Multiobjective Optimization for Switch Allocation in Radial Power Distribution Grids

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Plan of the talk

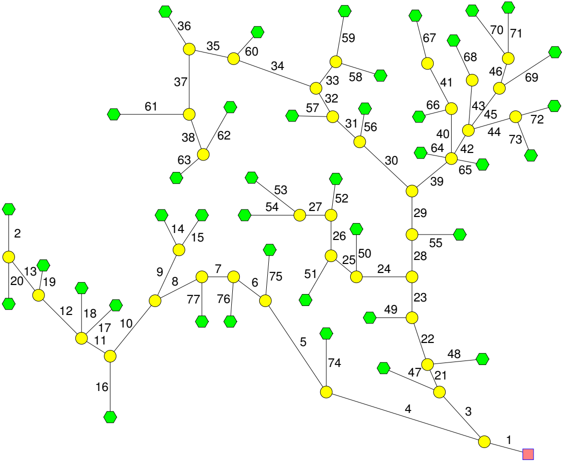
- Reliability model of power grids.
- Reliability factors:
    - the expected energy not supplied (EENS),
    - the system average interruption duration index (SAIDI),
    - the system average interruption frequency index (SAIFI).
- Multiobjective optimization.
- Multiobjective evolutionary algorithm.
- Example grid.
- Optimization Results.
- Conclusions.

Radial power distribution grids

- Assumptions:
  - The network has a radial structure and contains m connection lines (the number of nodes is $n = m + 1$).
  - There is a single generator/supply node.
  - Each load node is connected to a single node.
  - For each load node there exists a unique path connecting it to the supply node.
- For a given network, reliability of power supply to end users can be increased by introducing sectionalizing switches at selected line segments.
- If a failure occurs behind a given switch 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.

Example distribution power grid

- Power grid with 78 nodes and 77 line segments.
- Load nodes (hexagons), distribution nodes (circles), the supply node (square).



Reliability Model

- The grid is presented as a graph where vertices represent nodes and edges represent line segments between nodes.
- λ_i is the annual average number of failures for the ith element (node or line segment).
- τ_i is the average length of failure for the ith element.
- sectionalizing switches divide the whole network into subnets.
- The average outage rate μ_j and the average outage duration T_j for the load node j can be computed as:

$$\mu_j = \sum_{i=1}^{k} \lambda_i, \quad T_j = \sum_{i=1}^{k} \lambda_i \cdot \tau_i,$$

where k is the number of elements in subnets having nonempty intersection with the path from the feeder to the load node j.

Reliability Factors

- The expected energy not supplied (EENS):

$$\mathrm{EENS} = \sum_{j=1}^{\ell} P_j \cdot T_j,$$

  where ℓ is the number of load nodes and P_j is the total annual average power at the load node j.

- The system average interruption duration index (SAIDI):

$$\mathrm{SAIDI} = \frac{\sum_{j=1}^{\ell} N_j \cdot \mu_j}{N},$$

  where N_j is the number of customers served at the node j and $N = \sum_{j=1}^{\ell} N_j$ is the total number of customers.

- The system average interruption frequency index (SAIFI)

$$\mathrm{SAIFI} = \frac{\sum_{j=1}^{\ell} N_j \cdot T_j}{N}.$$

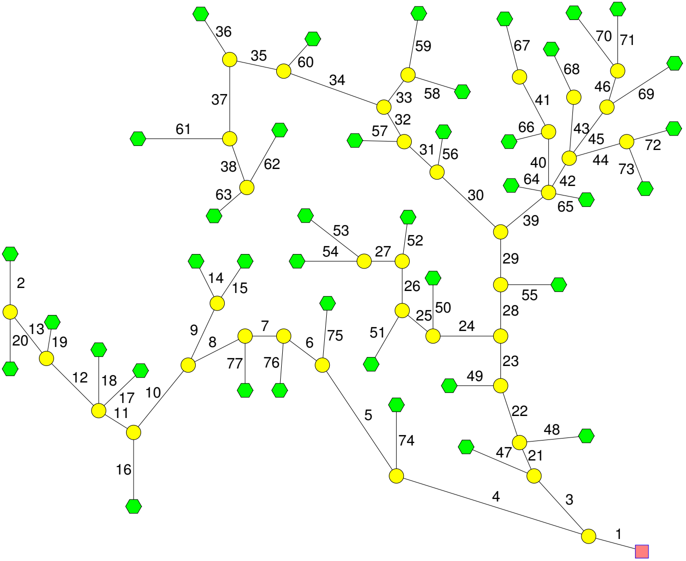
Multiobjective Optimization

- In general, optimization of one of the reliability factors is not equivalent to the optimization of other reliability factors.
- $\mathbf{x}$ — the vector of design parameters (binary vector of switch allocations), $\mathbf{x} \in X$, X — the solution space.
- $N_{\mathrm{obj}} > 1$ — the number of objective functions in the multiobjective optimization problem.
- $F_k(\mathbf{x})$, $1 \leq k \leq N_{\mathrm{obj}}$ — design objectives (EENS, SAIDI, SAIFI).
- We say that $\mathbf{x}$ dominates $\mathbf{y}$ ($\mathbf{x} \prec \mathbf{y}$) if $F_k(\mathbf{x}) \leq F_k(\mathbf{y})$ for all $1 \leq k \leq N_{\mathrm{obj}}$, and $F_l(\mathbf{x}) < F_l(\mathbf{y})$ for at least one l.
- $\mathbf{x} \in X$ is a non-dominated solution if there is no $\mathbf{y} \in X$ such that $y \prec x$.
- The Pareto front (the Pareto optimal set) $X_P \subset X$ — the set of non-dominated solutions.
- Multiobjective optimization: find all non-dominated solutions.

Multiobjective evolutionary algorithm

1. Initialize and evaluate population.
2. Perform selection (create parental pool)
   - use Pareto ranking fitness to promote non-dominated individuals (domination-based tournament selection),
   - use fitness sharing to reduce solution clustering by penalizing the solutions that are in the vicinity of other solutions.
3. Perform crossover.
   - use mating restrictions to avoid crossing-over of solutions that are away from each other (the offspring may be far from the Pareto front even though both parents are Pareto-optimal).
4. Perform mutation.
5. Evaluate population.
6. Update archive (the current pool of non-dominated solutions).
7. Update parameters of fitness sharing and mating restrictions.
8. Calculate relative number of new non-dominated individuals p.
9. If $p < p_{\min}$ END; else go to 2.

Analyzed distribution power grid with 78 nodes



Numerical description of the grid structure

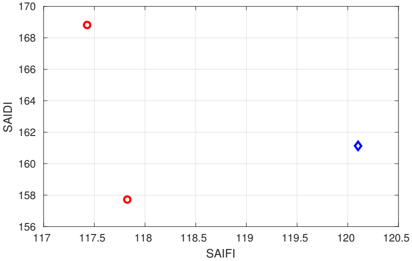
- Node list:
  - node index,
  - node location (coordinates),
  - node type:
    - supply node (1),
    - load node (2),
    - distribution node (3),
  - reliability parameters λ_i and τ_i,
  - average (active) power at the ith load node P_i.
- Line segment list:
  - the beginning-node index,
  - the end-node index,
  - reliability parameters λ_i and τ_i.

Optimization procedure

- Number of switches $k \in \{2, 3, \ldots, 10\}$.
- The objective: determine Pareto fronts for positions of k switches in three configurations of design object functions:
    - SAIDI/SAIFI,
    - SAIDI/EENS,
    - SAIFI/EENS.
- Optimization cost
    - generation size: 200 for $k = 2, 3, 4$.
    - generation size: 1000 for $k = 5, 6, \ldots, 10$,
    - number of generations: 20.

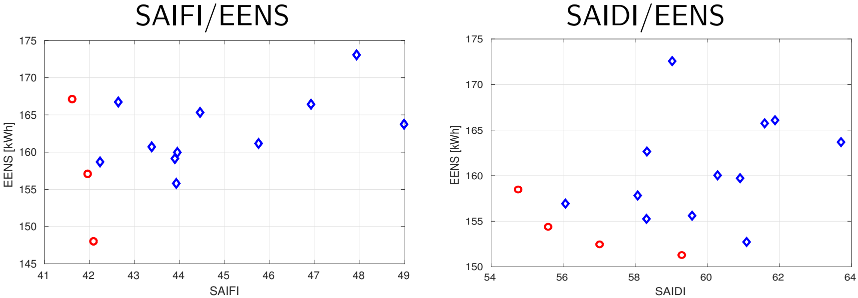
Pareto front for $k = 2$ sectionalizing switches

- Solutions belonging to the Pareto fronts are plotted using circles.
- One of the dominated solutions found by the optimization procedure is plotted using the diamond symbol.
- The Pareto front has two solutions.
- Even for the SAIDI and SAIFI indexes, which are strongly related to each other, we may obtain a nontrivial Pareto front.



Pareto fronts for $k = 10$ sectionalizing switches

- Design objectives: SAIFI/EENS and SAIDI/EENS.



- The Pareto front is composed of three or four elements.
- Neither solution can be assumed to be the optimal solution for both objectives simultaneously.

Switch locations for Pareto-optimal solutions, $k = 10$

EENS	SAIDI	SAIFI	Locations
151.29	59.29	—	3 4 5 23 24 27 30 39 40 45
152.46	57.01	—	3 5 23 25 28 30 32 39 41 42
154.39	55.58	—	3 5 10 23 24 30 39 40 42 45
158.49	54.75	—	5 8 22 23 24 29 30 34 39 42
148.02	—	42.08	3 5 23 24 25 28 30 32 40 42
157.09	—	41.95	4 11 22 23 24 29 30 31 39 42
167.12	—	41.61	5 22 23 24 30 32 35 40 42 46

- Solutions belonging to the Pareto fronts differ considerably in optimal locations of switches.

Conclusions

- A novel multiobjective optimization algorithm for switch allocation in radial power distribution grids has been proposed.
- The approach is based on evolutionary mechanisms.
- The developed evolutionary algorithm is reliable and computationally efficient.
- The method can be utilized for the analysis and optimization of power distribution network reconfiguration problem for networks with a one-sided supply.
- It has been shown that a single solution cannot be considered optimal from the point of view of EENS/SAIDI or EENS/SAIFI trade-offs in switch placement problems