CHARACTERISING LV NETWORKS ON THE BASIS OF SMART METER DATA AND ACCURATE NETWORK MODELS

Benoît BLETTERIE	Serdar KADAM	Matthias STIFTER
AIT – Austria	TU Vienna – Austria	AIT – Austria
benoit.bletterie@ait.ac.at	serdar.kadam@student.tuwien.ac.at	matthias.stifter@ait.ac.at
Andreas ABART	Daniel BURNIER DE CASTRO	Helfried BRUNNER
Energie AG Oberösterreich Netz GmbH	AIT – Austria	AIT – Austria
andreas.abart@netzgmbh.at	daniel.burnierdecastro@ait.ac.at	helfried.brunner@ait.ac.at

ABSTRACT

This paper focuses on the characterisation of LV networks on the basis of the Power Snapshot Analysis by Meters method (PSSA-M). By using the active and reactive power synchronously measured with a Power Snapshot in a suitable network computation program, unexplored possibilities are offered in terms of network characterisation. An obvious added value of a better know-how of the actual network situation is that networks can be better used, and the suitability and benefits of smart grids solutions can be estimated. This paper provides the first results of network characterisation work.

INTRODUCTION

One of the prerequisite for implementing smart grid solutions into LV networks is to have a better understanding of these networks. When investigating or developing innovative smart grids concepts to enable an optimal integration of DER (distributed energy resources), one of the first questions that arise is how to model the system. As mentioned in [1], LV network modelling remains a challenging task due to the lack of data (i.e. load profiles, phase information, neutral earthing). In the absence of detailed models, the validity of network studies can be questioned since they are based on unrealistic assumptions. In order to address the mentioned problems, some research work is on-going within the project ISOLVES:PSSA-M [2]. The main objectives of this work is, in a first step, to develop and validate accurate LV network models on the basis of smart meter data, and in a second step, to analyse a large set of low voltage networks in order to identify typical characteristics, which is the focus of this paper.
The concept of Power Snapshot (PSS) introduced in [3] consists in gathering synchronous measurements over a whole LV feeder or a whole LV network. The proposed trigger concept ensures that interesting snapshots (i.e. high/low voltage or large current) are collected on a regular basis (at least one snapshot per 15 min). One Snapshot consists as explained in [3] [4], of a synchronous measurement of voltage, active and reactive power per phase for each smart meter. By feeding these power values into a network computation program and comparing the simulation results with the measurements (voltages), the accuracy of the network model can be analysed, the models tuned and validated.
A comprehensive tool has been developed and is currently in the finalisation phase.

MODELLING

The models of the 38 LV networks selected for the study have been built in the simulation software DIgSILENT PowerFactory®. The models consist of the network model (including MV equivalent network, distribution transformer, and LV cables) together with unsymmetrical supply and load elements which are used for the unbalanced load flow computations.

Network model (three-phases four wires)

As previously explained, in order to study LV networks, load unbalance must be taken into account. Moreover, the system earthing (TN-C in the considered networks) has been accurately modelled by grounding the neutral according to the DNO practise. In these models, the neutral conductor impedance has been modelled explicitly instead of reduced into the zero sequence impedance as it is usually done. Two different options have been used to model the supply (slack element):

- three single-phase voltage sources fed with the measurements from the Power Snapshots (voltage and phase angle) for model validation purpose
- a symmetrical slack element at the MV side of the distribution transformer allowing to perform prospective studies taking into account the distribution transformer in later projects (e.g. impact of photovoltaic & electric vehicles scenarios).

Load model

Each meter (e.g. household, industry or generation meter) has been modelled by a three-phase unbalanced load which is directly fed with the active and reactive power measurements per phase from the Power Snapshots. Generation installations that might have an own meter are modelled as negative loads. Before using the models to characterise the networks and in a later stage to perform prospective studies on the potential of smart grid solutions, the network models must be validated and possible sources of deviations analysed:

- measurement uncertainties
- model uncertainties:
  - unknown (assumed) neutral earthing impedance
  - unknown coupling impedances
  - unknown cable length between connection cabinet and meter

For the validation purpose, the data from the PSS are used in the following way: the voltage measurements are compared to the voltage values obtained from the load flow computation which is fed by the active and reactive power measurements from the PSS. Deviations between measured and computed voltages are then analysed. This will be presented later once enough data is available to ensure a statistical relevance.

NETWORK CHARCATERISATION

For the purpose of network analysis and characterisation, a series of indicators have been proposed. Some of them are shortly explained here:

- lowest / highest voltage in the feeder
  - feeder spreading (between phases of a feeder: $\Delta U_{max\text{-}feeder}$, %)
  - network spreading (between feeders (all phases) of a network: $\Delta U_{max\text{-}network}$, %)
- voltage unbalance ($k_{U\text{-}max}$, %)
- sensitivity factor ($\delta U/\delta P_{max}$, %/kW)
- "load torque" ($\Delta U_{L\text{-}max}$, V)
- maximal "equivalent sum-impedance" (R_{Σ}, Ω) [6]
- "equivalent load location" (ε, %) [5]

Figure 1 provides an illustration of the voltage profile along one feeder of a LV network. The upper part corresponds to an original Power Snapshot and the lower part to an idealized situation (symmetrized).

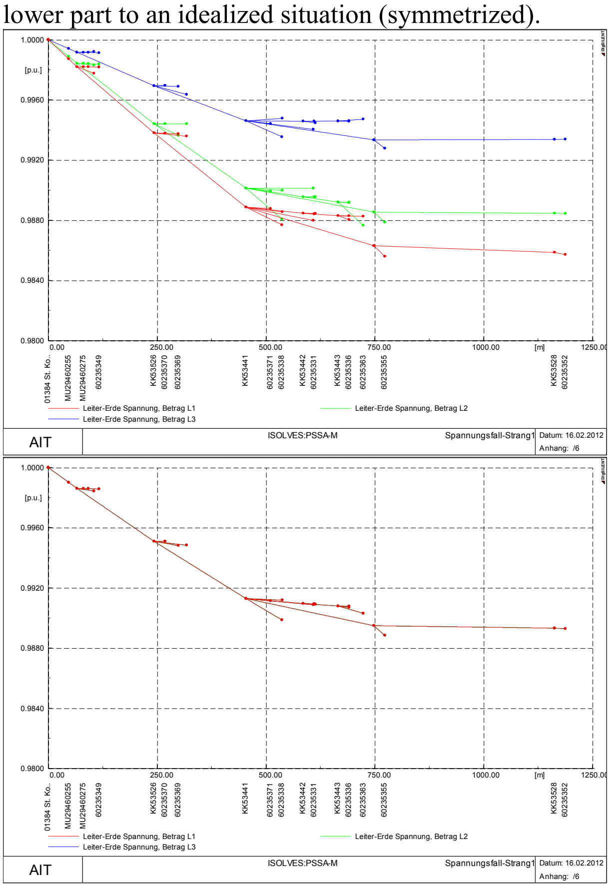

Figure 1. Voltage diagram for an exemplary PSS (upper part: original PSS / lower part: symmetrised PSS)

This figure shows that maximal feeder spreading for the considered PSS was $\Delta U_{max\text{-}feeder}$=1.4 %. This PSS corresponds to a situation with low loading conditions (weak load) leading to a small voltage drop even for this long feeder. As shown in the simulations in [1], the voltage difference between phases can reach large values and even lead to voltage rise in one phase due to neutral point displacement. The lower part of the figure shows that the maximal feeder spreading for idealized conditions (fully symmetrical situation) is smaller: $\Delta U_{max\text{-}feeder}$=1.0 %. Even if both spreading values are small (low loading conditions), this analysis based on real data (PSS) shows that even a rather small load unbalance leads to a significantly higher voltage drop. This spreading indicator provides very valuable information by showing how much of the voltage band is "consumed" by load (or generation) unbalance.

The sensitivity factor δU/δP allows classifying network nodes according to their strength. However, the expressiveness of this indicator is limited by the fact that load information is not considered. As an example, this indicator does not allow distinguishing between weak feeders supplying few or many customers.

As further indicator, the load torque allows taking into account the load connected to the considered node. It is computed as the product of the sensitivity factor with the load and represents a voltage drop. This indicator therefore contains more information than the sensitivity factor but does only consider the load directly connected to the considered node. Loads connected in the immediate surrounding which impact significantly the voltage profile are not taken into account. The concept of equivalent sum-impedance R_{Σ} as introduced in [6] and explained below for a simple case consisting of one LV feeder with homogenous current distribution and without laterals (equation (1)) has been generalized to more complex cases using load flow computations. It can be computed for LV feeders with laterals and a non-uniform current distribution. Contrary to more simple figures such as the grid impedance, the short-circuit power or load flow sensitivity factors (see Figure 2), the equivalent sum-impedance provides information about the network strength related to the actual loading conditions. A generalization has even been proposed for unbalance conditions. However, this unsymmetrical equivalent sum-impedance shall be carefully interpreted due to the coupling between phases through the zero-sequence impedance. The equivalent sum-impedance R_{Σ} can be computed as followed for a purely radial LV feeder with N loads a uniform current distribution:

$$R_{\Sigma} = \frac{1}{N} \cdot \sum_{k:1}^{k=N} \left(R'_k \cdot l_k \cdot (N - k + 1) \right) \qquad (1)$$

R'_k cable impedance per length of cable segment k
l_k length of cable segment k
N number of nodes on the feeder
k cable segment index

The implementation in the network computation program allows computing this equivalent sum-impedance by using a load flow computation instead of using the formulas and network topology information.

Finally, the "equivalent load location" as introduced in [5] provides the information about the location of an equivalent load along the feeder. A generalisation (for non-uniform cable cross-section) is proposed through equation (2). This indicator has been implemented into the network computation program. It takes an equivalent load (total power flow at the beginning of the feeder) and moves it along the feeder until the voltage obtained at the corresponding node is close to the voltage observed at the end node of the feeder. ε = 1 corresponds to a feeder with loads connected at the end only, ε = 0 to a feeder with loads at the beginning only.

$$\varepsilon = \frac{1}{N \cdot R} \cdot \sum_{k=1}^{k=N} \sum_{i=1}^{k} R'_i \cdot l_i \qquad (2)$$

ε equivalent load location
R'_i cable impedance per length of cable segment i
l_i length of cable segment i
k cable segment index
i cable segment index (→cumulated impedance)
N number of nodes on the feeder

These indicators can be computed for:

- standard (uniform) loads or for Power Snapshots (several timestamps)
- balanced or unbalanced conditions
- loads or generators

A generalisation of the proposed indicators is currently under work.

Figure 2 shows the distribution of load flow sensitivity factors for all the nodes of the 34 feeders from 5 LV networks. This figure corresponds to balanced conditions and provides an idea about the network strength and the R/X ratio. On this figure, the red points represent nodes which are situated at the end of feeders. This figure shows that for all the nodes, the resistive part of the network is larger than the inductive part.

Figure 3 shows the equivalent sum-impedance as a function of the distance from the distribution station for each feeder (9 in total) of a particular network. Moreover, the equivalent load location is shown by a point on each feeder. This diagram has been obtained by using "standard" uniform load data (each load has the same value) and therefore provides basic information on the network topology, partly disregarding the actual load situation. The first line section of the longest feeder consists of a 980 V overhead-line (to supply a small remote customer group) which can be clearly seen on this diagram. This figure shows that apart from this feeder, the maximal equivalent sum-impedance reached about 0.1 Ω. Except for the short feeders, the equivalent load location is after the middle of the feeder (ε>50 %), which leads to stronger voltage variations in general.

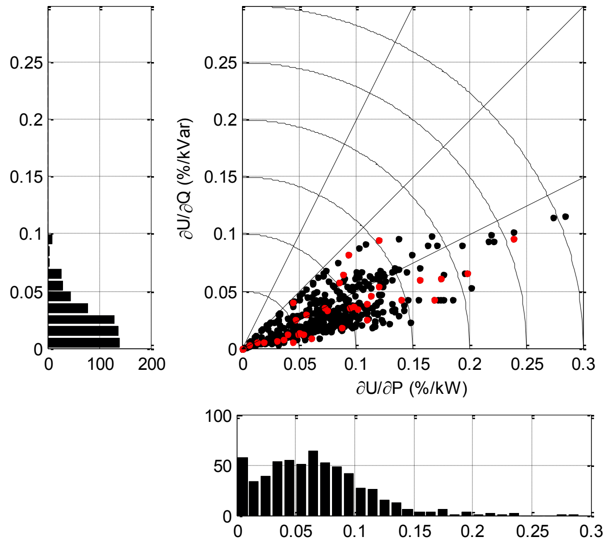

Figure 2. Distribution of load flow sensitivity factors, aggregated for 34 feeders from 5 LV networks

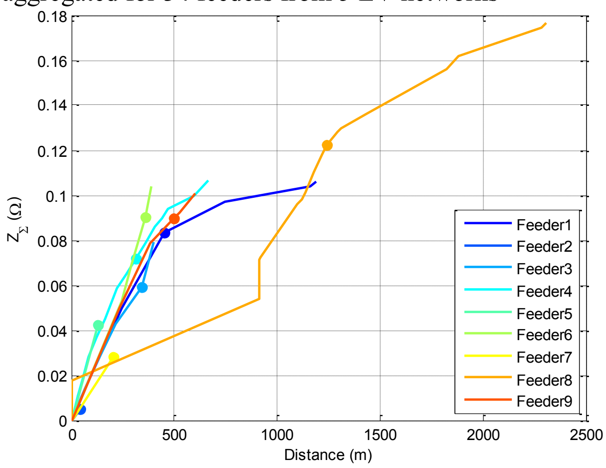

Figure 3. Equivalent sum-impedance and equivalent load location as a function of the distance from the distribution station – Network 1

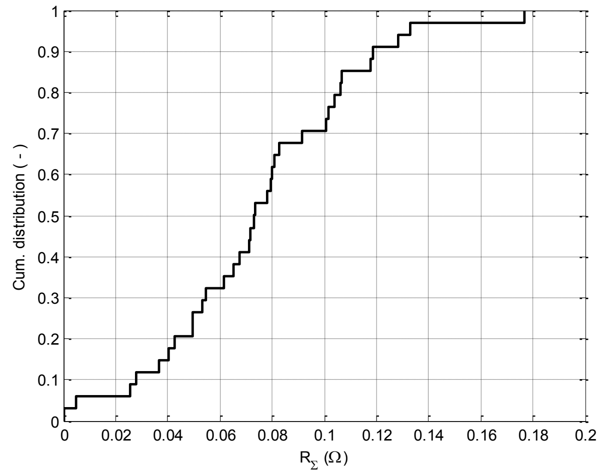

Figure 4. Distribution of the maximal equivalent impedance for 34 feeders from 5 LV networks for default (balanced) load values

Figure 4 shows the cumulated distribution of the equivalent sum-impedance for 5 of the 38 considered networks (34 feeders). It can been seen that the equivalent sum-impedance rarely exceeds 0.12 Ω. The maximal value was obtained for the longest feeder of network 1 as visible on Figure 3.

Finally, Figure 5 shows the aggregated distribution (aggregated over the phases) of the equivalent sum-impedance for a set of 50 Power Snapshots. The left part shows the distribution of the equivalent sum-impedance for two end-nodes of the feeder 1 and the right part the distribution of the equivalent sum-impedance for the end-node of feeder 8. Although these Power Snapshots are rather close to each other (in time), it can be seen that the equivalent sum-impedance changes significantly (for feeder 1). This means that observing the total current at the beginning of the feeder provides only limited information on the actual situation at the end of the feeder. Such analyses allow quantifying the diversity of the network conditions in terms of voltage drop (or rise). In this particular case, the variations of the equivalent sum-impedance during the time would allow estimating the performance of a line drop compensation applied to distribution transformer equipped with On Load Tap Changers.

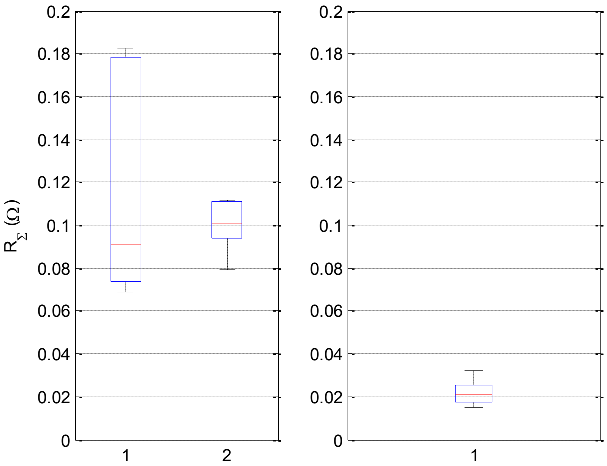

Figure 5. Boxplot representation of the equivalent sum-impedance for two LV feeders from 50 PSS

CONCLUSION AND OUTLOOK

An overview of the characterisation methods that will be used to systematically analyse a set of 300 LV feeders (38 transformer stations) including metering data from more than 6 000 meters in Upper Austria has been briefly presented. Various indicators have been proposed to characterize LV networks. While they have of course some limitations (a LV network cannot be fully captured with only a few numbers), they seem to provide valuable information. Once more data is available, a classification work can be done with suitable statistical tools. The outcome of this work can then be used during the planning process or when assessing the suitability and benefits of specific smart grids solutions. The indicators proposed in this work are mainly useful to capture the actual network situation in terms of voltage profiles, which is the most stringent constraint for the integration of DER (e.g. photovoltaic generation or electric vehicles in rural networks). In the frame of the project, further indicators capturing network loading information have also been proposed.

In parallel to this characterisation work, efforts are currently pursued in order to validate the network models. For this, a comprehensive set of Power Snapshots is necessary. These figures will be updated once all the measurement campaigns are completed and the network models fully validated. The expectations from these results are high: the detailed knowledge shall allow distribution network operators to better design the network, make a better use of existing networks and to evaluate the benefits of specific smart grids solutions. The data set gained from the measurement campaigns shall be used on a wide basis in further projects.

REFERENCES

[1] B. Bletterie, A. Gorsek, A. Abart, M. Heidl, “Understanding the Effects of Unsymmetrical Infeed on the Voltage Rise for the Design of Suitable Voltage Control Algorithms with PV Inverters”, *Proceedings 26th European Photovoltaic Solar Energy Conference and Exhibition, 5-9 September 2011, Hamburg, Germany*, Pages 4469 - 4478, DOI 10.4229/26thEUPVSEC2011-6DO.13.6

[2] K. Schauer, K. Hollaus, M. Hübner, „Smart Grids Projects in Austrian R&D Programmes 2003-2010“, *Austrian Federal Ministry for Transport, Innovation and Technology, Berichte aus Energie- und Umweltforschung* 16/2010

[3] A. Abart, B. Bletterie, M. Stifter, H. Brunner, D. Burnier, A. Lugmaier and A. Schenk, “Power SnapShot Analysis: A new method for analyzing low voltage grids using a smart metering system”, *Proceedings 21st International Conference on Electricity Distribution, 6-9 June 2011, Frankfurt*

[4] A. Abart, M. Stifter, B. Bletterie, H. Brunner, D. Burnier, R. Pointner, A. Schenk, R. Pitz and H. Taus, "Eyes to the grid": new ways to analyze electrical low voltage networks”, *e & i Elektrotechnik und Informationstechnik,* Volume 128, Number 4, 122-127, DOI: 10.1007/s00502-011-0821-y

[5] J. Scheffler, „Bestimmung der maximal zulässigen Netzanschlussleistung photovoltaischer Energieumwandlungsanlagen in Wohnsiedlungsgebieten“, *doctoral thesis, 2002*

[6] G. Kerber, “Statistical Distribution Grid Analysis and Reference Network Generation”, *ew magazine 6th issue 2008*, pages 22-26