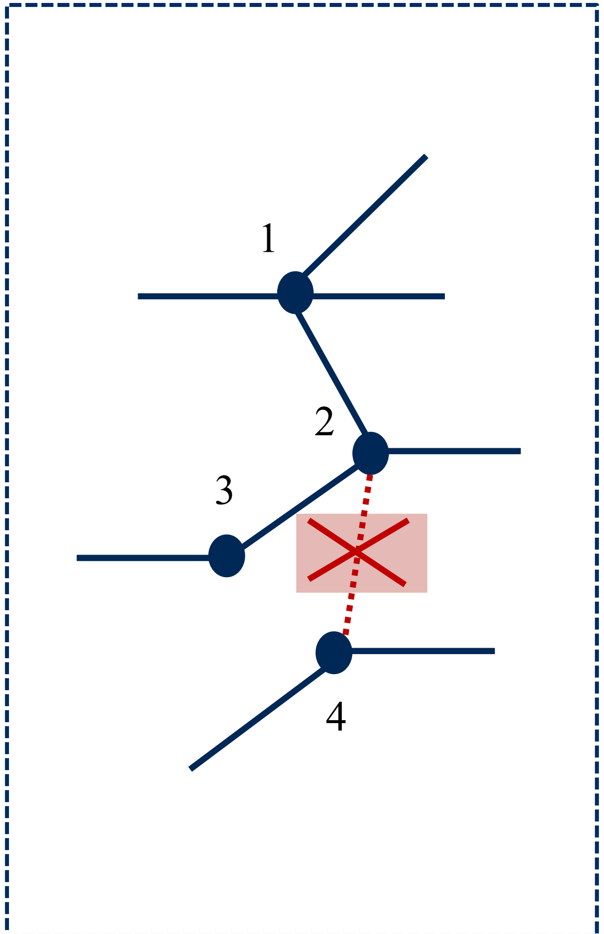
Network topology constraints

Fault Isolation Stage	Mathematic Model	Operation Constraints



$$\left(1-f_{ij,c}\right)\left(\mu_{ij,0}-s_{ij,0}\right)\le\mu_{ij,c,t}\le\left(1-f_{ij,c}\right)\mu_{ij,0},$$
$$\forall(i,j)\in k^{pipe}\bigcup k^{line},t=2,\forall c\in C,$$
$$n_{i,c,t}\ge f_{ij,c}\left(1-s_{ij,0}\right)+\mu_{ij,0}-1,$$
$$\forall(i,j)\in k^{pipe}\bigcup k^{line},t=2,\forall c\in C,$$
$$n_{j,c,t}\ge f_{ij,c}\left(1-s_{ij,0}\right)+\mu_{ij,0}-1,$$
$$\forall(i,j)\in k^{pipe}\bigcup k^{line},t=2,\forall c\in C,$$
$$n_{i,c,t}+\mu_{ij,c,t}-1\le n_{j,c,t},$$
$$\forall(i,j)\in k^{pipe}\bigcup k^{line},t=2,\forall c\in C,$$
$$n_{j,c,t}+\mu_{ij,c,t}-1\le n_{i,c,t},$$
$$\forall(i,j)\in k^{pipe}\bigcup k^{line},t=2,\forall c\in C,$$
$$n_{m,c,t}=n_{n,c,t},$$
$$\forall m\in k_{i,n}^{CHP},n\in k_{i,b}^{CHP},t=2,\forall c\in C.$$

Valve/switch equipped on a non-faulted closed pipe/line can be utilized for isolation

Valves/switches will function to separate nodes/buses when faults occur

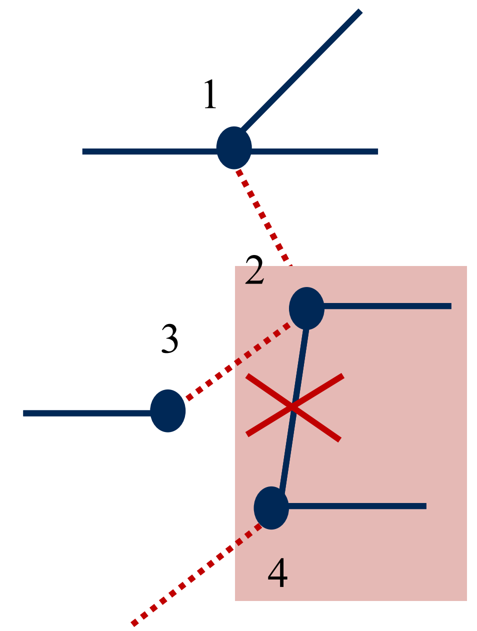
Nodes/buses of a closed pipe/line will be divided into the same region.

CHP units in DHS faulted region will participate in PDS analyses

2. Multi-stage coordinated recovery model

Network topology constraints

Service Restoration Stage



Mathematic Model

$$
\begin{aligned}
&\left(1-f_{ij,c}\right)\left(\mu_{ij,t\text{-}1}-s_{ij,0}\right)\le \mu_{ij,c,t}\le\left(1-f_{ij,c}\right)\left(\mu_{ij,t\text{-}1}+s_{ij,0}\right),\\
&\forall (i,j)\in k^{pipe}\cup k^{line}, t=3, \forall c\in C,\\
&\omega_{ij,c,t}+\omega_{ji,c,t}=\mu_{ij,t},\\
&\forall (i,j)\in k^{pipe}\cup k^{line}, t=3, \forall c\in C,\\
&\sum_{i\in\pi(j)}\omega_{ij,c,t}+\sum_{s\in\delta(j)}\omega_{sj,c,t}\le 1-g_j-p_j-\gamma_{j,c,t}d_j,\\
&\forall j\in k^{nd}\cup k^{bus}, t=3, \forall c\in C,\\
&n_{i,c,t\text{-}1}+\mu_{ij,t}-1\le n_{j,c,t\text{-}1},\\
&\forall (i,j)\in k^{pipe}\cup k^{line}, t=3, \forall c\in C,\\
&n_{j,c,t\text{-}1}+\mu_{ij,t}-1\le n_{i,c,t\text{-}1},\\
&\forall (i,j)\in k^{pipe}\cup k^{line}, t=3, \forall c\in C.
\end{aligned}
$$

Operation Constraints

The valve/switch equipped on a non-faulted pipe/line could be utilized for PDS/DHS reconfiguration

The practical PDS/DHN is commonly scheduled with a radial topology

The faulted and non-faulted regions in last stage will remain isolated

2. Multi-stage coordinated recovery model

System operation constraints

Steady-state Model of Heating System Based on Energy Flow Model

$$
\begin{aligned}
&\mathbf{p}^{CHP} \le diag\left(\bar{\chi}_1,\ \bar{\chi}_2,\ \ldots \bar{\chi}_n\right)\mathbf{h}^{CHP}, \mathbf{p}^{CHP} \ge diag\left(\underline{\chi}_1,\ \underline{\chi}_2,\ \ldots \underline{\chi}_n\right)\mathbf{h}^{CHP},\\
&\left[\mathcal{T}_{CHP}{}^{T}\left(1-\mathbf{n}\right)\right]\circ\underline{\mathbf{h}}^{CHP} \le \mathbf{h}^{CHP} \le \left[\mathcal{T}_{CHP}{}^{T}\left(1-\mathbf{n}\right)\right]\circ\bar{\mathbf{h}}^{CHP},\\
&\left[\mathcal{T}_{EB}{}^{T}\left(1-\mathbf{n}\right)\right]\circ\underline{\mathbf{h}}^{HB} \le \mathbf{h}^{HB} \le \left[\mathcal{T}_{EB}{}^{T}\left(1-\mathbf{n}\right)\right]\circ\bar{\mathbf{h}}^{HB},\\
&h^{\mathbf{HB}} = \eta\circ f^{\mathbf{HB}},\\
&h_{\mathbf{ij}}^{\mathbf{in}} - h_{\mathbf{ij}}^{\mathbf{out}} = h_{\mathbf{ij}}^{\mathbf{loss}},\\
&-\mu_{\mathbf{ij}}\circ\bar{h}_{\mathbf{ij}} \le h_{\mathbf{ij}}^{\mathbf{in}} \le \mu_{\mathbf{ij}}\circ\bar{h}_{\mathbf{ij}},\ \ -\mu_{\mathbf{ij}}\circ\bar{h}_{\mathbf{ij}} \le h_{\mathbf{ij}}^{\mathbf{out}} \le \mu_{\mathbf{ij}}\circ\bar{h}_{\mathbf{ij}},\\
&h^{\mathbf{HS}} = h^{\mathbf{CHP}} + h^{\mathbf{HB}},\\
&F_{\mathbf{h}}h_{\mathbf{ij}}^{\mathbf{in}} - T_{\mathbf{h}}h_{\mathbf{ij}}^{\mathbf{out}} = \mathcal{T}_{\mathbf{HS}}h^{\mathbf{HS}} - \left(h^{\mathbf{L}} - h^{\mathbf{Loss}}\right),\\
&-M\left(1-\mathbf{n}\right) \le \mathbf{h}^{L} - \mathbf{h}^{Loss} \le M\left(1-\mathbf{n}\right),\\
&0 \le \mathbf{h}^{Loss} \le \mathbf{h}^{L}.
\end{aligned}
$$

Operation Constraints

CHP unit output constraint

Heating boiler output constraint

Heat loss constraint

Heat transmission constraint

Energy flow balance constraint

Heat load loss constraint

2. Multi-stage coordinated recovery model

System operation constraints

Steady State Model of Power System

$$\mathbf{A}_e\mathbf{p}=\mathbf{P}-\mathbf{T}_e\left(\mathrm{rol}\right),\ \ \mathbf{A}_e\mathbf{q}=\mathbf{Q}-\mathbf{T}_e\left(\mathrm{xol}\right),$$

$$\mathbf{P}=\mathcal{G}_{\mathbf{DG}}\mathbf{p}^{\mathbf{DG}}+\mathcal{G}_{\mathbf{CHP}}\mathbf{p}^{\mathbf{CHP}}-\left(\mathbf{p}^{\mathbf{L}}-\mathbf{p}^{\mathbf{Loss}}\right),$$

$$\mathbf{Q}=\mathcal{G}_{\mathbf{DG}}\mathbf{q}^{\mathbf{DG}}+\mathcal{G}_{\mathbf{CHP}}\mathbf{q}^{\mathbf{CHP}}-\left(\mathbf{q}^{\mathbf{L}}-\mathbf{q}^{\mathbf{Loss}}\right),$$

$$-\mu_{\mathbf{ij}}\mathrm{o}\overline{\mathbf{S}}_{\mathbf{ij}}\le\mathbf{p}\le\mu_{\mathbf{ij}}\mathrm{o}\overline{\mathbf{S}}_{\mathbf{ij}},\ \ -\mu_{\mathbf{ij}}\mathrm{o}\overline{\mathbf{S}}_{\mathbf{ij}}\le\mathbf{q}\le\mu_{\mathbf{ij}}\mathrm{o}\overline{\mathbf{S}}_{\mathbf{ij}},$$

$$\left[\mathcal{G}_{\mathbf{CHP}}{}^{T}\left(\mathbf{1}-\mathbf{n}\right)\right]\mathrm{o}\underline{\mathbf{p}}^{\mathbf{CHP}}\le\mathbf{p}^{\mathbf{CHP}}\le\left[\mathcal{G}_{\mathbf{CHP}}{}^{T}\left(\mathbf{1}-\mathbf{n}\right)\right]\mathrm{o}\overline{\mathbf{p}}^{\mathbf{CHP}},$$

$$\left[\mathcal{G}_{\mathbf{CHP}}{}^{T}\left(\mathbf{1}-\mathbf{n}\right)\right]\mathrm{o}\underline{\mathbf{q}}^{\mathbf{CHP}}\le\mathbf{q}^{\mathbf{CHP}}\le\left[\mathcal{G}_{\mathbf{CHP}}{}^{T}\left(\mathbf{1}-\mathbf{n}\right)\right]\mathrm{o}\overline{\mathbf{q}}^{\mathbf{CHP}},$$

$$\left[\mathcal{G}_{DG}{}^{T}\left(\mathbf{1}-\mathbf{n}\right)\right]\mathrm{o}\underline{\mathbf{q}}^{\mathbf{DG}}\le\mathbf{q}^{DG}\le\left[\mathcal{G}_{DG}{}^{T}\left(\mathbf{1}-\mathbf{n}\right)\right]\mathrm{o}\overline{\mathbf{q}}^{DG},$$

$$\left[\mathcal{G}_{DG}{}^{T}\left(\mathbf{1}-\mathbf{n}\right)\right]\mathrm{o}\underline{\mathbf{p}}^{\mathbf{DG}}\le\mathbf{p}^{DG}\le\left[\mathcal{G}_{DG}{}^{T}\left(\mathbf{1}-\mathbf{n}\right)\right]\mathrm{o}\overline{\mathbf{p}}^{DG}.$$

Operation Constraints

Power balance constraint

Power transmission constraint

CHP unit output constraint

DG output constraint

System operation constraints

Steady State Model of Power System	**Operation Constraints**
$\mathbf{l}=(\mathbf{pop}+\mathbf{qoq})\mathbf{ou}^{-1},$ $\underline{\mathbf{u}}\le\mathbf{u}\le\overline{\mathbf{u}},$	**Branch current constraint**
$\mathbf{A}_e{}^T\mathbf{u}-\mathbf{2}\left[(\mathbf{rop})+(\mathbf{xoq})\right]+\left[(\mathbf{ror}+\mathbf{xox})\mathbf{ol}\right]\le M(\mathbf{1}-\mu_{\mathrm{ij}}),$ $-M(\mathbf{1}-\mu_{\mathrm{ij}})\le\mathbf{A}_e{}^T\mathbf{u}-\mathbf{2}\left[(\mathbf{rop})+(\mathbf{xoq})\right]+\left[(\mathbf{ror}+\mathbf{xox})\mathbf{ol}\right],$	**Voltage drop constraint**
$-\mathbf{M}(\mathbf{1}-\mathbf{n})\le\mathbf{p}^{L}-\mathbf{p}^{Loss}\le\mathbf{M}(\mathbf{1}-\mathbf{n}),$ $-\mathbf{M}(\mathbf{1}-\mathbf{n})\le\mathbf{q}^{L}-\mathbf{q}^{Loss}\le\mathbf{M}(\mathbf{1}-\mathbf{n}),$ $\mathbf{0}\le\mathbf{p}^{Loss}\le\mathbf{p}^{L},\ \mathbf{0}\le\mathbf{q}^{Loss}\le\mathbf{q}^{L}.$	Electric load loss constraint

2. Multi-stage coordinated recovery model

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Objective and Resilience Metrics

The objective aims at **minimizing the loss of electric and heat loads** during recovery progress. To assent the validity of coordinated reconfiguration strategy, the **resilience metric** is proposed to calculate the proportion of total lost loads in IEHS.

Objective and Resilience Metrics

$$\min \sum_{c\in C} p_c \left\{ \sum_{t=1}^{3} \left(\mathcal{T}_{t+1}-\mathcal{T}_t\right)\left[\left(\mathbf{a}^T\mathbf{p}_t^{Loss}\right)+\left(\mathbf{b}^T\mathbf{h}_t^{Loss}\right)\right]\right\}$$

$$R_{r,c}=1-\frac{\left(\mathbf{a}^T\mathbf{p}_t^{Loss}\right)+\left(\mathbf{b}^T\mathbf{h}_t^{Loss}\right)}{\left(\mathbf{a}^T\mathbf{p}^{L}\right)+\left(\mathbf{b}^T\mathbf{h}^{L}\right)}, t=3, \forall c\in C$$

$$R_c=1-\frac{\sum_{t=1}^{3}\left(\mathcal{T}_{t+1}-\mathcal{T}_t\right)\left[\left(\mathbf{a}^T\mathbf{p}_t^{Loss}\right)+\left(\mathbf{b}^T\mathbf{h}_t^{Loss}\right)\right]}{\left(\mathcal{T}_4-\mathcal{T}_1\right)\left[\left(\mathbf{a}^T\mathbf{p}^{L}\right)+\left(\mathbf{b}^T\mathbf{h}^{L}\right)\right]}, \forall c\in C$$

Minimizing the loss of electric and heat loads during recovery progress

The **proportion of total lost loads** in PDS and DHS during the restoration satge and the whole fault recovery process

03

Current-oriented Linearized Distflow model

Linearization of power balance equations

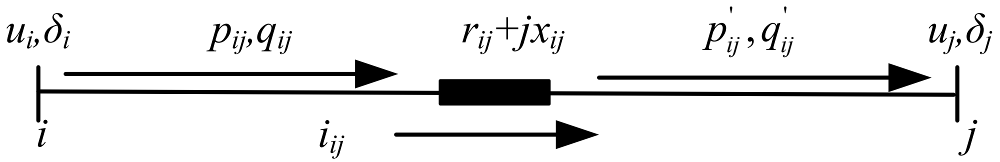
Known starting/ending power and voltage

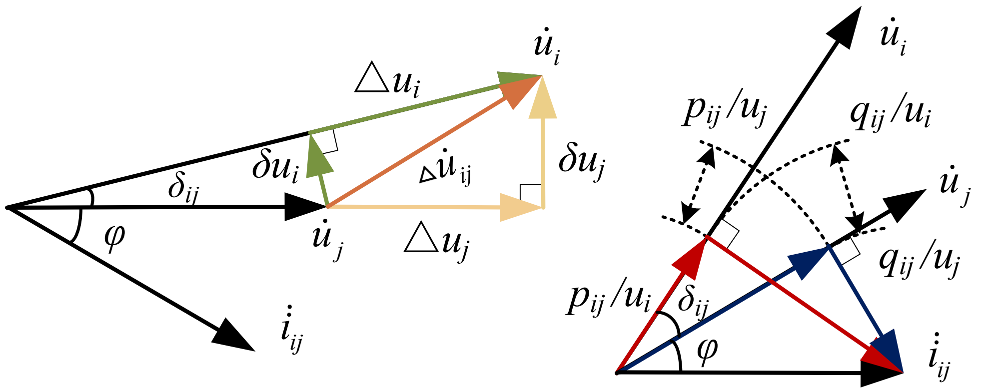
$$\Delta u_i = \frac{r_{ij}p_{ij} + x_{ij}q_{ij}}{u_i}, \quad \delta u_i = \frac{x_{ij}p_{ij} - r_{ij}q_{ij}}{u_i},$$

$$\Delta u_j = \frac{r_{ij}p_{ij}^{'} + x_{ij}q_{ij}^{'}}{u_j}, \quad \delta u_j = \frac{x_{ij}p_{ij}^{'} - r_{ij}q_{ij}^{'}}{u_j}.$$

$$\begin{aligned}\Delta u_i - \Delta u_j &= \left(u_i - u_j cos\delta_{ij}\right) - \left(u_i cos\delta_{ij} - u_j\right)\\ &\approx \left(u_i - u_j\right) - \left(u_i - u_j\right)\\ &= 0\end{aligned}$$

$$\delta u_i \text{-} \delta u_j = u_j sin\delta_{ij} \text{-} u_i sin\delta_{ij} \approx \left(u_j \text{-} u_i\right)\delta_{ij} \approx 0$$





$$\frac{p_{ij}}{u_i} - \frac{p_{ij}^{'}}{u_j} \approx 0, \quad \frac{q_{ij}}{u_i} - \frac{q_{ij}^{'}}{u_j} \approx 0.$$

The power to voltage ratio at the beginning and end of the branch is approximately the same

Reformation of power balance equation

Introduce auxiliary variables: $\tilde{p}_{ij} = \dfrac{p_{ij}}{u_i}, \ \tilde{q}_{ij} = \dfrac{q_{ij}}{u_i}, \ \tilde{P}_j = \dfrac{\tilde{P}_j}{u_j}, \ \tilde{Q}_j = \dfrac{\tilde{Q}_j}{u_j}, \ \tilde{u} = 1/u.$

$$
\begin{gathered}
\mathbf{A}\tilde{\mathbf{p}} = \tilde{\mathbf{P}}, \ \mathbf{A}\tilde{\mathbf{q}} = \tilde{\mathbf{Q}}, \\
\tilde{\mathbf{P}} = \tilde{\mathbf{p}}^{CHP} + \tilde{\mathbf{p}}^{DG} - \left(\tilde{\mathbf{p}}^{L} - \tilde{\mathbf{p}}^{Loss}\right), \tilde{\mathbf{Q}} = \tilde{\mathbf{q}}^{CHP} + \tilde{\mathbf{q}}^{DG} - \left(\tilde{\mathbf{q}}^{L} - \tilde{\mathbf{q}}^{Loss}\right), \\
-M\mu_{\mathrm{ij}} \le \tilde{\mathbf{p}} \le M\mu_{\mathrm{ij}}, \ -M\mu_{\mathrm{ij}} \le \tilde{\mathbf{q}} \le M\mu_{\mathrm{ij}}, \\
-\bar{\mathbf{S}}_{\mathrm{ij}} \circ \left(\mathbf{F}^{T}\tilde{\mathbf{u}}\right) \le \tilde{\mathbf{p}} \le \bar{\mathbf{S}}_{\mathrm{ij}} \circ \left(\mathbf{F}^{T}\tilde{\mathbf{u}}\right), -\bar{\mathbf{S}}_{\mathrm{ij}} \circ \left(\mathbf{F}^{T}\tilde{\mathbf{u}}\right) \le \tilde{\mathbf{q}} \le \bar{\mathbf{S}}_{\mathrm{ij}} \circ \left(\mathbf{F}^{T}\tilde{\mathbf{u}}\right), \\
\underline{\mathbf{p}}^{\mathbf{CHP}} \circ \tilde{\mathbf{u}} \le \tilde{\mathbf{p}}^{\mathbf{CHP}} \le \bar{\mathbf{p}}^{\mathbf{CHP}} \circ \tilde{\mathbf{u}}, \ \underline{\mathbf{q}}^{\mathbf{CHP}} \circ \tilde{\mathbf{u}} \le \tilde{\mathbf{q}}^{\mathbf{CHP}} \le \bar{\mathbf{q}}^{\mathbf{CHP}} \circ \tilde{\mathbf{u}}, \\
\underline{\mathbf{p}}^{DG} \circ \tilde{\mathbf{u}} \le \tilde{\mathbf{p}}^{DG} \le \bar{\mathbf{p}}^{DG} \circ \tilde{\mathbf{u}}, \ \underline{\mathbf{q}}^{DG} \circ \tilde{\mathbf{u}} \le \tilde{\mathbf{q}}^{DG} \le \bar{\mathbf{q}}^{DG} \circ \tilde{\mathbf{u}}, \\
-\mathbf{M}\left(1-\mathbf{n}\right) \le \tilde{\mathbf{p}}^{L} - \tilde{\mathbf{p}}^{Loss} \le \mathbf{M}\left(1-\mathbf{n}\right), -\mathbf{M}\left(1-\mathbf{n}\right) \le \tilde{\mathbf{q}}^{L} - \tilde{\mathbf{q}}^{Loss} \le \mathbf{M}\left(1-\mathbf{n}\right), \\
0 \le \tilde{\mathbf{p}}^{Loss} \le \tilde{\mathbf{p}}^{L}, \ 0 \le \tilde{\mathbf{q}}^{Loss} \le \tilde{\mathbf{q}}^{L}, \\
\tilde{\mathbf{p}}^{L} = \mathbf{p}^{L} \circ \tilde{\mathbf{u}}, \ \tilde{\mathbf{q}}^{L} = \mathbf{q}^{L} \circ \tilde{\mathbf{u}}.
\end{gathered}
$$

Power balance constraint

Power transmission constraint

CHP unit output constraint

DG output constraint

Electric load loss constraint

Approximation of voltage equations

Branch voltage equation

$$\Delta u_i = u_i - u_j cos\delta_{ij} \approx u_i - u_j$$
$$= r_{ij}\frac{p_{ij}}{u_i} + x_{ij}\frac{q_{ij}}{u_i} = r_{ij}\tilde{p}_{ij} + x_{ij}\tilde{q}_{ij}.$$

$$\tilde{u} = 1/u \approx 1 + \frac{-1}{u_0^2}(u - u_0)\Big|_{u_0=1}$$

First-order Taylor expansion

$$\tilde{u}_j - \tilde{u}_i \approx (2 - u_j) - (2 - u_i)$$
$$= r_{ij}\tilde{p}_{ij} + x_{ij}\tilde{q}_{ij}$$

Voltage constraint

$$-(\mathbf{1} - \mu_{\mathrm{ij}})M \le (-\boldsymbol{A}_e)^T \tilde{\boldsymbol{u}} - [(\boldsymbol{r} \circ \tilde{\boldsymbol{p}}) + (\boldsymbol{x} \circ \tilde{\boldsymbol{q}})],$$
$$(-\boldsymbol{A}_e)^T \tilde{\boldsymbol{u}} - [(\boldsymbol{r} \circ \tilde{\boldsymbol{p}}) + (\boldsymbol{x} \circ \tilde{\boldsymbol{q}})] \le (\mathbf{1} - \mu_{\mathrm{ij}})M,$$
$$-M(\mathbf{1} - \mathbf{n}) \le \tilde{\mathbf{u}}_{nf} \le (\mathbf{1} - \mathbf{n})M,$$
$$\mathbf{2} - \overline{\boldsymbol{u}} \le \tilde{\boldsymbol{u}}_{nf} \le \mathbf{2} - \underline{\mathbf{u}},$$
$$-M(\mathbf{1} - \mathbf{n}) \le \mathbf{1} - \tilde{\boldsymbol{u}}_f \le (\mathbf{1} - \mathbf{n})M,$$
$$\mathbf{0} = \tilde{\mathbf{u}}_f, \tilde{\boldsymbol{u}} = \tilde{\boldsymbol{u}}_f + \tilde{\boldsymbol{u}}_{nf},$$

Considering the **unit shutdown** in faulted regions after disasters, the actual voltage will drop to zero, which will lead to the modified power flow being infinitely large

3. Current-oriented Linearized Distflow model

Comparison of Model

Model	CLD model	SD model	SOC-based model	LTLF Model	LPI Model
State variables	Branch power flow			Voltage	
Branch flow equations	$\frac{p_{ij}}{p_{ij}^{'}}=\frac{u_i}{u_j},\frac{q_{ij}}{q_{ij}^{'}}=\frac{u_i}{u_j}$	$\frac{p_{ij}}{p_{ij}^{'}}=1,\frac{q_{ij}}{q_{ij}^{'}}=1$	$p_{ij}-p_{ij}^{'}=r_{ij}l_{ij},$ $q_{ij}-q_{ij}^{'}=x_{ij}l_{ij}$	/	/
Voltage drop equations	$u_i-u_j=r_{ij}\frac{p_{ij}}{u_i}+x_{ij}\frac{q_{ij}}{u_i}$	$u_i-u_j=r_{ij}\frac{p_{ij}}{u_{ref}}+x_{ij}\frac{q_{ij}}{u_{ref}}$	$u_i-u_j=\left(r_{ij}^2+x_{ij}^2\right)l_{ij}$ $+2\left(r_{ij}p_{ij}+x_{ij}q_{ij}\right)$	/	/
Line loss	Approximate	Neglect	SOC relaxation	/	/
Node injection power equations	/	/	/	$\dot{i}_i=\dot{s}_i\left(2-\dot{u}_i\right)+\dot{s}_i+\dot{s}_i\dot{u}_i^2$	$\dot{u}_i=1+\sum_{j=1}^{n}z_{ij}\dot{s}_j$
Load flow	/	/	/	Approximate	Approximate
Calculating efficiency	high	high	low	high	high
Application for PDS reconfiguration problem	Transferred into a mixed integer linear model			By heuristic algorithms	
Conditions for power flow calculation	None	None	The objective function is strictly increasing in branch current	PV nodes could not be considered	Satisfy Banach fixed point theorem

- ➢ The CLD model utilizes the practical feature that phase angle is close to zero, which avoids the arbitrary deletion of **line losses** when formulating branch flow equations.
- ➢ When deriving the voltage equation, the CLD model ignores **the vertical and horizontal difference** in current results in small errors.

04 Case Studies

4. Case Studies

Case setting

Two testing systems:

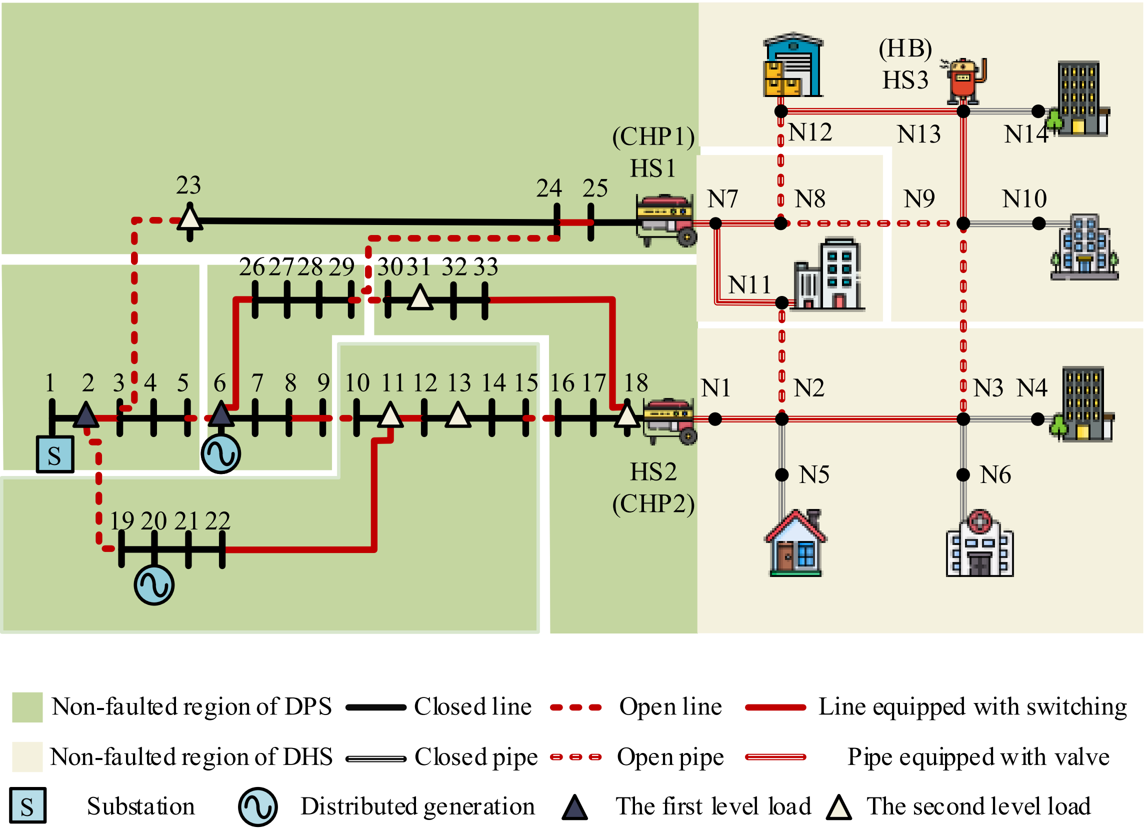
- **P33H14 systems**： 2 heat sources, 4 sectionalizing switches
- **P118H32 systems**： 3 heat sources

Three Fault Scenarios：

- **SCE-I**: DHS Fault Scenario
- **SCE-II**: PDS Fault Scenario
- **SCE-III**: Simultaneous fault scenario

Three Cases：

- **Case 1:** Only PDS reconfiguration is considered for service restoration.
- **Case 2:** Merely DHS reconfiguration is utilized for post-event service restoration.
- **Case 3:** PDS and DHN reconfigurations are coordinated for service restoration.



The P33H14 system

4. Case Studies

Case analysis | 01 Comparison of Load Loss in Different Scenarios

P33H14 testing systems

Scenario	Case	Total load curtailment (kW)	Load curtailment (kW)		Resilience metrics	
			Electric	Heat	$R_{r,c}$	R_c
SCE-I	Case 1	1145	309	836	0.73	0.64
	Case 2	775	327	448	0.80	0.73
	Case 3	713	247	466	0.86	0.75
SCE-II	Case 1	746	522	224	0.78	0.66
	Case 3	562	450	112	0.98	0.78
SCE-III	Case 1	1025	473	552	0.81	0.70
	Case 2	1127	851	276	0.72	0.66
	Case 3	715	439	276	0.94	0.77

P118H32 testing systems

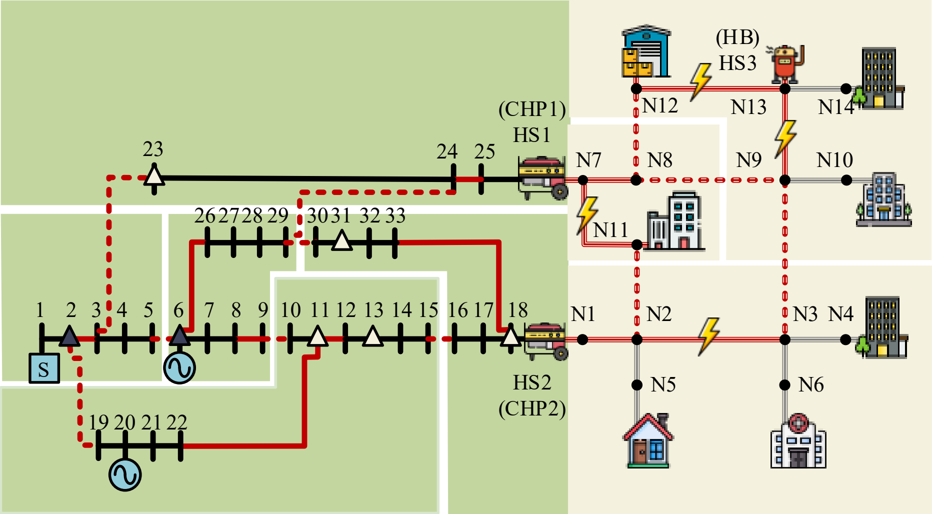
Scenario	Case	Total load curtailment (kW)	Load curtailment (kW)		Resilience metrics	
			Electric	Heat	$R_{r,c}$	R_c
SCE-I	Case 1	1166	201	965	0.84	0.73
	Case 2	991	760	231	0.88	0.85
	Case 3	677	195	482	0.98	0.80
SCE-II	Case 1	362	228	134	0.88	0.77
	Case 3	240	106	134	0.97	0.82
SCE-III	Case 1	1556	712	844	0.71	0.62
	Case 2	1063	665	398	0.83	0.74
	Case 3	674	296	378	0.91	0.79

- In P33H14, compared with results in Cases 1 and 2, the values of Rr,c and Rc under SCE-I were increased by **17.8%, 7.5%**, and **17.2%, 2.7%** respectively.
- In P111H32, the total load loss under SCE-III were decreased by **56.6% and 36.6%** in two fault scenarios, respectively.
- This indicates that **collaborative reconfiguration** can change the operating mode of the system and enhance its resilience.

4. Case Studies

Case analysis | **02 Resilience performance on the P33H14 system**

- Fault isolation stage



Percentage of load restoration at buses/nodes

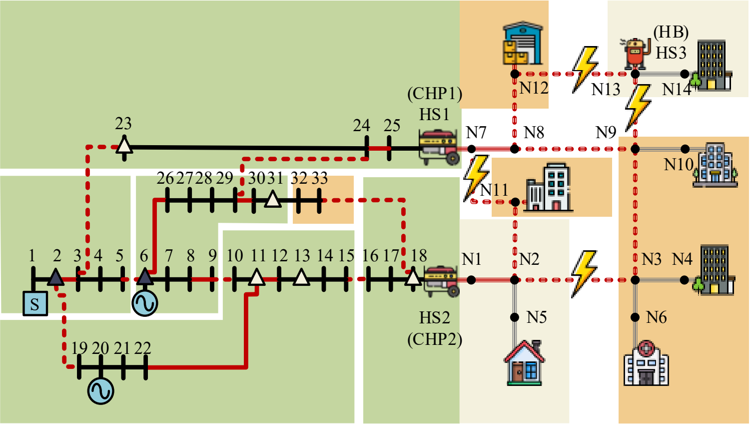
Bus/Node	B16	B17	B18	B30	B31	B32	B33	N3	N4	N6	N11
Stage 2	25	30	84	20	30	25	20	0	0	0	0
Stage 3 (Case 1)	100	100	100	100	100	68	20	0	0	0	0
Stage 3 (Case 2)	100	100	100	20	30	62	100	100	100	100	100
Stage 3 (Case 3)	100	100	100	100	100	100	100	100	100	100	41

- The DHS faults could propagate to PDS through coupling units, which can induce power blackouts and heat outages simultaneously.
- As shown in the Table, due to **the heat load shedding at nodes 3, 4, and 6** after the disaster, the power generation of CHP2 is limited and the second-level **electric loads at buses 18 and 31 are partially lost** at this Stage.

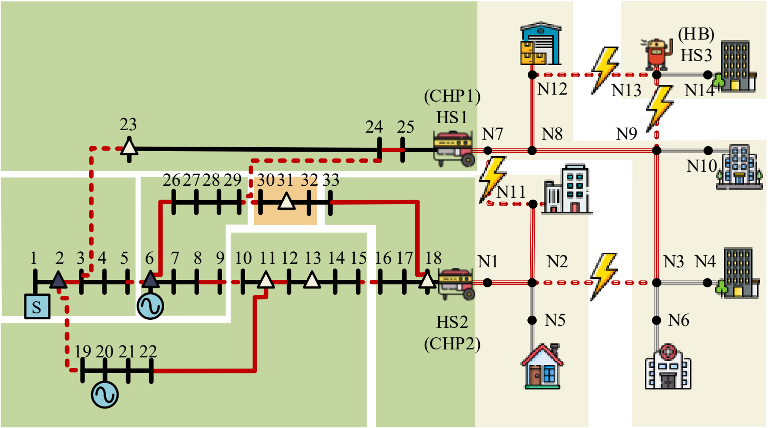
4. Case Studies

Case analysis | 02 Resilience performance on the P33H14 system

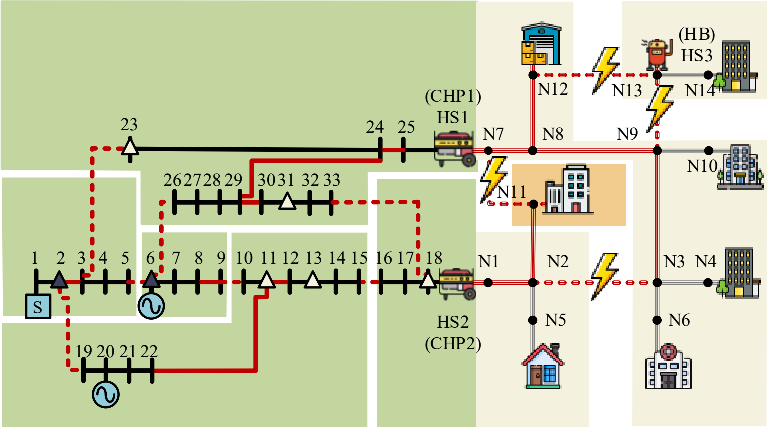
- ➢ Service restoration stage



(a) Case 1



(b) Case 2



(b) Case 3

- ➢ The DHS reconfiguration can achieve better fault restoration and enhance the DHS capability in natural disasters by remotely scheduling tie valves and redistributing heating loads among heat sources.
- ➢ The optimal service restoration cannot be achieved by DHS/PDS reconfiguration independently unless DHN reconfiguration is coordinated with switching operation in PDS.

4. Case Studies

Case analysis | 03 Comparison of accuracy and efficiency between Different Models

Comparison of power flow results

Model	Scenario	Case	Calculating time (s)	Error	Bus voltage	Power flow	
					u_i (%)	p_{ij} (%)	q_{ij} (%)
CLD	SCE-I	Case 1	1.21	Average Error	0.68	1.01	2.83
				Largest Error	0.73	1.27	3.28
SD	SCE-II	Case 2	0.89	Average Error	1.78	4.53	6.29
				Largest Error	2.12	5.17	7.55
SOC	SCE-III	Case 3	60.64	Average Error	0	0	0
				Largest Error	0	0	0
LPI	SCE-I	Case 1	-	Average Error	1.23	2.55	3.37
				Largest Error	1.57	3.84	5.31

- The results obtained from CLD model **are close to the results obtained from the classical Distflow model** and **have higher accuracy** than the SD/LPI model.
- Compared to the SOC-based model, CLD model could be utilized to solve the multi-stage fault recovery problem **with significantly higher efficiency without loss of accuracy, which is significantly important for online analysis.**

05 Conclusions

5. Conclusions

The extensive case studies validate that:

- the **faults** occurring in DHS/PDS can **propagate** to another subsystem through coupling units;
- the **DHS reconfiguration** can provide a viable tool for DHS resilience enhancement by remotely scheduling tie valves and redistributing heating loads among heat sources;
- the **coordinated reconfiguration** can enhance the park-level IEHS resilience by optimally readjusting the DHS heat supply structure to match PDS line switching and prevent wider fault propagations.

The numerical simulations illustrate that:

- **CLD model** could obtain an acceptable **accuracy** with **high efficiency**, which could be extensively applied to the IEHS planning problems especially when DHS and PDS network reconfigurations are taken into account.

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Thank you!