Optimum Placement of Sectionalizing Switches in Distribution Networks with Alternative Supplies

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Plan of the talk

- Distribution networks with alternative supplies.
- Reliability indexes: SAIFI, SAIDI, and AENS.
- Efficient computation of reliability indexes.
- Optimization problem.
- Limiting the search space.
- Computational example.
- Conclusions.

Distribution networks with alternative supplies

- The distribution grid has a radial structure with m line segments and $m+1$ nodes,
  - $V = \{v_1, v_2, \dots, v_{m+1}\}$ is the set of nodes,
  - v_{m+1} is the main supply node (main generator),
  - distribution nodes: connected to at least two other nodes,
  - user nodes and auxiliary generators: connected to a single node,
  - c_j is the connection line between v_j and its parent node,
- λ_{v_j} and λ_{c_j} are the average failure rates (the average number of failures during one year) of the node v_j and the line segment c_j, respectively,
- t_{v_j} and t_{c_j} are the average total duration of failures during one year of the node v_j and the line segment c_j.

Notations

- P_j is the average active power dissipated at the jth node.
- N_j is the number of users at the jth node.
- $\bar{N} = \sum_{i=1}^{m} N_i$ is the total number of users.
- $\bar{P} = \sum_{i=1}^{m} P_i$ is the total average power.
- $\bar{\lambda} = \sum_{i=1}^{m+1} \lambda_{v_j} + \sum_{i=1}^{m+1} \lambda_{c_j}$ is the total failure rate (the sum of failure rates of all components in the network).
- $\bar{t} = \sum_{i=1}^{m+1} t_{v_j} + \sum_{i=1}^{m} t_{c_j}$ is the total interruption duration (the sum of failure durations of all components in the network).

Reliability indexes: SAIFI, SAIDI, and AENS

- System Average Interruption Frequency Index (SAIFI),
- System Average Interruption Duration Index (SAIDI)

$$\mathrm{SAIFI} = \frac{\sum_{j=1}^{m} \mu_j N_j}{\sum_{j=1}^{m} N_j}, \qquad \mathrm{SAIDI} = \frac{\sum_{j=1}^{m} U_j N_j}{\sum_{j=1}^{m} N_j},$$

  μ_j is the average number of interruptions and U_j is the average total duration of all interruptions involving the node v_j during one year.

- Average Energy Not Supplied (AENS)

$$\mathrm{AENS} = \sum_{j=1}^{m} U_j P_j.$$

Optimization problem

- Without sectionalizing switches a failure at any location causes energy supply interruption in the entire network, i.e., $U_j = \text{const} = \bar{t}$, $\mu_j = \text{const} = \bar{\lambda}$ and

$$\text{SAIFI} = \bar{\lambda}, \qquad \text{SAIDI} = \bar{t}, \qquad \text{AENS} = \bar{t} \cdot \bar{P}.$$

- Coefficients SAIFI, SAIDI, and AENS can be reduced by introducing sectionalizing switches at selected line segments.
- In case of a failure, we may disconnect a part of the grid and energy supply to the remaining part of the grid may be continued in spite of the fault.
- $\Gamma = \{\gamma_1, \gamma_2, \ldots, \gamma_S\}$ is the set of admissible positions of sectionalizing switches. Switches may be placed at both ends of each line segment, i.e. $S \leq 2m$.
- The optimization problem: find the minimum value of AENS (SAIFI, SAIDI) which can be obtained using p sectionalizing switches, $p \in \{1, 2, \ldots, S\}$.

Efficient computation of SAIFI, SAIDI, and AENS

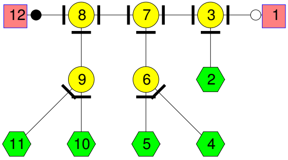
- Let $Q = \{\gamma_{i_1}, \gamma_{i_2}, \ldots, \gamma_{i_p}\} \subset \Gamma$ be a selected set of positions of p sectionalizing switches.
- Placing p switches splits the network into $p+1$ components.
- Each $\gamma_k \in Q$ starts a single component. The last component starts at the generator γ_0 (the root vertex).
- A tree structure based algorithm to compute AENS, SAIFI, and SAIDI:
  - the algorithm starts at γ_0,
  - the depth-first search (DFS) algorithm is used to visit the nodes,
  - gains achieved by installing switches in partial solutions are computed recursively starting from leaf nodes and moving towards γ_0,
  - the computations can be carried out in a single pass of the tree structure,
  - the computations are very fast.

Solving the optimization problem

- Methods
  - Exhaustive search.
  - Heuristic methods:
    - Monte Carlo techniques,
    - evolutionary algorithms,
    - simulated annealing,
    - ...
- For all methods it is important to limit the size of the search space.

Limiting the search space

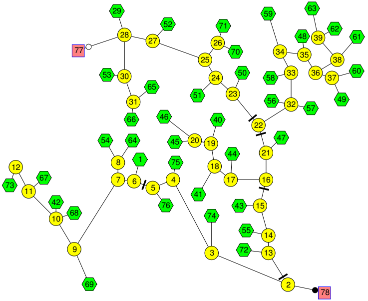
- An example network with $m = 11$ line segments including $m_s = 7$ single-powered line segments, $m_g = 2$ generator nodes, 5 user nodes and 5 distribution nodes,



- the number of admissible switch positions is $S = 2m = 22$ (both ends of each line segment),
- $N_{\mathrm{ES}} = \binom{S}{p}$ is the number of test selections for p switches in the exhaustive search approach,
- we do not need to consider sectionalizing switches at positions closest to each supply node: S is reduced to $2m - m_g = 20$,
- in case of single-powered line segments it is sufficient to consider the position at the end which is closer to the power supply: S is reduced to $2m - m_g - m_s = 13$,
- the number of selections can be further reduced by eliminating partial solutions which cannot lead to optimal solutions.

Computational example

- A real network with from the southern part of Poland:
  - $m = 77$ line segments,
  - 78 nodes,
  - the number of supply nodes: $m_g = 1, 2, 3$.



- Failure rates (data provided by the electricity company):
  - 3.1 faults in one year for every 100 km of a line segment,
  - $\lambda_{c_j} = 3.1 \times 10^{-5} l_j$ for a line segment with the length l_j,
  - $\lambda_{v_j} = 0.03$ for user nodes,
  - $\lambda_{v_j} = 0.002$ for distribution nodes.
- Average fault durations:
  - $\tau_{c_j} = 0.983\,\mathrm{h}$ for line segments,
  - $\tau_{v_j} = 1\,\mathrm{h}$ for user nodes,
  - $\tau_{v_j} = 0.5\,\mathrm{h}$ for distribution nodes.

Optimization of AENS using the exhaustive search

- Limiting the search space:
  - ES1: $S = 2m = 154$ (full search space),
  - ES2: $S = 2m - m_g - m_s = 154 - 2 - 64 = 88$,
  - ES3: eliminating non-optimum partial solutions.
- N_{ES} is the number of evaluations.
- t_{ES} is the total computation time.

p	N_{ES1}	t_{ES1} [s]	N_{ES2}	t_{ES2} [s]	N_{ES3}	t_{ES3} [s]
1	154	0.00	88	0.00	47	0.00
2	11781	0.14	3828	0.06	1081	0.02
3	$5.97 \cdot 10^5$	3.77	$1.10 \cdot 10^5$	0.74	16234	0.25
4	$2.25 \cdot 10^7$	142.93	$2.33 \cdot 10^6$	14.65	$1.79 \cdot 10^5$	2.01
5	$6.76 \cdot 10^8$	4423.42	$3.92 \cdot 10^7$	249.80	$1.55 \cdot 10^6$	16.92
6			$5.41 \cdot 10^8$	3586.63	$1.10 \cdot 10^7$	128.34
7			$6.35 \cdot 10^9$	41231.31	$6.54 \cdot 10^7$	781.40
8					$3.35 \cdot 10^8$	3542.02
9					$1.50 \cdot 10^9$	16838.91

- The computation algorithm can handle approximately 150000 selections in one second.
- the search space is considerably reduced by using the proposed elimination methods.

Optimization results versus the number of generators m_g

- Results relative to $\mathrm{AENS}(\emptyset) = 7159$ and $\mathrm{SAIDI}(\emptyset) = 2.329$.

p	$m_g = 1$		$m_g = 2$		$m_g = 3$	
	AENS	SAIDI	AENS	SAIDI	AENS	SAIDI
0	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
1	0.6619	0.7371	0.4970	0.4998	0.4970	0.4998
2	0.5049	0.5424	0.3477	0.3516	0.3359	0.3516
3	0.4183	0.4288	0.2555	0.2513	0.2420	0.2508
4	0.3397	0.3247	0.2238	0.2225	0.1967	0.2039
5	0.2891	0.2906	0.2011	0.1974	0.1673	0.1789
6	0.2574	0.2725	0.1806	0.1793	0.1468	0.1571
7	0.2430	0.2564	0.1661	0.1633		
8	0.2316	0.2420	0.1563	0.1536		

- A general observation: increasing m_g significantly improves reliability indexes.
- Exception: when $p = 1$ no improvement for $m_g = 3$ when compared with $m_g = 2$.
- The improvement grows with p.
- For $m_g = 1$: $\mathrm{AENS} > 0.1651$ for any p, for $m_g = 2$ one can reach $\mathrm{AENS} = 0.1563$ using $p = 8$ switches.

Multi-objective optimization

- The optimum value obtained versus the value obtain when optimizing another index:

p	$\mathrm{SAIDI}_{\mathrm{OPT}}$	$\mathrm{SAIDI}_{\mathrm{AENS}}$	$\mathrm{AENS}_{\mathrm{OPT}}$	$\mathrm{AENS}_{\mathrm{SAIDI}}$
0	1.0000	1.0000	1.0000	1.0000
1	0.4998	0.5385	0.4970	0.4972
2	0.3516	0.3520	0.3477	0.3514
3	0.2513	0.2514	0.2555	0.2558
4	0.2225	0.2359	0.2238	0.2328
5	0.1974	0.2070	0.2011	0.2123
6	0.1793	0.1819	0.1806	0.1825
7	0.1633	0.1658	0.1661	0.1680
8	0.1536	0.1536	0.1563	0.1563
9	0.1448	0.1448	0.1493	0.1493

- Optimizing a given reliability index may not necessarily lead to a close-to-optimum values of other indexes.
- For simultaneous optimization of several reliability measures a multi-objective optimization should be used.

Conclusions

- Efficient algorithms for the evaluation of reliability indexes for radial distribution networks with alternative supplies in the presence of sectionalizing switches have been presented.
- Methods to reduce the search space in the problem of optimum allocation of switches have been described.
- The proposed approach permits solving switch allocation problems using the exhaustive search method for a small number of switches and heuristic methods which require handling large number of test selections.
- Algorithms have been tested using a real network of a moderate size.