Estimating Network Topology and Hosting Capacity: A Multi-Level Approach

Adrien Godfraind[1], Adrien Leerschool[1], Manon Cornet[1], Loïc Perot[1], Alireza Bahmanyar[1], Laurine Duchesne[1], Simon Gerard[2], Thomas Wehenkel[2], Damien Ernst[3]

[1]*Haulogy, Neupré, Belgium*
[2]*RESA, Liège, Belgium*
[3]*University of Liège, Liège, Belgium*
{adrien.godfraind, adrien.leerschool, manon.cornet, loic.perot, alireza.bahmanyar, laurine.duchesne}@haulogy.net, {simon.gerard, thomas.wehenkel}@resa.be, dernst@uliege.be
authors contributed equally in the manuscript

Abstract

The widespread adoption of electric vehicles (EVs) and photovoltaic (PV) systems, driven by global governmental incentives, is posing significant challenges for distribution system operators (DSOs). To maintain power quality, DSOs must estimate the Hosting Capacity (HC) of their networks for these technologies and strategically plan future investments. However, this task is particularly complex due to the uncertainties involved, as well as the limited availability and quality of data at the distribution level. To address this challenge, this paper introduces an overview of a three-level architecture developed for low voltage (LV) distribution networks. The architecture estimates network topology, constructs an equivalent circuit, and calculates HC using limited static data, thereby enabling optimized investment planning and efficient network management.

1 Introduction

Following governmental incentives worldwide, there has been a surge in the adoption of electric vehicles (EVs) and photovoltaic (PV) systems. However, accommodating these technologies on a large scale requires significant upgrades to the distribution networks, a challenge that goes beyond the financial and workforce capabilities of most Distribution System Operators (DSOs). This raises a critical question: to what extent can the existing network host these new installations without major infrastructure investments? In response and to also optimize investments, several DSOs worldwide are developing tools to estimate the Hosting Capacity (HC) of their networks for the new installations.

Various research efforts have explored HC estimation in distribution networks [1], employing methods such as rules of thumb, static deterministic [2] and stochastic [3] approaches, temporal deterministic [4] and stochastic [5] methods, and optimization techniques [6]. Despite the approach adopted, a reliable HC estimate requires knowledge of the network topology, which must be estimated if not available.

There are two general classes of topology estimation algorithms. The first class consists of methods that rely on metering data to dynamically estimate the network topology [7-9]. In contrast, the second class employs static data available in the DSO database about network components to estimate the topology [10,11]. The second class, or a combination of the two, is generally favored by DSOs due to the current low penetration of smart meters or the lack of frequent data retrieval.

Building on the challenge of leveraging limited metering and static data, a three-level architecture is developed in cooperation with RESA, a Belgian DSO, to estimate network HC and optimize related investments. The first level focuses on optimally estimating the network topology. An intermediate level then constructs an electrical equivalent circuit of the network based on the estimated topology. The second level estimates the HC, while the third level optimizes the investment plans. A high-level overview of the first two levels and the intermediate level is provided in this paper.

2 Proposed approach

2.1 Topology estimation

For the first level, a tool has been developed to discover the topology of low-voltage (LV) electrical networks. The algorithms used for this topology estimation are powered by a combination of data inputs, including geographic information on network assets, specific information about distribution network customers, and time series of voltage measurements for a subset of network customers. Geographic data provides the precise location of electrical network assets, such as medium-to-low-voltage (MV/LV) substations, overhead lines, underground cables, utility poles, and the position of network customers. Customer-specific data provides critical insights for the algorithms, such as data indicating which feeder of which substation supplies power to each customer and information on whether the connection of the customer to the network is via overhead or underground lines.

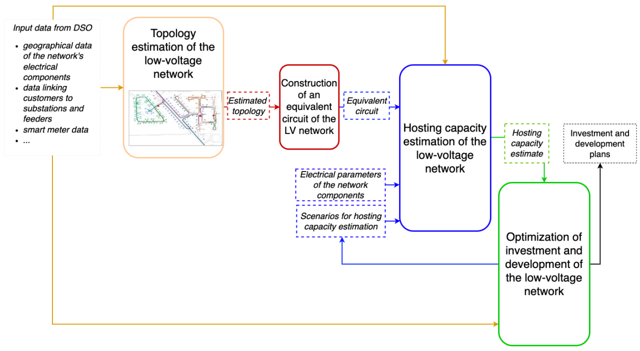

Fig. 1 Multi-Level Approach to Topology and Hosting Capacity Estimation for Investment Optimization

In addition to these data, a set of business rules was exploited to obtain results that closely reflect real field conditions. These rules encompass both physical principles of electrical networks and considerations specific to the DSO, such as the historical evolution of its networks and the operational practices employed in their construction and management. For example, a rule was implemented to specify that the LV network is operated in a radial configuration, ensuring that there are no loops in operation mode.

The topology estimation algorithm leverages these input data and business rules to connect the network elements and reconstruct a topology that is plausible according to the provided inputs. This estimation is performed using the steps outlined below and illustrated in Fig. 2. Note that some data, such as the connection type (overhead or underground) of a customer, may be missing or incorrect. Hence the data is continuously validated and updated throughout the reconstruction process.

2.1.1 Interconnection of network elements: the first step involves exploring the various network elements and interconnecting them based on the distances between them, and business rules defined in collaboration with the DSO [9]. For instance elements are connected if they are close enough to each other: overhead lines are connected to utility poles, underground cables to cabinets, lines and cables to electrical substations, and network customers to these elements, depending on whether the customer's connection is expected to be overhead or underground. Once these connections are established, it allows the creation of a large set of electrical paths from network customers to MV/LV substations, passing through different lines, cables, poles, and distribution cabinets. A path is defined as starting from a network customer and ending at a substation. In a radial network configuration, no element can appear more than once within the same path. Each network customer may have several potential paths at this stage of the algorithm.

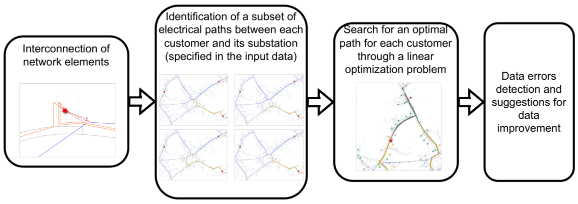

Fig. 2 Topology estimation algorithm main blocks.

2.1.2 Identification of a subset of electrical paths between network customers and their substation: the next step is to identify the most probable subset of electrical paths between each customer and the substation specified for them in the input data. The most probable subset corresponds to the x shortest paths, where x is a parametrisable value influencing calculation performance. This search is conducted using a combination of the “K Simple Shortest Paths One to Many” algorithm (inspired from [12]) and an “A*-like” pathfinding algorithm.

2.1.3 Search for an optimal path for each customer through a linear optimization problem: Once the subsets of paths are obtained for each customer-substation pair, we determine the optimal path to retain for each customer. This is formulated as a linear optimization problem, designed to maximize the total number of paths identified. The optimization ensures that, for the maximum number of network customers, the optimal path is selected while adhering to specific constraints, such as each customer having one and only one path, and each line or cable being associated with only one feeder.

2.1.4 Data errors detection and suggestions for data improvement: based on the obtained result, all unconnected network customers are identified as those for whom the algorithm could not find a path consistent with the topology or whose with lacked (or incompletely provided) information about the feeder and substation supplying them with electricity. The next step is to attempt to integrate these customers into the reconstructed topology by suggesting corrections or completing their data through an iterative process. Indeed, missing or erroneous data may arise, and in such cases, the algorithm suggests completing or correcting the data with the most plausible values based on the initial inputs and implemented business rules. The algorithm follows an iterative process:

1. An initial topology discovery is performed, assuming the input data is correct.
2. Unconnected customers are detected.
3. Suggestions are made to correct or complete these customers’ data.
4. A new topology discovery is conducted, incorporating the suggested corrections and the previously obtained topology.

5. The suggestions are validated; if valid, they are accepted; if not, additional suggestions are made, or the customer is definitively discarded, requiring human intervention.

In this approach, the newly discovered topology is leveraged to refine the suggestions, meaning that steps 2 through 5 are repeated until the iterative process converges.

The key data used to calculate the topology for a given customer include their location, whether their connection is overhead or underground, and the feeder to which they are connected. These inputs are adjusted iteratively until a valid topology is identified, if possible. Notably, the feeder and substation assignment is reassessed by using dynamic data from smart meters and a quarter-hourly comparison of their voltage curves.

2.2 Construction of an equivalent circuit

The second level involves utilizing the reconstructed topology to estimate the network's hosting capacity (HC). However, before this can be achieved, an equivalent electrical circuit of the network must first be constructed. This is essential for our approach because hosting capacity estimation will be performed with the help of load flow calculations, which in turn requires an equivalent circuit. This equivalent circuit is constructed based on the estimated topology of the network.

Mathematically, the equivalent circuit is a graph $G(E,B)$ containing nodes B called the buses connected together by edges E called the branches, the latter representing a direct electrical connection between two buses. A bus is created in the following cases:

1. At each customer connection point to the network.
2. At each branching point between three or more lines.
3. Between two lines if their characteristics are different.
4. On both sides of the MV/LV voltage transformer.

The overhead and underground branches are modeled by their series impedance obtained using Carson's equations [13].

2.3 Hosting capacity estimation

This section is dedicated to the presentation of our algorithm developed to estimate the HC of the LV distribution network. Two primary objectives are defined for this analysis. The first is to estimate the network's capacity for new installations of technologies in consumption and production (e.g. EVs, PV panels) based on scenarios representing the current network status. The second is to identify areas of the network that will require investments under future scenarios. For each scenario, the designed tool will provide either the remaining network capacity or the amount of power that must be curtailed once capacity limits are reached due to congestion or voltage constraints.

Let us now describe in more details our hosting capacity algorithm, including the required input data as summarized in Fig. 3.

2.3.1 Input data: as mentioned above, the first input for the hosting capacity estimation module is the equivalent circuit of the network. The construction of this equivalent circuit is described in detail in Sec. 2.2.

The second input is the scenario for which one wants to compute the margins. A scenario could be for instance the worst case in consumption or production. For the worst consumption scenario every customer consumes at its peak value with zero production. For the worst production case every customer has a low consumption (e.g. 10% of their peak value) and each customer owning PVs produces at its maximum power. In practice, a scenario file can give the active and reactive powers for production and consumption for each customer and at each time step.

The last inputs are the simulation parameters. They include the electrical characteristics of the network such as the line impedances and their maximum current limits, nominal bus voltages, transformer apparent powers ratings, the IDs of the customers for whom the margin is to be calculated, and the selected precision for the margin computation.

2.3.2 Hosting capacity module: based on the input data, the hosting capacity module estimates the margin of the network as the remaining network capacity for consumption or production. The calculation is performed independently for each substation and its associated network feeders, using the primary substation voltage as the reference. The method uses a power flow module such as the one of pandapower [14] to compute the bus voltages and the branch currents for the given network.

Starting from the input scenario, the consumption or production of the customers of interest is incrementally increased using a dichotomous approach. In this approach, each customer's consumption or production is increased by the same step in apparent power, denoted as Δs, at each step. When a network constraint violation occurs at any step, the process returns to the previous step and divides Δs by 2. The process then restarts with this new increment until another constraint violation occurs. The process stops when Δs reaches a predefined precision. The margin is thus defined as the total amount of apparent power that can be safely added to each considered load or production unit in the network without causing any violations, such as over-voltage, under-voltage, or line or transformer congestion.

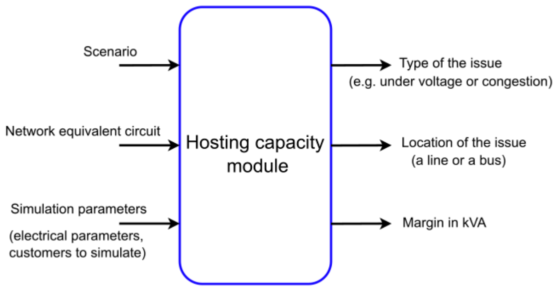

Fig. 3 Inputs and outputs of the HC estimation algorithm.

2.3.3 Output data: finally, a report is released containing the location and the type of the first constraint(s) that occurred in the network. The margin is then given for each customer. A visualisation of the margins or the violations in the network is also provided using a colour scale.

3 Results

3.1 Topology estimation

The methodology described in Section 2.1, developed in collaboration with RESA, is applied to several areas of its LV network. Fig. 4 illustrates the reconstructed network for a small section of a neighborhood, with different feeders distinguished by unique colors.

3.2 Construction of an equivalent circuit

Once a topology is constructed, the creation of the equivalent circuit can be conducted. Fig. 5 shows the result for the same area as Fig. 4. The series impedance of each line section is determined using a database of per-unit-length impedances, derived from conductor characteristics and calculated with Carson's equations.

3.3 Hosting capacity estimation

We have used our hosting capacity tool to estimate the margins for a part of the low-voltage distribution network of RESA. Fig. 6 presents the consumption margin (in kVA) computed starting from a worst case scenario in consumption. In this scenario, all the customers consume a peak value given as the apparent power of their feeding transformer at peak divided by the number of downstream customers. The production of all the customers is set to zero. We can see that there exist some zero margins in this network: in this case, the initial state of the network given by the scenario already violates network constraints. Some outlier values for the margins above ~10 kVA also exist: these particular situations occur when few (or only one) customers are connected to a transformer.

Fig. 7 presents the locations of the first violations of the constraints appearing in a part of the low-voltage distribution network of RESA for the same consumption scenario. In this case, we can see that the most frequent violations are under voltages.

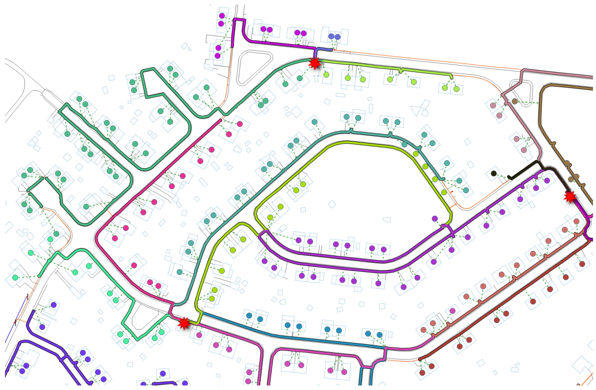

Fig. 4 Topology estimation algorithm results. Feeders are represented by different colors, circles represent customers and the red stars (✸) represent the MV/LV substations.

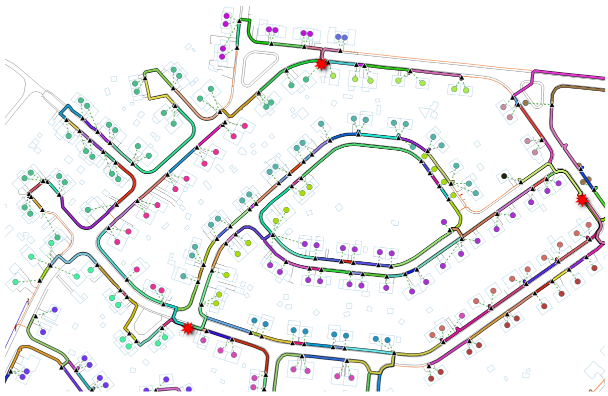

Fig. 5 Equivalent circuit formed. Each bus is represented by a small black triangle (▲) and each branch by a randomly chosen color.

These under voltages primarily occur at the ends of the feeders of the network, i.e. far from the substations. Additionally, some occasional line congestions also occur.These under voltages primarily occur at the ends of the feeders of the network, i.e. far from the substations. Additionally, some occasional line congestions also occur.

4 Conclusion

A three-level method was proposed and implemented to estimate the Hosting Capacity of distribution networks using limited data, without relying exclusively on metering data. The approach seeks to leverage every type of available information, even when some data are incomplete or inaccurate. The method involves reconstructing the network topology, constructing an electrical equivalent circuit, and estimating the HC for given future scenarios based on the available data. This demonstrates the potential to support DSOs in integrating new energy sources effectively, even with limited information on the network.

Future work in the third level will focus on optimizing investment strategies for network upgrades.

5 References

[1] A. Benzerga, A. Bahmanyar, G. Derval, et al., "A Unified Definition of Hosting Capacity, Applications, and Review," IEEE Access, vol. 13, pp. 7819-7836, 2025.

[2] L. Ravier, V. Delemazure, T. Buffard, et al., "CAPTEN: A service providing access to a map of hosting capacities and a simplified multiple load insertion simulator," in Proc. CIRED 2024, Vienna, Austria, 2024.

[2] A. Shawki, M. Maximini, S. Schulze, et al., "Determination of the maximum LV grid hosting capacity for a rapid integration of photovoltaics, electric vehicles, and heat pumps," in Proc. CIRED 2024, Vienna, Austria, 2024.

[3] B. Guo, V. Piana, J. Pouget, et al., "Co-simulation of behavioral and technical decisions: An application to impact analysis of EV charging on hosting capacity of LV distribution network," in Proc. CIRED 2024, Vienna, Austria, 2024.

[4] A. Benzerga, S. Mathieu, A. Bahmanyar, et al., "Probabilistic capacity assessment for three-phase low-voltage distribution networks," in Proc. IEEE 15th Int. Conf. Compatibility, Power Electronics and Power Engineering (CPE-POWERENG), Florence, Italy, 2021, pp. 1-6.

[5] H. Khajeh, S. Seyyedeh-Barhagh, and H. Laaksonen, "Quantifying the impact of day-ahead renewable forecasts on DER hosting capacity estimation," in Proc. CIRED 2024, Vienna, Austria, 2024.

[6] H. Wei, W. Wang, C. Fang, et al., "Online distribution system topology monitoring with limited smart meter communication," IEEE Trans. Power Syst., vol. 38, no. 6, pp. 5714-5725, 2022.

[7] V. Srinivas, V. L. Lakshmi, and J. Wu, "Topology and parameter identification of distribution network using smart meter and µPMU measurements," IEEE Trans. Instrum. Meas., vol. 71, pp. 1-14, 2022.

[8] A. B. Pengwah, Y. Z. Gerdroobari, R. Razzaghi, et al., "Topology Identification of Distribution Networks with Partial Smart Meter Coverage," IEEE Trans. Power Deliv., vol. 39, no. 2, pp. 992-1001, Apr. 2024.

[9] M. Vassallo, A. Bahmanyar, L. Duchesne, et al., "A systematic procedure for topological path identification with raw data transformation in electrical distribution networks," in Proc. Int. Conf. Energy, Electrical and Power Engineering, Yangzhou, China, Apr. 2024.

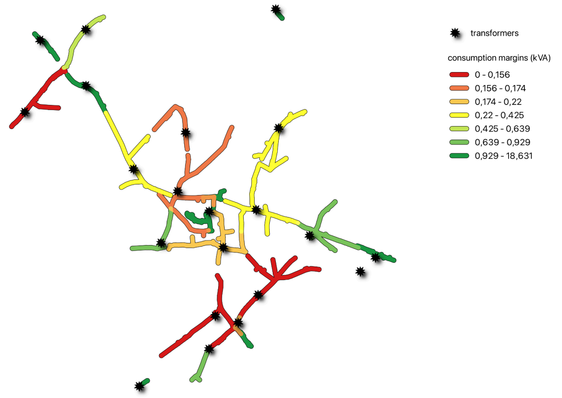

Fig. 6 Consumption margins (in kVA) for a part of the RESA's distribution network, starting from a worst case scenario in consumption.

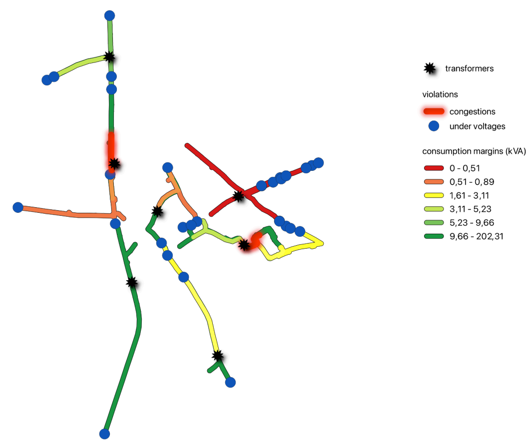

Fig. 7 Zoom on the violations of the constraints.

[10] A. Seack, J. Kays, and C. Rehtanz, "Generating low voltage grids on the basis of public available map data," in Proc. CIRED Workshop, Rome, Italy, June 2014.

[11] S. V. Udhayasekar, K. K. Srinivasan, P. Kumar, et al., "Label-setting algorithm for multi-destination k simple shortest paths problem and application," Algorithms, vol. 17, no. 8, p. 325, 2024.

[12] W. H. Kersting and R. K. Green, "The application of Carson's equation to the steady-state analysis of distribution feeders," in Proc. IEEE/PES Power Systems Conf. and Expo., pp. 1-6, IEEE, 2011.

[13] L. Thurner, A. Scheilder, F. Schäfer, et al., "pandapower - an Open Source Python Tool for Convenient Modeling, Analysis and Optimization of Electric Power Systems," IEEE Trans. Power Syst., vol. 33, no. 6, pp. 6510-6521, Nov. 2018.