Electrical Grid Asset Work Studies

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AUTOMATIC STUDY, GRAPH THEORY, STEINER TREE, INVESTMENT OPTIMIZATION

Abstract

This paper presents a new methodology developed by Enedis to simulate investment scenarios at the scale of MV (Medium Voltage) pockets, i.e. sub-parts of the network isolated by remote-controlled switches. The method combines existing MV lines with the road network to identify feasible underground routes, creating a joint graph that represents both current assets and potential new connections. Costs are assigned according to the type of line, the presence of risks such as wooded areas, and specific connection rules for substations.

Since the model relies on weighted costs for different types of risks, several scenarios can be produced depending on how strongly risk factors, such as wooded areas, are penalised. For example, using moderate penalties may lead to solutions that retain short segments of overhead lines at limited risk, while stronger penalties generate more extensive undergrounding. This flexibility allows different options to be compared and provides insights into the trade-off between cost and resilience. The resulting scenarios are evaluated by considering both the cost of investment and the expected improvement in network reliability.

By providing a systematic way to generate and compare investment scenarios, this approach supports the national strategy of Enedis to strengthen network resilience while ensuring efficient use of resources.

1 Introduction

For the Overhead MV lines, Enedis' investment plans foresee, by 2032, the undergrounding of 20,000 km of the 38,000 km identified as being at proven risk regarding the climate benchmark and the presence of wooded areas.

These trajectories were built using general models without all local studies having been completed. However, the conclusions of these studies may ultimately cause these trajectories to shift. Indeed, while undergrounding has proven to be an effective long-term solution, a systematic burial of all overhead assets is neither technically nor economically realistic, as it may yield a return on investment far too low (investment decisions must be carefully built to maximize both reliability and cost efficiency).

Today, this trend is confirmed: many local studies no longer align with the trajectory built using the general models. It becomes necessary to refine these trajectories, by learning to estimate the return on investment at broad scale without waiting for the completion of local studies. This can be done by developing an algorithm that mimics these studies, considering Enedis' planning rules, and relying on numerous internal and external data sets.

2 Input DataSet

At Enedis, the structure of the public distribution network is described in a GIS (Geographic Information System) repository, which links mapped network assets to connectivity relationships. These relationships —often referred to as topological relationships— make it possible to represent the electrical continuity of the network beyond geometry alone (spatial proximity) by explicitly specifying which assets are electrically connected.

The dissemination of these data is a major challenge, since they are used in particular for distribution network sizing and planning. In addition to cartographic rendering (geographic layers and attribute data), the existence of connectivity relationships makes it possible to reconstruct the network as a graph in order to directly exploit the system's structure (traversal, connectivity, upstream/downstream analysis, etc.).

2.1 Topological Modeling of the Electrical Network

In the adopted model, electrical components are represented as nodes: MV line segments, switches, transformers, etc. Edges represent an electrical connection between two components.

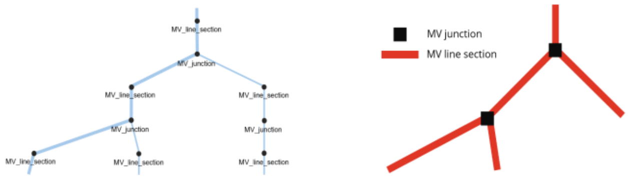

Fig. 1 Comparison between topological modeling and cartographic representation.

2.2 Data used

In addition to the topological modeling of the network, the work relies on several data sources that enrich the graph with risk attributes and with candidate elements representing alternative corridors along which the electrical network could be routed.

2.2.1 Risks on the MV Network

In this study, climate-related risk focuses primarily on tree-related risk, i.e., the exposure of overhead MV lines to tree falls and branch breakage during storms. Other climate hazards (wind, snow, icing) are not detailed here, as the objective is to focus the analysis on the predominant factor identified in historical analyses of climate-related incidents occurring on the MV network [1].

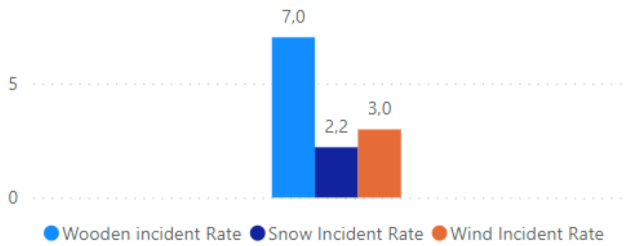

Fig. 2 Incident rate in 2023 (inc/100km) on different risks.

An inventory of network sections potentially exposed to tree-related risk was established through a spatial overlay with data from the IGN (French National Institute of Geographic and Forest Information), notably BD TOPO, and in particular areas classified as "closed forest". This step makes it possible to quantify exposure using a simple indicator: the length of network located in forested areas.

This enrichment was complemented by the identification of two additional families of asset-related risk:

- **Small conductor cross-section (overhead):** certain small cross-section conductors have limited power transfer capability and increased vulnerability to incidents.
- **CPI (underground):** CPI cables (Câble Papier Imprégné, impregnated paper cables) are an old underground technology associated with higher incident rates and are therefore targeted by renewal programmes.

These two risks are integrated as boolean attributes indicating, for each line segment, whether it matches the "small cross-section" criterion and/or the "CPI" criterion.

2.2.2 Road Network

Once the MV sections at risk have been identified, the objective is to propose alternative routes for a future underground network. In practice, underground assets mostly follow existing infrastructure corridors (notably roads), since crossing private properties entails additional land, administrative, and financial constraints.

To model these alternative routes, the BD TOPO "road segments" layer was used. It provides, in particular, the road category (motorway, single-carriageway road, track, footpath, etc.), which is used to differentiate installation costs in the graph weighting. For instance, installing an underground network under a national road is more costly than under a minor road.

2.2.3 MV/LV Substations

Replacing overhead sections with underground sections may require adapting MV/LV substations, for example by converting a pole-mounted substation into an underground substation. Moreover, depending on the surrounding network structure and the power to be supplied, the substation must be able to accommodate a certain number of upstream MV connections as well as a certain number of downstream LV feeders, consistent with the customer demand to be served.

Substation attribute data are sourced from Enedis' GIS. The power levels to be supplied come from annual calculations performed by BERE (Bureau d'Études Régionales d'Électricité) and are used to characterize the sizing constraints associated with the scenarios studied.

3 Methodology

The method is based on a weighted graph that merges the existing MV (Medium Voltage) network with the road network. Each segment of the graph is assigned a cost, which subsequently allows for the application of an optimization algorithm to propose simulations for undergrounding works within the network pocket.

3.1 Construction of the Merged Graph

The road network is first selected around the pocket. Classes that are incompatible with undergrounding (trails, tracks, highways) are excluded. Intersections between roads and MV segments are identified, and all segments are then split at these points to obtain a single graph where both networks are accessible.

MV/LV substations located in the immediate vicinity of a road (less than 50 m) are linked to the graph by a short fictitious underground connection. This ensures that each substation can be connected via a potential underground segment without artificially maintaining a very short overhead segment.

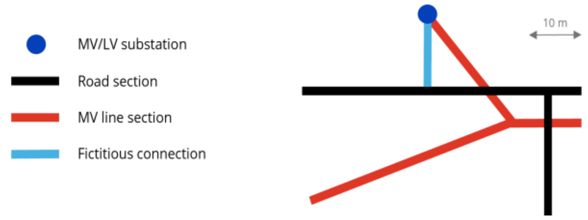

Fig. 3 Schema of a fictitious underground connection to MV/LV substations.

3.2 Definition of Terminal Nodes and Costs

Once the merger is complete, the objective is to obtain a coherent topological representation suitable for topological optimization calculations.

The terminal nodes are the points that must absolutely remain connected in the simulation of the works:

- Remote-controlled switches, as they define the boundaries of the pocket;
- MV/LV load points of the substations, as they represent the LV supplies that must maintain an MV arrival.

These nodes dictate the global structure of the tree (an acyclic subgraph) to be calculated.

The graph is then weighted:

- Existing MV segments have a weighting of zero, except for overhead segments located in wooded areas, to which a penalty is applied.
- Road segments receive a weight equal to their length multiplied by an average undergrounding cost per meter.
- Individual point assets (equipment) receive a weight equal to their installation cost.

This weighting allows the algorithm to favor underground solutions in high-risk zones while maintaining overhead options when road detours would be too significant.

3.3 Steiner Tree Calculation and Scenario Generation

The problem consists of connecting all terminal nodes within the weighted graph while minimizing the sum of the costs. This corresponds to the Steiner Tree Problem, for which no efficient exact solution exists for large graphs. An approximation is therefore used [N]: it selects a minimal set of segments in the merged graph to form a tree connecting all terminal nodes at the lowest cost. The algorithm thus automatically selects the most favorable segments, whether they belong to the existing network or the road network.

The weighting depends on an internal parameter that adjusts the intensity of the wood risk penalty. By increasing this penalty, the algorithm produces more underground solutions. Conversely, by reducing it, the algorithm tolerates certain short overhead sections. In this way, several scenarios can be produced.

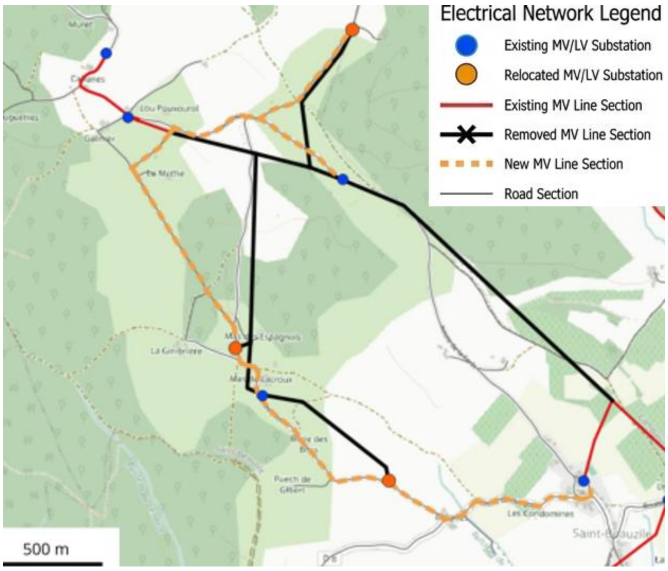

Fig. 4 Example of output.

3.4 Verification and Evaluation of Work Simulations

Each generated tree is checked to verify its compatibility with MV operations:

- A substation in a loop-feed configuration must remain so.
- No substation should support an excessive number of MV links.

The algorithm also automatically determines the required substation type if a local modification is necessary (e.g., converting a radial substation to a loop-feed substation).

To evaluate the relevance of the results, the algorithm's proposed solutions were compared with work programs currently underway or under study by Enedis Decision-Making Authorities. Overall, the results are very satisfying, though some differences persist. For example, in certain cases (Figures 5), the algorithm suggests retaining a few hundred meters of overhead network with low-risk exposure around a new underground network.

This algorithmic choice is explained by the search for minimal cost. However, in practice, planning engineers avoid leaving isolated overhead segments and prefer a homogeneous solution, even if it incurs extra costs. These adjustments are often based on tacit MOAD rules that the algorithm does not yet incorporate.

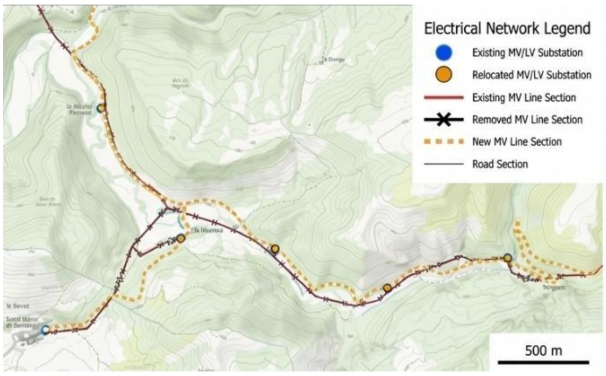

Fig. 5.1 Example of Human-made solution.

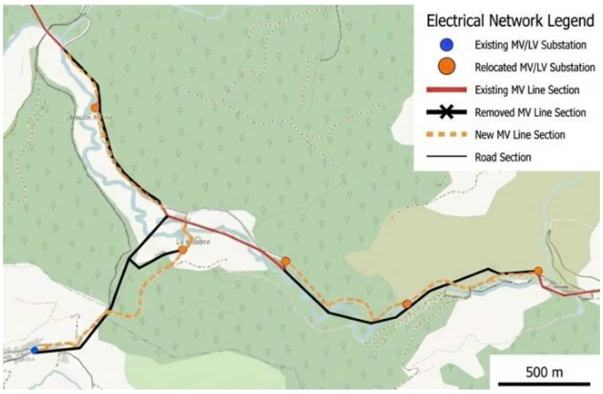

Fig. 5.2 Example of Algorithm-made solution.

Furthermore, the installation of loop-feed substations is sometimes preferred even when business rules would suggest a spur substation. This occurs particularly when the substation is in immediate proximity to a main line (Figures 6)

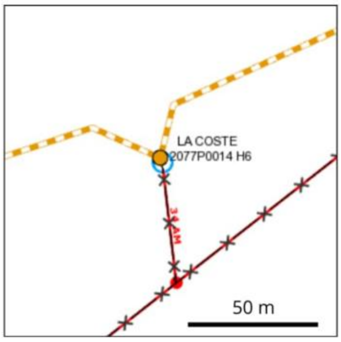

Fig. 6.1 Example of Human-made solution.

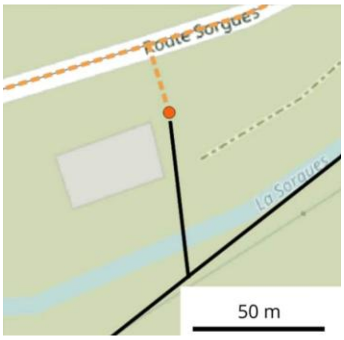

Fig. 6.2 Example of Algorithm-made solution.

3.5 Searching for a Technico-Economic Optimum

The minimal tree calculation described above is performed based on several input variables, such as the penalty cost. While this algorithm minimizes the solution's cost, it does so within the limits of that cost: if the penalty is zero, the network remains unchanged; if it is very high, all at-risk parts will be decommissioned, regardless of the cost.

To find the optimal solution, a tool called the Net Present Value (NPV) balance (or discounted balance) is used. This is the indicator Enedis uses to evaluate long-term network performance and compare different work scenarios. It is calculated by summing several costs:

- Investment cost: includes the cost of installing new overhead and underground sections, decommissioning removed sections, and investments in substations.
- Failure costs: evaluates the socio-economic impact of incidents by integrating incident rates per kilometer of MV sections (by type), the power capacity of disconnected substations, and the time required to restore power.
- Operating costs: includes annual expenses related to network maintenance, such as tree trimming for overhead lines in wooded areas.
- Joule loss costs.

Incident rates also depend on the cable type and environment. Thus, a network with a large portion of overhead sections in wooded areas will have a higher reliability cost and, consequently, a poor NPV balance.

In this way, Enedis prioritizes greater network robustness over low investment costs.

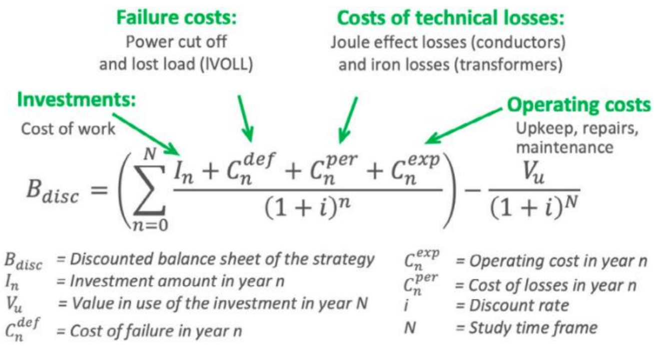

Fig. 7 Formula for the discounted balance.

By "vibrating" (varying) the penalty cost variable around a standard value, the algorithm can propose slightly different solutions, which are then cross compared via the NPV balance to finally select the one that minimizes it.

4 Discussion

Once the algorithm is parameterized, it can be run across the whole network.

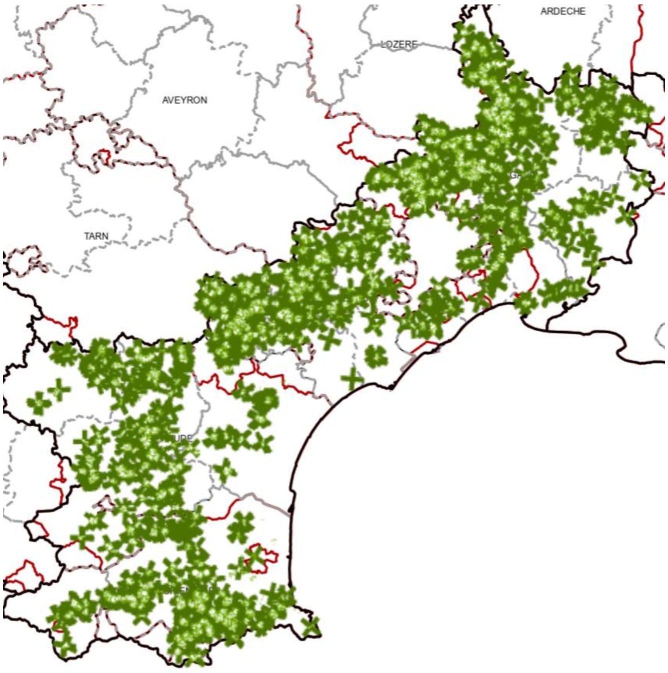

Fig.8 Solutions over south of France

It is then necessary to prioritize the solutions relative to each other, considering Enedis's investment capacity and power quality imperatives.

The envisaged path for this is the use of Operations Research tools. In the context of electricity distribution network asset management, the trade-off between different investment projects can be modeled, for example, as an extension of the 0/1 Knapsack Problem. In this paradigm, each project is characterized by a cost vector (weight) and a performance indicator (value), often derived from the reliability cost.

The objective is to select a subset of projects that maximizes global value while respecting a strict budget constraint over a given period. Unlike classic greedy approaches based on a simple profitability/cost ratio, the implementation of dynamic programming algorithms or branch-and-bound methods allows for the identification of the Pareto optimum, ensuring efficient resource allocation.

5 Conclusion

In the face of climate change and the aging of the French distribution network, it has become imperative for Enedis to accelerate and secure asset renewal works. While automatic network renewal studies are not yet optimal, areas for improvement have already been identified:

- Simulation at the scale of the MV feeder.
- Formal inclusion of network structure rules.
- Inclusion of multi-utility undergrounding opportunities.

Nonetheless, this method currently provides a macroscopic view of the required works and associated potential gains. It proves highly useful for optimizing the balance between technical objectives and the financial constraints of Enedis' long-term investment plan.

6 References

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