Network Reconfiguration and DER Scheduling for Improved Distribution System Resilience

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Background and motivation:
- A resilient distribution system means serving as much load as possible after N-K contingencies caused by natural disasters, which is common in some coastal regions.
- The traditional works on resilient distribution system operation are based on the ideal assumption that the penetration of (distributed energy resources) DERs is high enough to supply the local load.
- The combination of network reconfiguration and DER scheduling is not fully studied.

Technical approach:
- Propose an outage management strategy (OMS) for post-fault load restoration by network reconfiguration and DER scheduling.
- Linearize the constraints for radial network topology and distribution system operation.
- Adopt an empirical line fragility model to quantify the probability of line fault under a specified wind speed.

Conclusion:
- Develops an OMS for resilient distribution system operation against extreme weather.
- The OMS consists of both network reconfiguration and DER scheduling. It can maintain a high percentage of load in service after N-K contingency.
- The OMS has advantage when being applied to those distribution systems with several normally-open tie lines and low DER penetration.
Proposed Outage Management Strategy

Objective function: \[ C(G_k) = \min \sum_{i \in \Omega} \Delta t \left( \sum_{i \in \Omega_i} c_i^p p_i^G + \sum_{i \in \Omega_i} c_i^L \Delta p_i^L \right) \]

Radial topology
\[ \sum_{i \in \Omega_i} s_i = N - 1 \]
\[ s_i = 0, \quad \forall i \in \Omega_{k, \text{Base}} \]
\[ \text{rank} (E') = N - 1 \]

Dispatchable DG
\[ p_i^G = p_i^G \leq p_i^G \leq p_i^G, \quad \forall i \in \Omega \]
\[ p_i^G - p_i^G \leq U R_{i}^{\text{max}}, \quad \forall i \in \Omega \]
\[ p_i^G - p_i^G \leq D R_{i}^{\text{max}}, \quad \forall i \in \Omega \]

Load curtailment
\[ 0 \leq \Delta p_i^L \leq \Delta p_i^L, \quad \forall i \in \Omega \]
\[ \Delta q_i^L = \lambda_i \Delta p_i^L, \quad \forall i \in \Omega \]
\[ \lambda_i = \frac{q_i^L}{p_i^L}, \quad \forall i \in \Omega \]

PV system
\[ p_i^{\text{PV}} = \min \left( I R_{i} \cdot p_i^{\text{PV, rated}}, p_i^{\text{PV, rated}} \right), \quad \forall i \in \Omega_{\text{PV}} \]

Shunt capacitor
\[ q_i^C = q_i^C, \quad V_i^2 \approx q_i^C, \quad (2(V_i - 1)), \quad \forall i \in \Omega \]

Bus power balance
\[ P_i = p_i^G + p_i^{\text{PV}} + 0 - (p_i^L - \Delta p_i^L), \quad \forall i \in \Omega_{N_i, i \neq 1} \]
\[ Q_i = 0 + 0 + q_i^C - (q_i^L - \Delta q_i^L), \quad \forall i \in \Omega_{N_i, i \neq 1} \]

Voltage constraint
\[ V_{\text{min}} \leq V_{ij} \leq V_{\text{max}}, \quad \forall i \in \Omega, i \neq 1 \]
\[ \delta_{ij} = 0 \quad V_{ij} = V_{\text{sub}} \]

Line thermal limit
\[ -0.95 S_{ij}^{\text{max}} \leq P_{ij} \leq 0.95 S_{ij}^{\text{max}}, \quad \forall (i, j) \in G_k \]
\[ -0.5 S_{ij}^{\text{max}} \leq Q_{ij} \leq 0.5 S_{ij}^{\text{max}}, \quad \forall (i, j) \in G_k \]

Linearized power flow in distribution system
\[ P_{i,j} = \sum_{j=1}^{N} P_{i,j} = \sum_{j=1}^{N} \left[ B_{2,0} (\delta_{ij} - \delta_{ij}) + B_{2,1} (V_{ij} - V_{ij}) \right], \quad \forall (i, j) \in G_k \]
\[ Q_{i,j} = \sum_{j=1}^{N} Q_{i,j} = \sum_{j=1}^{N} \left[ -B_{2,0} (\delta_{ij} - \delta_{ij}) + B_{2,1} (V_{ij} - V_{ij}) \right], \quad \forall (i, j) \in G_k \]

Flowchart of the OMS

One/multiple line fault happen

Locate the faulted lines and identify their areas

Look up the reconfiguration topologies from the existing database: \( \{ G_1, G_2, \ldots, G_N \} \)

Turn to next topology \( G_k \), formulate \( E \) matrix by (4)

Perform DER scheduling (linear programming):
Objective function: min. cost (DG + load reduction)
Constraint: radial topology, DG operation, power flow

Find feasible solution?

Yes

Save the total cost \( C(G_k) \), bus voltage, MT response and load response

All \( G_k \) scanned?

No

Select the optimal \( G_k \) and output the DER scheduling result

Yes
Verification Study of IEEE 69-bus System

Scenario 1: Lines 10-11 and 54-55 are tripped at 13:00.
Scenario 2: Lines 12-13 and 47-48 are tripped at 13:00.

10 candidate topologies and the corresponding optimal cost

<table>
<thead>
<tr>
<th>( G_i )</th>
<th>Scenario 1</th>
<th>Switching action</th>
<th>( C(G_i) ) ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( G_1 )</td>
<td>Close TS1 and TS3</td>
<td>( 4346 )</td>
<td></td>
</tr>
<tr>
<td>( G_2 )</td>
<td>Close TS1 and TS4</td>
<td>N/F (^1)</td>
<td></td>
</tr>
<tr>
<td>( G_3 )</td>
<td>Close TS2 and TS3</td>
<td>( 4346 )</td>
<td></td>
</tr>
<tr>
<td>( G_4 )</td>
<td>Close TS2 and TS4</td>
<td>N/F</td>
<td></td>
</tr>
<tr>
<td>( G_5 )</td>
<td>Close TS3 and TS4</td>
<td>N/F</td>
<td></td>
</tr>
<tr>
<td>( G_6 )</td>
<td>Close TS1, TS3 and TS4, open SS1</td>
<td>N/F</td>
<td></td>
</tr>
<tr>
<td>( G_7 )</td>
<td>Close TS1, TS3 and TS4, open SS2</td>
<td>( 4401 )</td>
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<tr>
<td>( G_8 )</td>
<td>Close TS1, TS3 and TS4, open SS3</td>
<td>( 6435 )</td>
<td></td>
</tr>
<tr>
<td>( G_9 )</td>
<td>Close TS2, TS3 and TS4, open SS2</td>
<td>( 4401 )</td>
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<tr>
<td>( G_{10} )</td>
<td>Close TS2, TS3 and TS4, open SS3</td>
<td>( 6435 )</td>
<td></td>
</tr>
</tbody>
</table>

\(^1\) no feasible solution

Optimal reconfiguration of Scenario 1

Optimal reconfiguration of Scenario 2

The total DG and load scheduling results of Scenario 1 & 2
Acknowledgements

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