ANALYSIS OF VOLTAGE PATTERNS FOR TOPOLOGY IDENTIFICATION AND GIS CORRECTION

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ABSTRACT

The topology is the cornerstone of the analysis of the low voltage grid. However, the current information is often a not-up-to-date GIS storing the bulk of information about the Distribution System Operator's assets' characteristics and location. Its content is not complete and accurate enough to perform a modelling of the low voltage network. Providing the meter – phase – feeder – transformer connection, the topology would pave the way to a greater operation.

This lack can be filled thanks to the analysis of smart meters data. The paper presents the methods available to retrieve the topology, their pros and cons and evaluates a new algorithm using the voltage curve of every meter in a defined geographical area in order to find it out.

INTRODUCTION

The energy market has switched from unidirectional electricity consumption to a complex and bidirectional system. Because of changes, such as massive photovoltaic hosting and electric vehicle charging infrastructures, the low voltage network is undergoing a 'revolution'. In order to support these changes, and to enable energy transition, the low voltage network must be re-evaluated as a strategic asset.

The fundamental knowledge of the network's topology must therefore be considered. This is done by looking at the composition of its geographical and connectivity information. This information can pave the way to new opportunities of studying the low voltage network such as impact studies of new connection, follow-up of power quality supply, efficiency enhancement in losses and assets' lifetime, predictive maintenance, and increased investments relevance.

Because the low voltage network is both extensive and dispersed it has been denied modernisation. Currently, the Geographical Information System (GIS) stores the bulk of information about the topology, but this part of the network is constantly changing and, as a result, is often not up to date. Furthermore, the GIS currently operates on a single wire model which is not accurate enough to perform modelling and so enhance the network's operation.

The latest major investment throughout the low voltage network is the roll out of smart meters. They provide electrical data on a frequent basis. This new information is mainly used for billing purpose however, the insight it contents could enable Distribution System Operators (DSO) to go much further in the understanding of the low voltage grid's behaviour.

Odit-e's value proposal on topology, developed through a technical partnership with Schneider-Electric Spain, consists in the analysis of this data to provide the connectivity scheme.

This paper is organized in the following way. A state of the art is provided to evaluate the available methods. The algorithm is then presented with its results and the opportunities it brings into low voltage network's operation.

AVAILABLE METHODS

Power-Line Communication (PLC)

Depending on the technology used for the Advanced Metering Infrastructure (AMI), insights on the topology can be provide. It is the case for DSO using PLC. As the communication is realized through the grid, the signal itself contains the connection information. G3 and IEEE 1901.2 protocols offer this feature of phase detection [1].

However, this technology has two main drawbacks:

- PLC technology is not used worldwide, another alternative must be found for Radio Frequency (RF) AMI
- The topology found out through the analysis of PLC infrastructure can be false due to electrical crosstalk.

Energy conservation

A method used to confirm and complete the topology consists in the setting up of sensors in substations. Those sensors record the power consumed in every feeder and phase. Applying the principle of energy conservation – the consumption at the meter level must be found back at the phase, feeder and substation level – the problem boils down to combinatorial optimisation problem.

Such a method has the advantage of requiring only the load curves of the smart meters, this data collection is easily implemented.

A similar solution is described in V. Arya et al. [2]. However, it has multiples drawbacks:

- Most of the meters downstream the substation must be smart and working. Otherwise, the energy conservation principle cannot be applied.
- The previous argument implies the algorithm's performance is impacted by measurements errors, desynchronization in dataset and, technical and non-technical losses.
- Combinatory approach can't be done on a large scale, the topology must be partially known in order to select the appropriate meters
- The power going through the substation must be recorded for every phase of every feeder. This needs the setup of a sensor in the substation for the study's period. This is expensive and time consuming.

Power correlation

The energy conservation principle is also used in another method which implies a Principle Component Analysis (PCA) and its graph-theoretic interpretation [3]. It takes advantage of the correlation between the load curve of the power consumed at the level of a meter and the load curve of the cable – one phase of a feeder – it is linked to in the switchboard. This way, the connectivity can be defined. It particularly works well for high energy consumer, small one being more difficult to locate. The major drawbacks is that it still needs measurements at the substation level.

THE USE OF VOLTAGE PATTERNS

The voltage is an indicator of the network's local state. Methods based on this data instead of power measurements are theoretically more reliable. However, the voltage curve is harder to collect as the AMI has, in most case, not been designed to store and transfer it on a frequent base. The opportunities arising from this data collection are under study within the Odit-e and Schneider Electric Spain partnership.

Principles

Concerning the topology's retrieval, an innovative way to find it out through the analysis of voltage patterns has been developed. The proposed algorithm is based on a combination of various machine learning techniques and has been proven effective on two sets of real data collected by two DSO. This article shows the results obtained on one of those data sets.

The algorithm includes different steps:

- Removing external influence
- Clustering of resulting voltage patterns
- Grouping clusters into transformers, feeders and phases
- Final connectivity tree reconstruction
- Upgrade of the GIS with this new information and consistency checking with the location information

Figure 1 shows the upgrade toward an Advanced GIS which allows to correct errors and add the phase connectivity information. This Advanced GIS is therefore complete and accurate enough to be the support of a broad range of studies of the Low Voltage network described in the results and consequences part.

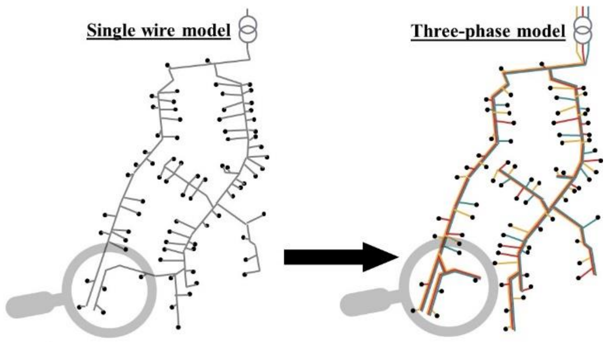

Figure 1: GIS Upgraded: Topology correction & phase connectivity addition

Input data

In order to perform the algorithm, the data needed is the voltage, during a given time period and on a frequent basis. The data collected in this partnership presents the following characteristics:

- 7 days collection on a 10 minutes frequency basis representing around 1000 observations
- 388 three-phase smart meters communicating voltage data and divided in 18 substations
- A mV accuracy

Intermediate results

Through a clustering algorithm performed on the voltage data, substation's clusters are established and errors in the GIS can be highlighted, see figure 2.

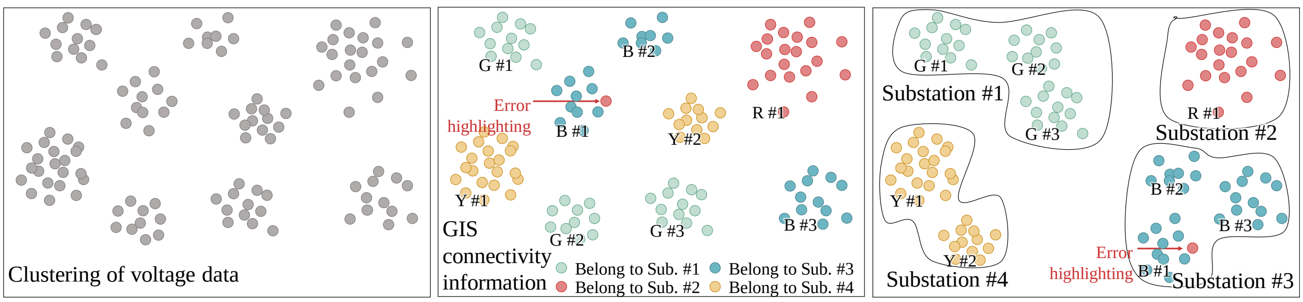

Figure 2: Principle of the substation's identification

At this step of the algorithm, it is then possible to validate or correct the GIS information. In our case, one smart meter was, according to the data analysis, not connected to the right transformer inside the GIS: figure 3, the red point among blue points should be blue but was referenced as belonging to the red substation in the GIS. This information has been verified and turned out to be true according to the geolocation of said meter. This is a simple but valuable result.

Once substation's clusters defined, we are able to recover the voltage at the substation considering only smart meters' voltage curves (see figure 3, left and middle). Then, this estimate of transformer's voltage curve is used to remove the external influences coming from the medium voltage level. This allows to focus on low voltage fluctuations only (see figure 3, right).

The pre-processed voltage curves (figure 3, right) are more interesting than the raw data (figure 3, left) as they highlight similarities between them. A sub-clustering is then performed for each substation. It groups pre-processed voltage curves by feeders and phases (see Figure 4, the four graphs represent the four identified feeders).

This step determines the meter - phase - feeder connexion.

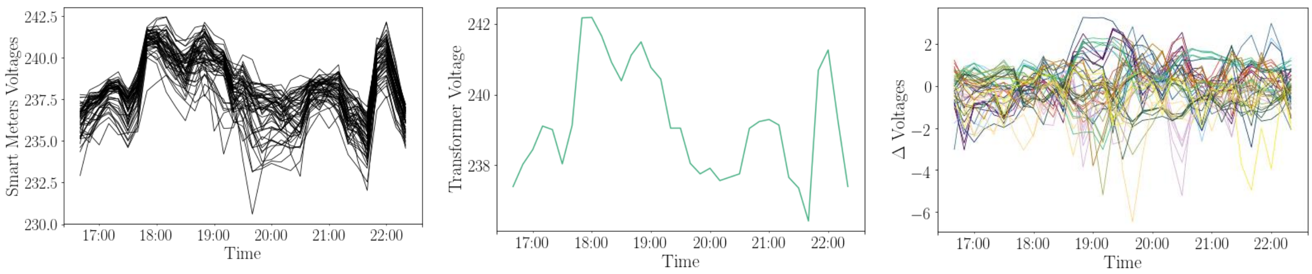

Figure 3: Pre-processing of the voltage data - Removal of medium voltage influence – Example for an identified substation

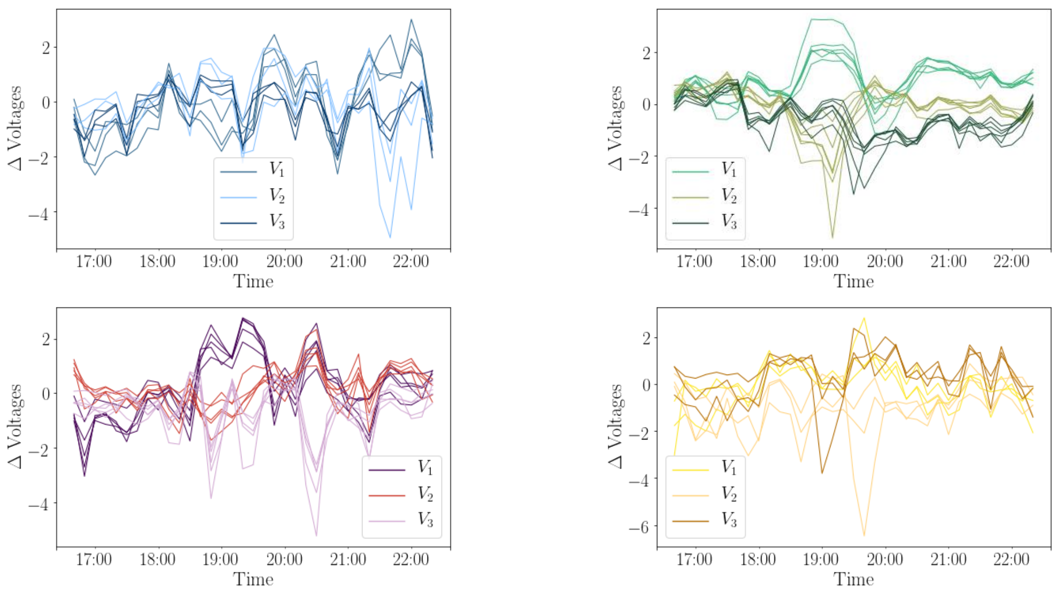

Figure 4: Voltage curves for every feeder with phase identification

Results on topology and opportunities

A last analysis of the distance between meters of a same sub-cluster bring the order of the connection (see figure 5).

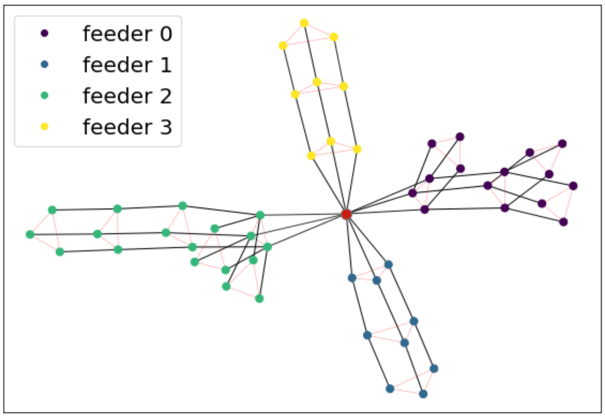

Figure 5: Final tree reconstruction

When the topology is retrieved, it can be used to correct existing GIS databases, using the following process:

- Identification of the topology from voltage patterns with a confidence index relative to its position
- Cross-checking for any errors in the GIS about transformer / feeder / smart meter connection
- Addition of the feeder / phase / smart meter connection in the precedent model

Once uploaded in the GIS, the topology upgrades it from a patrimonial database to an actual analytic and operational tool.

This process brings several results which are, independently, a breakthrough in the operation of low voltage networks.

Non-Technical Losses detection (NTL)

With the roll out of smart meters, substations have been equipped by a meter which measures the energy consumed downstream. Several DSOs took the chance to implement Key Performance Indicator to follow the energy balance and identify area where energy consumed and energy billed do not match, that is to say area with a high rate of NTL. However, this simple and cost-effective analysis could not be performed because of GIS errors bringing wrong scope comparison.

Our topology algorithm solves the issue of this use case making comparison possible and goes further. Using the topology and modelling the network, the detection of NTL can be more precise, with their location inside the grid and their estimated amount and profile.

Upgraded operation and asset management

Through the increase of the network's knowledge, any intervention is made easier thanks to a more accurate and reliable location of the customers. In case of a planned power cut, every concerned customer can be informed of the situation in advance without breach. If it's not planned, the design of a feedback scheme is facilitated.

The GIS could then be able to perform analysis on the low voltage network's state. This would take benefit from the smart meters data to provide operational advantages such as insights about the load level of transformers and lines or help in a phases re-balancing initiative.

Planning, Renewable Energy & Electric Vehicle

A last consequence is the ability to model the network to predict the impact of new loads or production facilities. In this way, the existing infrastructure would be wisely used and would promote distributed renewable energy insertion and electric vehicle charging infrastructure in the most cost-effective way.

Necessary data

After studying the amount of data necessary to obtain the results described above, the following conditions have been set for this project:

- A period of collection higher than 5 days
- A periodicity of the collection lower than every hour
- A minimum of 300 observations

Those conditions are described in figure 7.

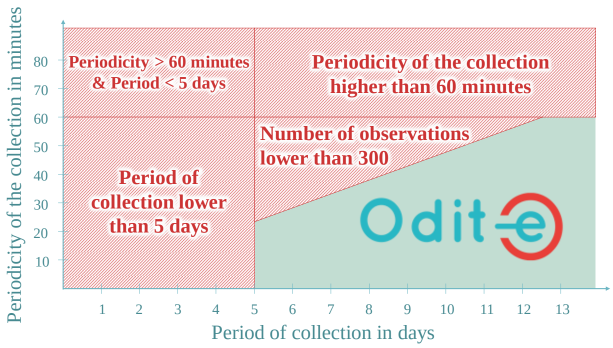

Figure 6: Conditions of the data collection

CONCLUSION

This partnership has developed innovations which bring new opportunities in transforming the low voltage grid into a smart one.

With a comprehensive topology, dynamic modelling of the low voltage grid is now possible. Therefore, new insights for investment or operational decision making can be provided. It is an opportunity to improve low voltage grid just as SCADA did for medium and high voltage grid operation.

REFERENCES

[1] N. Uribe-Pérez, L. Hernández, D. de la Vega, and I. Angulo, 2016, “State of the Art and Trends Review of Smart Metering in Electricity Grids”, *Appl. Sci. 2016, 6, 68*, 7-9

[2] V. Arya, D. Seetharam, S. Kalyanaraman, K. Dontas, C. Pavlovski, S. Hoy, and J. R. Kalagnanam, 2011, “Phase Identification in Smart Grids.”, *IEEE International Conference on Smart Grid Communications (SmartGridComm)*, 25–30

[3] S. J. Pappu, N. Bhatt, R. Pasumarthy and A. Rajeswaran, 2016, "Identifying Topology of Low Voltage Distribution Networks Based on Smart Meter Data", *IEEE Transactions on Smart Grid*, vol. 9, no. 5, pp. 5113-5122