# Smart Meter Data as a Basis for Smart Control in Low Voltage Distribution Networks

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***Abstract*—The Shift from consumers to prosumers, who produce energy especially on the low voltage distribution level will challenge the network operation. Voltage levels have to be kept within allowed limits to guarantee power quality and save operation of devices. Voltage control will become a necessity in networks with high share on renewable generation. With smart meters and automatic meter reading systems power quality measurement devices are available in almost every node. The power snap shop analysis is used to measure synchronous condition of voltages and power of the network. Automatic analysis of this huge amount of data can identify network characteristics and critical nodes. This paper shows the automatic evaluation of critical voltage nodes based on power snap shot data, which is the basis for development of efficiently operated low voltage grids.**

## I. INTRODUCTION

Low voltage distribution grids are not designed for hosting a large number of distributed generation (DG). Common grid nodes limit the voltage drop at maximum load at 7% of the nominal voltage. The total available voltage band for deviations at the low voltage level in Europe is typical 10% [1]. Based on worst case assumption like 100% generation and 0% load at the interconnection assessment for generation is done with a safety high factor. But due to the lack of real voltage conditions this limits the number of installable generation.

To ensure the non-discriminating network access and integration of generation without cost-intensive network reinforcement, a profound knowledge of the hosting capacity must be gained. This can be done on basis of smart meter readings and automatic analysis systems.

Due to the nature of renewable generation, a high share of DGs needs an active distribution network: the smart grid. An important electrical parameter is the voltage level in the network. The network operator must ensure that the voltage is within the operational limits.

### A. Voltage control

Various control paradigms for distribution networks have been developed and investigated. Basically they can be classified into voltage control by use of a tap changer (only working locally at the transformer), distributed control (based on voltage measurements of critical nodes) and coordinated control (DGs provide reactive power, centrally coordinated).

*1) Medium Voltage Networks:* Automatic voltage control (AVC) with on-load tap changers (OLTC) is state of the art in medium voltage networks. The secondary voltage is kept to a static set point by changing the number of windings on the primary voltage side, thus changing the tap position. The voltage is controlled locally at the transformer, deviations of the voltages in the grid due to loads or generations are not taken into account. To take the voltage drop or rise in the feeder into account, voltage measurements of critical nodes (CN) can be communicated to a central controller, which can optimise the tap position according the the actual grid condition [2], [3].

Voltage can be influenced by reactive power from a DG according to the impedance ratio or sensitivity of the network node. Sometimes voltage control by reactive power is operated independently, e.g. for DGs on the far end of feeders, where the voltage rise would violate allowed limits. The local controller follows a droop schema for maximum voltage or dependent of the active power [4], [5].

Coordinated control is achieved by the coordinated use reactive power. The contributions can be globally optimised in terms of a minimum or losses. Coordinated voltage control in medium voltage networks (MV) have been developed and studied for various years [6], [7], [8], [9].

*2) Low Voltage Networks:* When it comes to 3 phase / 4 wires LV networks (including neutral line) there are big differences compared to the MV network. Beside the voltage levels, the physical characteristics of the network regarding the length and reactance to resistance ratio (X/R) is lower than in MV networks. Another main difference is the unbalance of the LV network. Unsymmetrical loads or generation can cause a displacement in the neutral point and cause additional voltage drops in the neutral line, or voltage rise on the other, less burdened phases [10]. Figure 1 shows an example feeder of a LV network in one line diagram representation, as a 3 phase / 4 wire model with grounding.

Voltage control concepts rely on voltage measurements, but since the LV system is unbalanced, deviations between the phases make it not trivial to decide on the exact value, since only the mean or the highest can be completely false. Control paradigms for LV networks, based on smart meter readings are presented in [11] and utilizing vehicle-to-grid in [12].

There are different approaches to realise a on-load change capable transformer for LV, like using power electronics (secondary side) or decoupling control. One advantage to use power electronic switches is, that the phases can be changed independently. Also the number of available tap positions is much smaller and the voltage step differs from medium voltage transformers.

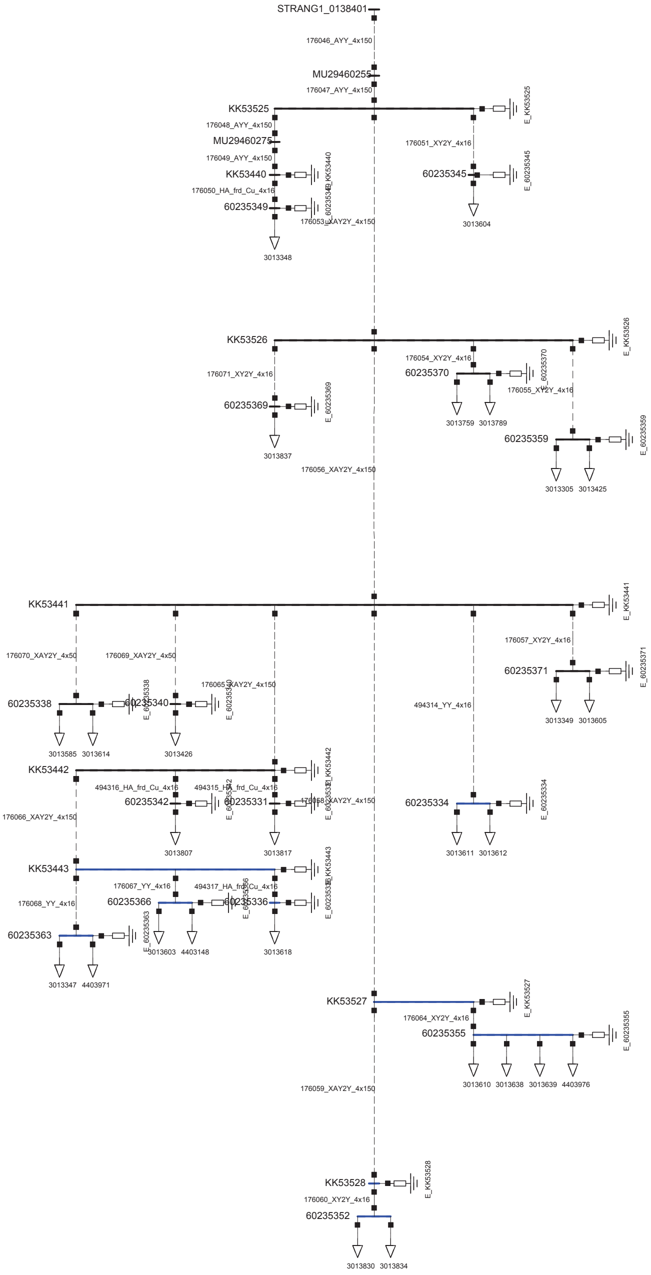


Fig. 1. Exemplary feeder of a low voltage network with grounding.

## B. Voltage measurement

Both measurement and control signals have to be communicated via a communication infrastructure. Since the installation, maintenance and communication access to voltage instrument transformers on the MV level is costly, the number of measurement devices and their position has to be optimized. Once installed they won't be changed unless the grid topology would completely change due to extension or re-reinforcement.

With smart meters and automated meter reading (AMR) systems, calibrated power quality measurement devices are available at every node, capable of delivering the exact voltages, angle, active, reactive power for every phase.

Using power line communication (PLC) for the smart meter system, has important advantages, like it is based on the electric infrastructure belonging to the network operator and has therefore a long tradition in electric utilities. One mayor drawbacks of the PLC solution is the narrow bandwidth of the channel. When a master slave protocol based on polling is implemented, the response time of the system is limited with periodically cycling all meters for updates. Additionally the noise on the line, due to higher frequency emitting consumer devices and appliances, make it often necessary to use the smart meters as routers to hop to the next meter [13], [14].

## II. DEFINITION OF CRITICAL NODES

*1) Static critical nodes:* The selection of a statical critical node subject to a voltage control algorithm, like it is deployed in a medium voltage network [7] is based on the following criteria:

$$\forall t\ \mathbf{U}(t, \mathbf{N}_{Simulation})\ \{t\,|\,0 < t < 1\,year\}$$

$$N_i \in \mathbf{CN}, \exists\, u_i = \begin{cases} \max\{u_1, u_2, \dots, u_n\} \\ \min\{u_1, u_2, \dots, u_n\} \end{cases}$$

$$\forall u_i : u_1^{'} = u_2^{''} = u_3^{'''}$$

Where $\mathbf{N}$ are the nodes with the subset of critical nodes $\mathbf{CN}$ and $\mathbf{U}$ are their voltages.

The voltage range is defined as:

$$u_{Range}(t) = u_{max}(t) - u_{min}(t)$$

*2) Dynamic critical nodes:* Due to the limited communication bandwidth when it comes to query actual voltage measurements of critical nodes from smart meters, the number of CN has to be held low. Therefor the set of critical nodes is dynamically evaluated, based on power snap shots $\mathbf{N}_{PSS}$ at trigger times $t_{trigger}$:

$$\forall t\ \mathbf{U}(t, \mathbf{N}_{PSS})\ \{t\,|t_{trigger}\}$$

$$N_i(t_+) \in \mathbf{CN}(\mathbf{t}_+),$$

$$\exists\, u_i(t) = \begin{cases} \max\left\{u_1^{'}, u_1^{''}, u_1^{'''}, \dots, u_n^{'}, u_n^{''}, u_n^{'''}\right\} \\ \min\left\{u_1^{'}, u_1^{''}, u_1^{'''}, \dots, u_n^{'}, u_n^{''}, u_n^{'''}\right\} \end{cases}$$

$$\forall u_i(t) : u_1^{'} \neq u_2^{''} \neq u_3^{'''}$$

And the voltage range in one phase:

$$u_{Range}^{'}(t) = u_{max}^{'}(t) - u_{min}^{'}(t)$$

With the maximum voltage range over all phases defined as the maximum spread between the highest and lowest voltage of all phases:

$$\hat{u}_{Range}(t) = max(u_i^{'}, u_i^{''}, u_i^{'''}) - min(u_i^{'}, u_i^{''}, u_i^{'''})$$

$$\neq max(u_{Range}^{'}, u_{Range}^{''}, u_{Range}^{'''})$$

## III. Power Snap Shot Analysis

### A. Automated Metering and Information System - AMIS

Communication is based on the AMIS PLC system of Siemens [15]. The communication has to be initiated from the data concentrator (DC) which acts as the master. Transmission on the physical layer of AMIS PLC is based on fast frequency hopping spread spectrum technology in CENELEC A-Band between 3 and 95 kHz. The coded bit stream is segmented into blocks and interleaved before transmitted. The influence of the electrical network on the power line communication may lead to packet losses. Therefore, not directly accessible devices are reachable by retransmissions or so called hop layers. Two main characteristics can statistically describe the communication channel: the loss probability and the Gaussian distributed delay time [16].

Smart meters can be equipped with internal registers for storing measurement values. If 10 minutes power quality values are classified depending on e.g. the voltage level, various statistical parameters can be evaluated. The possibilities of investigating impacts of load unbalance by statistical analysis of voltage levels by smart metering is discussed in [1].

### B. System configuration

While MV networks are good known in terms of operation, there are still many unknown parameters when it comes to low voltage networks, like the influence of the grounding impedance on the neutral displacement. Especially as mentioned before, the impact of distributed generation regarding interconnection assessment is based on worst case assumptions. As a first step for more appropriate analysis, the power snap shot analysis (PSSA) by smart meters has been developed and implemented as described in [17] and [18].

The basic idea is to have a synchronous snapshot of measurements of all power and voltages in the network for validating the corresponding network models. Then environmental influences or other physical parameters can be examined. Snapshots are triggered by highest or lowest value of a characteristic (like voltage, current or unbalance) which occur during the snap shot measurement interval of 900 seconds. In 'campaign' mode snapshots for several intra-day intervals are taken to gain a good coverage over work and non-workdays, where the 'time series' mode is capable of continuous measurements series, typically 60 seconds, without the need for trigger criteria.

This power snap shot campaigns and time series generate a huge number of data, which is automatically imported to a database. The validation with the network model is done by comparing the results of the simulated voltages with the measured voltages. Measured active and reactive power are taken as the input to the simulation and the voltages are the results. In [19] the simulation environment for studying low voltage networks has been presented. The measurement data is assigned to the loads of the detail model of the network. A power flow is conducted in the power system simulation software PowerFactory and the voltage results are then compared with the measurement data of the voltages. A parameter variation of various factors (e.g., grounding impedances) minimizes the model error until the model is valid and approximates the measurements. The data acquired by power snap shots can also be used together with the electrical properties of the network to characterise LV networks, like determine the equivalent sum-impedance ([20]).

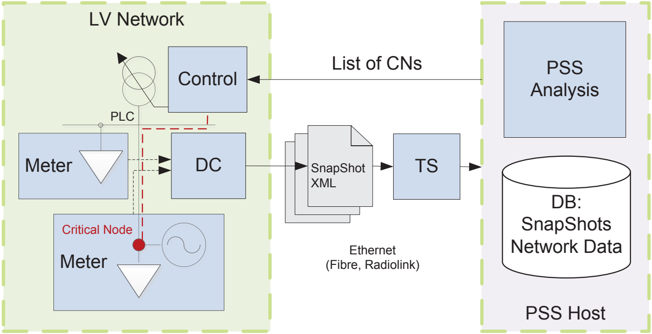


Fig. 2. Overview of identifying critical nodes with the Power Snap Shot Analysis (PSSA) for voltage control. Measurements are sent via the data concentrator (DC) and the transaction server (TS) to the analysis environment, where the critical nodes are identified and communicated back to the controller.

Figure 2 shows the schematic setting of the power snap shot analysis (PSSA) and the controller for low voltage on-load tap changers and distributed generation. The more snap shots of a measurement interval is requested from the participating meters, the longer it takes the data concentrator (DC) to query and receive the data via the PLC communication channel. When all meter data are received, the snap shot file is transmitted to the PSSHost via the transaction server (TS), where the snapshot data is imported to the database. After the evaluation of the received snapshot, the list of critical nodes can be sent to the controller where this limited list of critical nodes are queried, thus saving bandwidth and increasing cycle time when polling only these meters. The total round time for the identification may be between 30 and 60 minutes.

Example of power snap shot series of 60 seconds (= 60 PSS) for the feeder depicted in Figure 1 is given in Figure 3, where the frequency of the minimum, mean and maximum voltage per phase is shown. The maximum range over all phases is the spread between the highest and lowest voltage for every time step. The corresponding active and reactive powers per phase and summed up is shown in Figure 4.

## IV. RESULTS

Figure 5(a) shows the number of minimum voltage occurrences per meter over the interval of 60 seconds (= 60 PSS) on the 13.11.2012 from 8:00:00 to 8:00:59. Compared to the interval of 900 seconds (= 900 PSS) on the 19.10.2012 from 9:00:00 to 9:14:59 in Figure 5(b) the difference is clearly visible. Not only the meters with the highest number of minimum voltage occurrences are different – one would expect the meters at the far end of the feeders to have always the lowest voltages (e.g. 3013638 or 3013639) – also a share of minimum voltages occur midway in the feeder (e.g. 3013614) or at another branch of the feeder (e.g. 3013347)

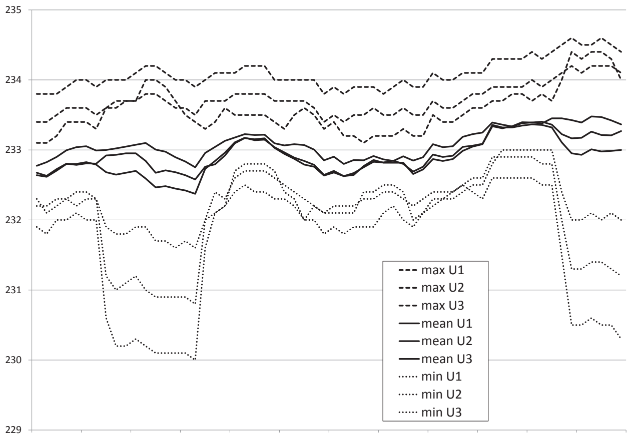


Fig. 3. Minimum, mean and maximum voltages per phase for the example interval.

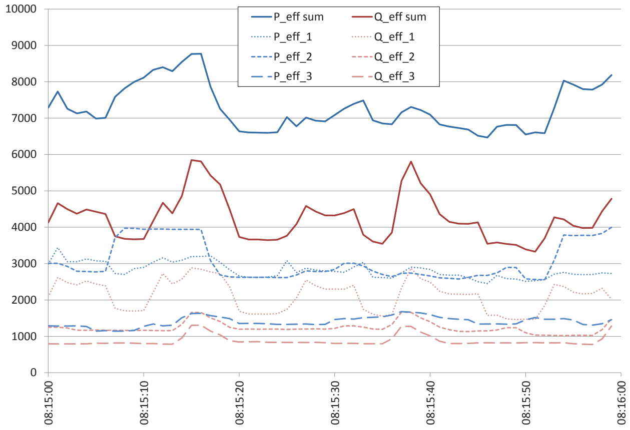
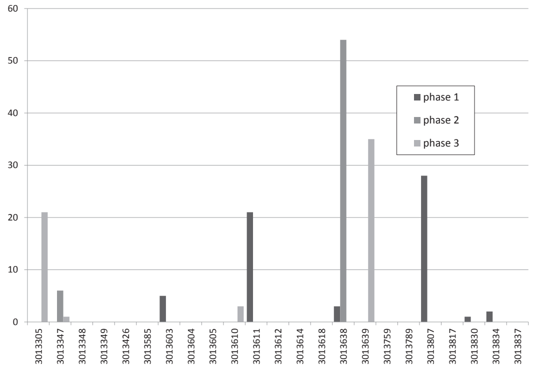


Fig. 4. Corresponding active power ($P_{eff}$) and reactive power ($Q_{eff}$) per phase and sum for the example interval.

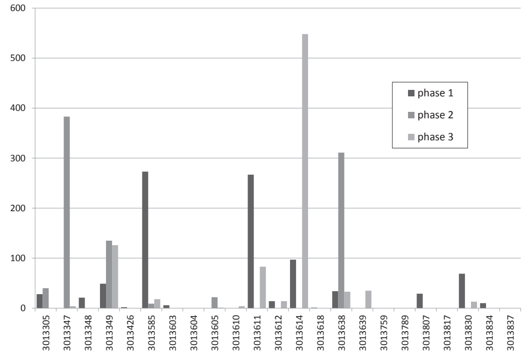
As one could expect the nodes with the highest voltages at the begin of the feeder (e.g. 3013604) like in Figure 6(a), the second interval in Figure 6(b) shows also significant high occurrences of maximum voltages in nodes in the middle of the feeder (e.g. 3013614). This is due to the unbalanced phases and the displacement of the neutral point, which can increase phases, while others are decreased. If a voltage rise in a single phase takes place due to distributed generation (e.g. photovoltaic), the voltage in outer phases would decrease (this is not the case in this example.)

## V. CONCLUSION

Smart meters can provide information about the necessary grid conditions, like voltages for voltage controllers in low voltage networks. Due to limited bandwidth in PLC based smart meter networks, the number of critical nodes, where the voltages might be violated is too large to access in a timely manner. Static evaluation may be error-prone because of the ever changing load and generation situation and impact on the voltage range per phase or maximum voltage range in the grid.

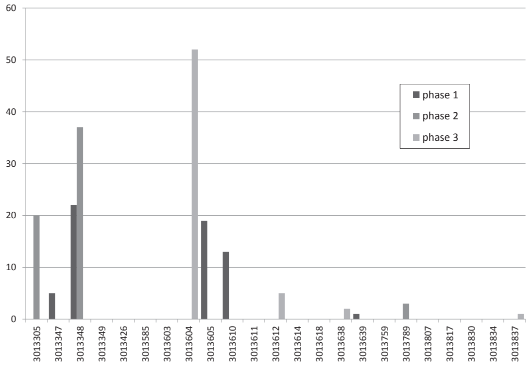


(a) 60 power snap shots interval

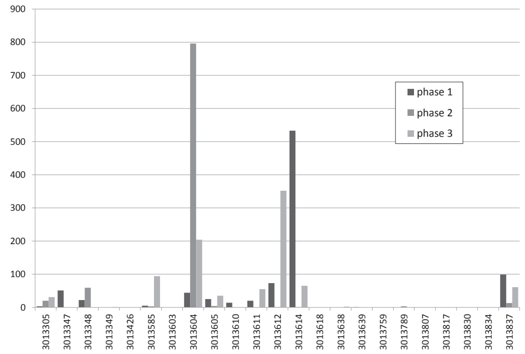


(b) 900 power snap shots interval

Fig. 5. Number of minimum voltages per meter



(a) 60 power snap shots interval



(b) 900 power snap shots interval

Fig. 6. Number of maximum voltages per meter.

The power snap shot analysis is an adequate instrument for monitoring and for determine the voltage situations in the grid. This can be done without time critical constraints, but still fast enough to cover or detect new voltage situations.

Smart control in low voltage networks can be based on that measurement analysis, like changing the set point of local controls to balance phases (e.g. 3 phase inverters) during operation or during planning of the connected phase of single phase inverters. Results of balance situation can also server as a decision support for rotating phases on whole branches of feeders.

Results have shown, that the analysis of dynamic change of critical nodes and unbalance in respect to day or seasonal situation is necessary for identifying critical nodes. Future work will include the evaluation of the impact of using dynamical critical nodes for smart low voltage control applications.

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