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Preventive Power Outage Estimation Based on A Novel Scenario Clustering Strategy

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Background and Contributions

Background

- In recent decades, the number of disaster events and the corresponding economic loss have continued to increase.
- Distribution systems, located at edges of power systems, play a critical role in restoring system after outages.
- Accurately predicting the power outage, identifying vulnerable areas, and evaluating the unserved load in a disturbance are critical for the whole restoration process.

Contributions

- An optimal three-phase distribution system restoration model is established considering the allocation of MERs and the schedule of RCs.
- A novel scenario clustering algorithm is proposed to reduce the scenario scale based on the accumulated nodal unserved load.
- The integration of MERs and RCs has been proved to significantly reduce the unserved load, and the representative scenarios can effectively preserve information of original scenarios.

Three-phase Distribution System Restoration Model

Objective function

$$min.\ \sum_{t\in\Omega_T}\Delta t\sum_{i\in\Omega_B}\sum_{\phi\in\Omega_\Phi}P_{i,\phi,t}^{eens}$$

Power flow constraints

$$P_{i,\phi,t}^{MT}+P_{i,\phi,t}^{PV}+P_{i,\phi,t}^{MER}-P_{i,\phi,t}^{D}+P_{i,\phi,t}^{eens}=\sum_{k\in\delta(i)}P_{ik,\phi,t}-\sum_{j\in\pi(i)}P_{ji,\phi,t}$$

$$Q_{i,\phi,t}^{MT}+Q_{i,\phi,t}^{PV}-Q_{i,\phi,t}^{D}+Q_{i,\phi,t}^{eens}=\sum_{k\in\delta(i)}Q_{ik,\phi,t}-\sum_{j\in\pi(i)}Q_{ji,\phi,t}$$

$$0\le P_{i,\phi,t}^{eens}\le P_{i,\phi,t}^{D}$$

$$0\le Q_{i,\phi,t}^{eens}\le Q_{i,\phi,t}^{D}$$

$$-\left(S_{ij,\phi,t}^{max}\right)^2\cdot\gamma_{ij,t}\le {P_{ij,\phi,t}}^2+{Q_{ij,\phi,t}}^2\le\left(S_{ij,\phi,t}^{max}\right)^2\cdot\gamma_{ij,t}$$

$$v_{j,\phi,t}=v_{i,\phi,t}-\Delta v_{ij,\phi,t}-2\left(\tilde{\boldsymbol{r}}_{ij,\phi}\boldsymbol{P}_{ij,t}+\tilde{\boldsymbol{x}}_{ij,\phi}\boldsymbol{Q}_{ij,t}\right)$$

$$\left(V_{i,\phi,t}^{min}\right)^2\le v_{i,\phi,t}\le\left(V_{i,\phi,t}^{max}\right)^2$$

$$-M\left(1-\gamma_{ij,t}\right)\le\Delta v_{ij,\phi,t}\le M\left(1-\gamma_{ij,t}\right)$$

$$\gamma_{ij,t}\in\{0,1\}$$

$$\boldsymbol{P}_{ij,t}=\left[P_{ij,\phi,t},P_{ij,\phi',t},P_{ij,\phi'',t}\right]^{\mathrm{T}}$$

$$\boldsymbol{Q}_{ij,t}=\left[Q_{ij,\phi,t},Q_{ij,\phi',t},Q_{ij,\phi'',t}\right]^{\mathrm{T}}$$

Stationary Distributed Generator Constraints

$$0\le P_{i,\phi,t}^{PV}\le P_{i,\phi,t}^{PV,fore}$$

$$-P_{i,\phi,t}^{PV}\tan(\arccos\alpha_i)\le Q_{i,\phi,t}^{PV}\le P_{i,\phi,t}^{PV}\tan(\arccos\alpha_i)$$

$$-\left(S^{PV,max}\right)^2\le {P_{i,\phi,t}^{PV}}^2+{Q_{i,\phi,t}^{PV}}^2\le\left(S^{PV,max}\right)^2$$

$$P_{i,\phi}^{MT,min}\le P_{i,\phi,t}^{MT}\le P_{i,\phi}^{MT,max}$$

$$0\le Q_{i,\phi,t}^{MT}\le P_{i,\phi,t}^{MT}\tan(\arccos\alpha_i)$$

Mobile energy resource allocation

$$\sum_{i\in\mathrm{N_m}}y_{m,i,t}\le 1,\ \forall m\in\Omega_M$$

$$\sum_{m\in\Omega_M}y_{m,i,t}\le Cap_i,\ \forall i\in\cup_{m\in\Omega_M}\mathrm{N_m}$$

$$z_{m,t}=1-\sum_{i\in\mathrm{N_m}}y_{m,i,t},\ \forall m\in\Omega_M$$

$$y_{m,i,t+\tau}+y_{m,j,t}\le 1,\forall m\in\Omega_M,\forall i,j\in\mathrm{N_m},\ \forall\tau\le t_{m,i,j}^{tr},\ \forall t+\tau\le|\Omega_{\mathrm{T}}|$$

Repair crew scheduling

$$\gamma_{ij,t}\le\frac{\sum_{\tau=1}^{t}y_{m,ij,t}}{t_{m,ij}^{rc}},\forall m\in\Omega_{RC},\forall ij\in\Omega_F$$

$$\gamma_{ij,t}\le\gamma_{ij,t+1},\forall ij\in\Omega_F$$

K-means-based Scenario Clustering

- Traditional scenario clustering strategies are based on a scenario's self-characteristics (e.g., similar PV/load profiles).
- Tripped line scenarios are represented by binary variables which is not easy to directly find similar characteristics.
- Nodal unserved load profile can work as the characteristic for the scenario clustering.

Algorithm 1: Scenario Clustering

1. Scenario generation: Enumerate all possible faulted line scenarios based on the OPM outputs.

2. Initialization: For each $s \in \Omega_S$, compute:

$$\boldsymbol{E}^s \in argmin \ \sum_{t\in\Omega_T} \Delta t \sum_{i\in\Omega_B} \sum_{i\in\Omega_\Phi} P_{i,\phi,t}^{eens}$$

3. *K*-means clustering:

3.1. Select a proper *k*.

3.2. Run the *k*-means algorithm by using the "sklearn" package. The algorithm aims to minimize the within-cluster sum of squares (WCSS):

$$WCSS \in argmin \ \sum_{i=1}^{k} \sum_{s\in\Omega_{Si}} \|\boldsymbol{E}^s - \boldsymbol{\mu}_i\|^2$$

where $\boldsymbol{\mu}_i$ is the centroid of cluster *i*.

3.3. Update the probability of clusters.

$$p(i) = \sum_{s\in\Omega_{Si}} p(s)$$

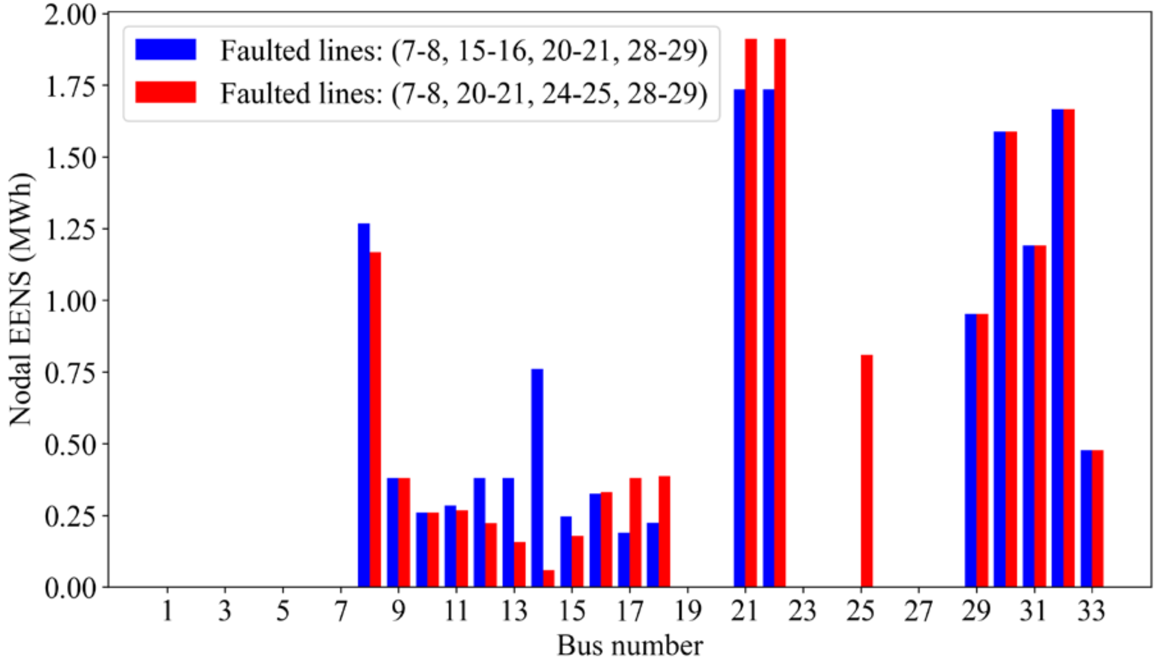

Fig. 1. Example of two nodal unserved load profiles.

Simulation Results

Scenario clustering

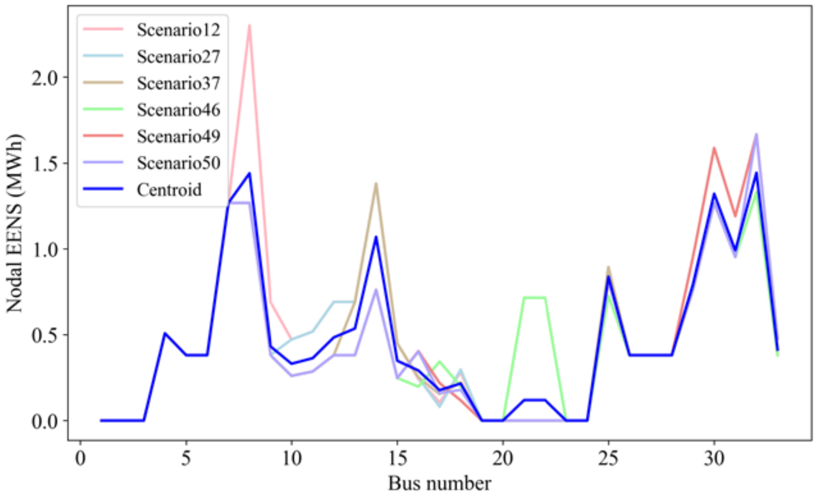

Fig.2. Original scenarios and the centroid of Cluster 8.

Resource allocation

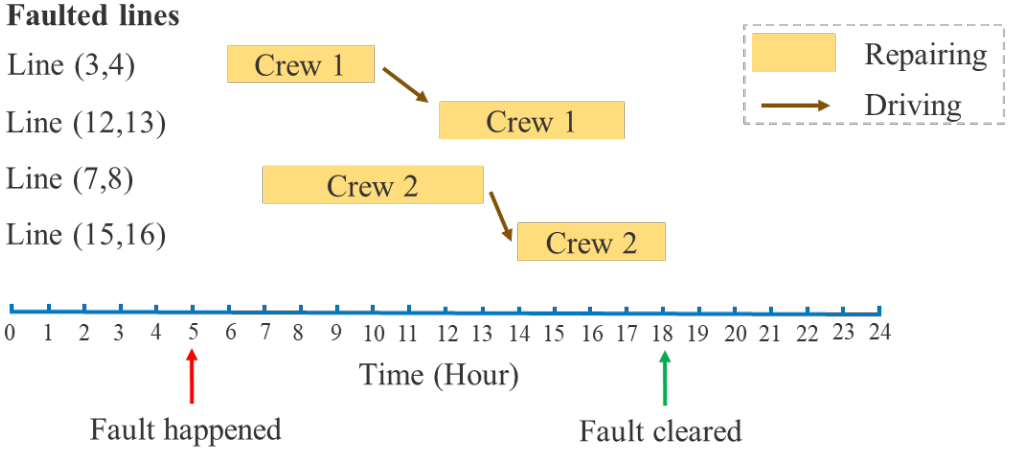

Fig. 3. RC schedule.

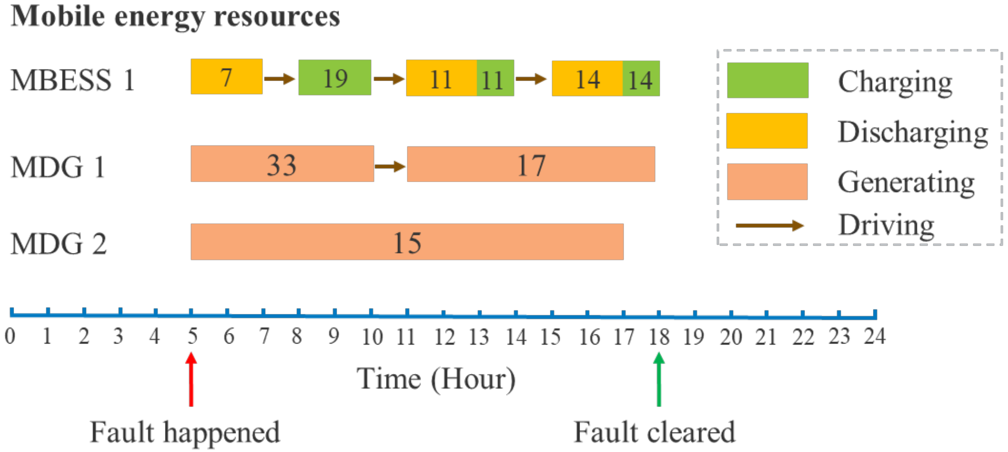

Fig. 4. MER allocation.

Simulation Results

Table 1 Comparison of the original and clustered scenarios without MERs.

Total EENS (MWh)	Unserved load ratio (%)	Original probability (%)	Clustered probability (%)
0 - 5	0 - 4.77	1.59	0
5 - 10	4.77 - 9.55	20.63	28.57
10 - 15	9.55 - 14.32	27.78	23.82
15 - 20	14.32 - 19.09	36.51	37.30
20 - 25	19.09 - 23.87	11.90	10.32
25 - 30	23.87 - 28.64	1.59	0

Table 2 Comparison of the original and clustered scenarios with MERs.

Total EENS (MWh)	Unserved load ratio (%)	Original probability (%)	Clustered probability (%)
0 - 5	0 - 4.77	37.30	37.30
5 - 10	4.77 - 9.55	23.81	26.98
10 - 15	9.55 - 14.32	36.51	34.92
15 - 20	14.32 - 19.09	2.38	0.79
20 - 25	19.09 - 23.87	0	0
25 - 30	23.87 - 28.64	0	0

Conclusions and Future Works

Conclusions

- The numerical simulation verifies that the representative scenarios can maintain the characteristics of the original scenarios.
- The improvement of the MER integration in the restoration process is also quantitively evaluated.

Future Works

Future work will focus on investigating the applications of preventive outage analysis:

- Determine how to collaborate with neighboring utilities to best allocate the available MERs;
- Utility can optimally allocate its budget to bolster resilience through various measures based on the representative scenarios.

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