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Urban medium-voltage distribution network planning under a complete back-up regime

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Abstract: The thrust of this study is to show how the reach of a planning algorithm can be extended to provide backup for urban distribution networks from adjacent primary substations, while also treating the planning constraints of thermally constrained networks with the likely increase in almost coincident loads such as electric vehicle charging, and the possible increase in coincident distributed energy resource generation from increased roof-top photovoltaic production. Innovation is to use the slime mould algorithm to aid in producing a good initial network. The initial network is then passed to the planning algorithm to refine the final solution. The simulation results are based on realistic networks for target horizon Greenfield planning scenarios. The hypothetical (but relevant to consider) reduction in network investments that would result if the inter-primary substation back-up requirement is relaxed will also be explored.

1 Introduction

Urban distribution networks with high load densities have primary substations that are located near each other and the lengths of their underground medium-voltage (MV) cables are relatively short. Such an environment makes it reasonable to pursue topological solutions where the distribution network is built meshed but operated radially. While the technical solutions at the primary substation are manifold, full back-up connections and reserves are to be deployed in the case of major failures in primary substations or MV distribution lines. To reach this kind of network structure, a long-term development strategy is needed to direct investment to achieve these goals over decades. As a result, full back-up has been reached in Helsinki. This, and judicious placement of remote switches, has also enabled impressive interruption indices, such as system average interruption duration index (SAIDI), system average interruption frequency index (SAIFI), e.g. realised in Helsinki, Finland [1]. However, one practical implication of the aforementioned considerations and the continuous development of an aging network is to ensure the security of supply and fast restoration times is the provision of back-up to MV/low-voltage (LV) substations from adjacent primary (high-voltage (HV)/MV) substations. Sometimes the planning requirement is to provide back-up from adjacent primary substations as well as from the same primary substation, which used to be sufficient. In coastally constrained cities such as Helsinki, this presents quite a challenge, as many secondary substations do not lie between primary substations, but on the outer periphery.

This paper will use Section 2 to present the use of the slime mould algorithm as an alternative to the methodology presented in [2] for producing an initial network for the planning algorithm, and detail some modifications to the planning algorithm [3] to provide it with the necessary reach to achieve full inter-primary substation back-up. Simulation results are then presented with cost breakdowns for various Greenfield scenarios.

2 Methodology

This section introduces the slime mould algorithm, which is used to produce a radial initial network that is then refined to provide different levels of back-up by a planning algorithm.

2.1 Slime mould algorithm

The proposed algorithm for forming an initial radial network is inspired by the behaviour of an acellular slime mould organism Physarum polycephalum. The slime mould explores the surrounding surface by growing in all directions. Once it finds several pieces of food, it tries to connect them with each other. The unused exploration material is then used for building tubes to transport nutrients from one food source to another. In this way, the slime decays in previously explored areas, leaving only a network of tubes that connects food sources through direct connections.

The slime mould algorithm has been proven to solve mazes [4] and construct Steiner trees [5]. Later, the algorithm was applied to solve practical problems, such as highway planning [6], supply chain design [7] and, most noticeably, Tokyo railroad network modelling [8].

2.2 Slime mould model

The network can be represented as a graph with nodes and tubes as vertices and edges. The tubes conduct nutrient fluid pushed by a pressure \( p \) at each node. Suppose a pressure \( p \) at nodes \( i \) and \( j \), pushes flux \( F_{ij} \) through the tube with conductivity \( D_{ij} \) and length \( L_{ij} \) by the following equation:

\[
F_{ij} = \frac{D_{ij}}{L_{ij}} (p_i - p_j)
\]
Each sink node has a demand of flux of $-1$ and each source node supplies to the system the total demand divided by a number of source nodes. Kirchhoff's law conserves the total flux at each node, keeping the net flux at the rest of the nodes equal to zero by the following equation:

$$\sum_j F_{ij} = \begin{cases} n_{\text{sink}}, & i = \text{source} \\ n_{\text{source}}, & i = \text{sink} \\ 1, & i = \text{rest} \\ 0, & i = \text{rest} \end{cases}$$

(2)

The adaptive network formation is described by the difference (3). The tube conductivity reacts to the flux by gradually shrinking the tubes without flux and expanding conducting tubes. Input parameters $\mu$ and $\gamma$ are flow feedback rate and tube decay rate. By finding the appropriate balance between $\mu$ and $\gamma$, a suitable initial network topology can be achieved.

$$D_k^{t+1} = D_k^t + (\mu |F| - \gamma D_k^t) \Delta k$$

(3)

Equation (1) is a system of linear equations and is solved at every iteration $k$. The simulation is initialised with tube conductivities equal to one. During the simulation, the conductivity values of non-conducting tubes will converge to zero and the rest will converge to a positive value.

In order to achieve a suitable topology, the input parameters $\mu$ and $\gamma$ must be adjusted to find the best balance between them. Typically, a desired result corresponds to a rather high $\mu$ and low $\gamma$, while the intervals of the two are [1, 5] and [0, 1], respectively. Values of $\mu$ lower than one will prevent the model from convergence, while exceeding the upper bound will result in snapping some of the node connections. However, the upper limit of $\mu$ can vary depending on the size of the network. On the other hand, the value of $\gamma$ around the upper bound will result in a star topology with direct connections to each node. By decreasing $\gamma$, the network topology will tend towards a minimum spanning tree.

### 2.3 Planning algorithm

The planning algorithm used in this paper has been under sporadic periods of intense development for many years. The algorithm is described in, e.g., [2, 3]. The main development as far as this paper is concerned is to increase the reach of the reserve connections alongside the reach of the underlying radial network, to enable backup between primary substation areas, and to improve the efficiency of the overall algorithm. The other heuristic imposition is that reserve lines can only be connected to end nodes in the underlying radial network. Switch optimisation is kept to the final iterations, as in an urban network, there are switches at every secondary substation anyway, and the upgrading of some of these switches to remote has very little impact on topology, which would not be the case in rural planning. Fig. 1 provides a flowchart of the main algorithm functions, with the new developments in bold text.

### 3 Results

Fig. 2 shows the initial network provided by an adaption of the slime mould algorithm as presented in Section 2.1. The initial network is well-suited to form a purely radial or optimally backed-up network, as shown in Fig. 3. This network is hypothetical, however, as in Finland, regulation will soon stipulate that substations have to wait longer than switching time to regain supply during a contingency, as a cable repair typically takes $>10$ h.

Fig. 4 shows a solution with full back-up, but the back-up does not necessarily come from an adjacent primary substation (of which there are 5), meaning that not all of the 352 secondary substations are protected from a primary substation outage.

Nevertheless, this level of back-up provides good security against more common line faults, on average 1/100 km/year. The costs given in Table 1 reflect the present value of societal costs for a planning horizon of 40 years, where the interest rate and load growth are 4 and 0.12% per annum, respectively. Interruption is valued at 1.1 €/kW/fault and 11 €/kWh, both based on peak demand in Finland. The range of secondary substation demand is 400–5000 kVA and generation up to 691 kVA per secondary substation. The network operates at 10 kV.

When full back-up is stipulated, and additionally, the back-up has to come from another primary substation, the network solution in Fig. 5 is achieved. This solution also relied on sector-based initial network methodology. As mentioned earlier, the reach of the topology modifying routines had to be increased, in particular, the reach of the reserve connections had to cover the closest end nodes from feeders fed by other primary substations. Such a stipulation carries a significant cost, which should perhaps be considered by regulators. The investment cost increment going from an optimal back-up (Fig. 3) to a full back-up paradigm (Fig. 4) is moderated by the lowering of interruption costs. It tends to even the service provided to different customers in the distribution network, given that customers of a certain type tend to pay the same network tariffs, but those connected to substations without back-up are likely in the long-term to suffer longer interruption times. The question may be raised, however, about the merits of enforcing full back-up from adjacent primary substations (Fig. 5). In real-world use, the planning algorithm runs with a...
geographic interface, which serves to yield more elegant plans than the line-of-sight routing shown in Figs. 3–5.

The cost summaries of these Greenfield network plans are shown in Table 1.

![Fig. 2](image1) **Fig. 2** Initial network produced by the slime mould algorithm – the most elegant, but least functional solution

![Fig. 3](image2) **Fig. 3** Hypothetical solution network (evolved from the slime mould initial network shown in Fig. 2) with optimal back-up and switching, but not allowing for 6 h maximum interruption time

![Fig. 4](image3) **Fig. 4** Solution network evolved from a sector-based initial network [2] with full back-up, but sometimes only from the same primary substation

![Fig. 5](image4) **Fig. 5** Solution network with full back-up provided from an adjacent primary substation (southern connection truncated)

**Table 1** Cost summary of network solutions

| Scenario  | $C_{inv}$, M€ | $C_{losses}$, M€ | $C_{int}$, M€ | $C_{tot}$, M€ | Switches Man/Rem/CB/backup degree |
|-----------|---------------|------------------|---------------|---------------|----------------------------------|
| Fig. 3    | 9.23          | 1.44             | 4.83          | 15.5          | 158/110/2/42%                    |
| Fig. 4    | 14.44         | 0.99             | 3.37          | 18.8          | 556/153/3/100%                   |
| Fig. 5    | 18.82         | 1.48             | 3.90          | 24.2          | 536/167/3/100%                   |
4 Conclusion

The demands of society for high availability of electricity reflected in legislation such as forcing distribution companies to reimburse their customers a part or all of the annual tariff if interruption times exceed 6 h has consequences on the investment costs of MV networks. It is the perennial problem of being prepared for events that are extremely unlikely, but which have a large impact should they occur. The distribution networks are ageing, and perhaps full primary substation outages may start to occur as transformers, the feeding sub-transmission network and associated components are reaching end-of-life, even if they have been almost unheard of in the past. More likely, however, is a failure of a secondary or primary component associated with one primary transformer while the other is under service.

The other offering of this paper was to introduce the slime mould algorithm for aiding distribution network planning by providing an initial network alternative for an established planning algorithm. This will be developed further in the future, embedding it in a new sector-based methodology, so that it can provide technically complying initial networks for a planning algorithm to further coax towards the impossible to reach the global optimum for a given planning scenario.

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