MEASUREMENT CONCEPT FOR EFFICIENT PLANNING OF DISTRIBUTION GRIDS

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ABSTRACT

This paper presents a measurement concept that is designed to provide or validate input parameters for network planning guidelines in the distribution grid, mainly low voltage level. Therefore, we conceived a hardware setup to measure completely the low voltage distribution of a transformer station and partly within the subordinated grid. It consists of three types of measurement devices, namely power quality analyzers, four-phase power meters, and smart domestic supply meters. A substantial part of the concept is an integrated data architecture that also collects existing company data about the physical distribution network and its customers. This will be used for a statistical analysis of effective usage of the network equipment. A comprehensive set of questions has been identified. The hardware rollout and software integration is in progress. First results and experiences are shown on a qualitative basis.

MOTIVATION

Distribution networks operate with the same equipment for many decades. Thus, investment decisions have a long-term effect on capital and operational expenditure. Furthermore, network planning relies on guidelines, which are based on several assumptions regarding network usage.

However, distribution networks are facing a historic change of technology in their design, components and operation. This change is caused by an increasing integration of intermittent renewable generation, but also due to an increase in electric consumer devices requiring an AC/DC conversion, such as smartphones, computers, etc. Furthermore, the number of mobile loads, such as electric vehicles, continues to rise. In the past, the end customer received incentives to install electric boilers or heaters by the utilities. Nowadays, most national governments subsidize the installation of photovoltaic units. In the future, the same might happen with charging boxes for electric vehicles – and purely electric boilers might be forbidden by regional or local legislation.

Medium voltage (MV) and low voltage (LV) levels are mostly affected by recent political incentives; however, the last permanent measurements are available at the MV feeders of the substations (network level 4). Thus, with the current measurement design, the actual state of the MV and LV network (network level 5 to 7) remains unknown. This causes uncertainty both in planning and operation of the grid. On the other hand, the requirements on an efficient quantity and location of measurement points are yet unclear. In this context, the knowledge of the actual situation in distribution networks is considered essential to update grid planning guidelines in order to ensure an efficient allocation of investment budget.

Smart technologies, such as smart meters and other smart grid components, are part of most national energy strategies [1]. Their use has been studied to decrease the cost of maintaining, renewing and adapting the energy infrastructure significantly [2]. However, the optimum extent to which smart components are required needs to be evaluated from both a technical and an economic point of view.

In this paper, we present a measurement concept in order to obtain a detailed energy balance and load profiles in a selected area of a distribution grid. In a following step, the minimum required measurement points and rates at a minimum cost level can be identified.

In general, the total energy E_S within a section S is the integral of all power P_n measured within in the section.

$$E_\mathrm{S}(t) = \int_{\mathrm{t_0}'}^{\mathrm{t}'} P_\mathrm{n}\,dt. \qquad \text{[Eq. 1]}$$

In this project we study the minimum setup by comparing the power measured on network level 4 with the power measured on network level 7 with

$$P_\mathrm{l4,measured} = P_\mathrm{l7,measured} + P_\mathrm{loss,calculated}, \qquad \text{[Eq. 2]}$$

where P_l is the power measured on network level 4, and on network level 7, respectively, and P_loss is the loss power calculated from the difference.

We also assess the actual voltage band usage in the medium and low voltage network. Power quality (PQ) is measured at network level 6 (medium/low voltage transformation) and partly inside network level 7. By this, the variance and distribution of PQ issues can be analyzed and identified along the whole LV network. Again, besides a better understanding of the current grid operation conditions, a key question is the best location, number and minimum required accuracy of measurements for a rollout of such measurements.

CONCEPT

BKW as the distribution system operator (DSO) of the Swiss cantons of Berne and Jura initiated a project to equip about 100 transformer stations (MV/LV level) with permanent measurement devices on the LV side. The transformer stations (TS) have been picked out of a representative contiguous area to be able to draw conclusions also on MV level. Five MV feeders connected to two different substations supply this area. In four selected LV networks, the cable distribution cabinets (DC) are equipped with the same type of measurement devices, and about 700 smart meters are deployed in the houses as shown in Figure 1.

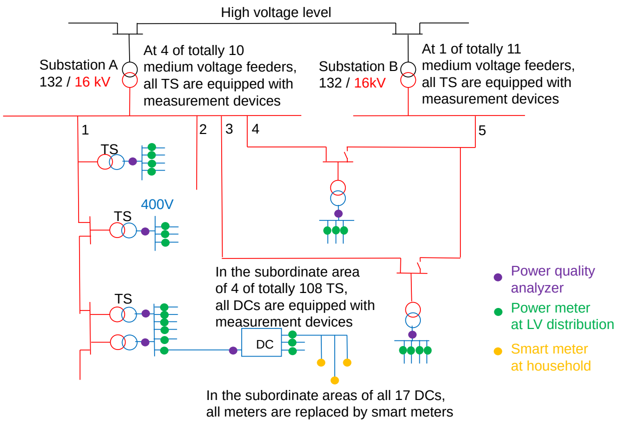

Figure 1: Measurement setup

Measurement setup in the low voltage grid

The measurement hardware for TS and DC was selected specifically for this task/project, which grants a certain flexibility. There are no additional requirements like the billing process for household customers in the case of smart meters. From an organizational point of view, these devices belong entirely to the responsibility of network operation. Therefore, the choice and composition of hardware could be adapted to the objective of analyzing the actual power flow situation in the network. The concept is designed for the LV distribution of a TS, but is applied in the same way to a DC.

The employed components are all commercially available and were combined with a reasonable degree of standardization. The outcome is designed to serve the network planning process, i.e. the focus lies on statistical analysis of historical data. Real-time monitoring in order to initiate corrective measures is not required. However, the system itself monitors the status of the devices and the communication channel.

Concerning the accuracy of the measurement devices, the following aspects were considered. In order to be able to answer one of the key questions of this project, namely what is the required accuracy to be able to draw reasonable conclusions, rather high-end equipment is necessary. Consequently, a PQ analyzer of Class A according to IEC 61000-4-30 is selected for the LV bus bar voltage [3]. It measures as well the feeding line between transformer and LV distribution. On the one hand, this IEC standard defines the quality of the measurement device. On the other hand, this assures that PQ results are comparable with temporary PQ measurements at different places.

Outgoing lines can be measured with less accuracy. Instead of that, it is more important to design a flexible and scalable setup because the number of outgoing lines per station varies between one and 20 with median seven. Therefore, a modular system was chosen. It is comprised of a programmable logic controller to which the necessary number of power measurement modules is directly connected. Furthermore, this terminal station contains a mobile radio module for data communication, acting as a gateway for the PQ analyzer. Figure 2 shows one measuring cabinet equipped for three outgoing lines installed next to a pole-mounted TS.

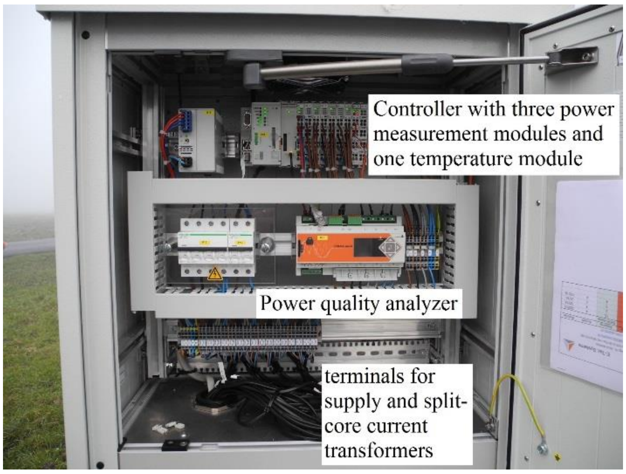

Figure 2: Measurement devices in housing for pole mounted TS

The measurement data are sent via the mobile radio network to a server at the head office that hosts the backend software of the PQ analyzer. It is used for parametrisation of the devices and evaluation of the results. Besides the existing recorders for disturbances, PQ events and root mean square (rms) values, the software developer defined a new data class for the rms values originating from the third-party power measurement modules. With this approach, all data are gathered in the same database. An exploratory analysis or fundamental evaluation of only TS and DC measurements can be done with this proprietary software. However, for a systematic statistical examination and a comparison with smart meter data, the content of the proprietary database is exported in flat format to be loaded to a dedicated platform. This is described in the data architecture section of this chapter. The hardware rollout as well as the software and database integration is ongoing.

Measurement setup at low voltage connections

Current electricity meters, such as the Landis+Gyr E450, include the possibility to measure a subset of EN50160 PQ values and load profile down to one-minute intervals. Thus, smart meters are a low cost possibility to measure energy and power profiles of the distribution grid. For the latter, an optimal recording interval has been chosen based on comparable measurement data from a previous project [4]. The raw data with one-second resolution has been aggregated to one, five and ten minutes. The deviation from the exact values for voltage and current for the three phases is shown in Figure 3.

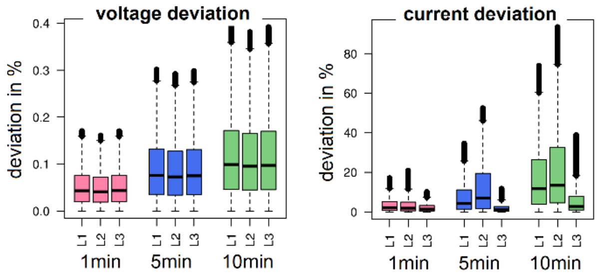

Figure 3: Comparison of different aggregation intervals

The average deviation for voltage is below 0.1% for one-minute and five-minute aggregation. In case of current, the result is less clear due to poor accuracy for very low currents (noise). Considering that the amount of data to be transmitted affects the operation costs, the choice was made for a five-minute interval. Furthermore, this eases the comparison with both the 15-minute pace of standard load profiles and the ten-minute pace of PQ recordings. Data are treated separately from billing data. The measurement accuracy under standard operation is class B (according to EU measurement instruments directive) with an accuracy of ±3.5 % and a measuring range from 0.250..120.000 A. Data are transmitted via Power Line and mobile communication. Within the project, all meters in the area of four TS will be replaced by smart meters, including meters for households, public lighting, and industrial or energy production applications. This complete rollout for a closed section of the grid allows to compare the values measured at the TS and from the meters. This enables the identification of the minimum number of measurement parameters and rates for future projects.

Data architecture

In order to integrate the data for further analysis, a platform is developed where all the data elements are stored using CIM as standard format, as shown in Figure 4. The latest network topology and customer information data will be updated weekly and loaded into a Hadoop Distributed File System (HDFS).

On the other hand, the measurement data collected by the PQ analyzers and smart meters will be stored using two different processes, through a SQL-export and an ESB-interface respectively. Then these four data inputs will be combined using a CIM-reader function integrated in Spark. The aim of this platform is a robust and standardized database that allows further advanced data analytics.

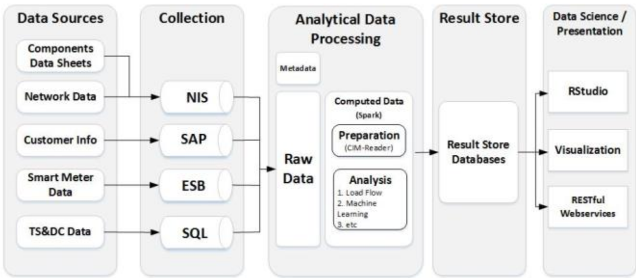

Figure 4: Data architecture and process flow

This cloud-based solution enables the development of advanced algorithms directly integrated on the different nodes (parallelization capability) and also the opportunity to use external tools as RStudio, where data scientists are enabled to implement exploratory analysis on the data in order to identify new questions or ideas that allow a more efficient planning of the distribution network.

RESULTS

As the hardware rollout as well as the software integration is still ongoing, this chapter focusses on qualitative aspects, i.e. on the way that results are obtained.

Power quality in the low voltage grid

Having PQ analyzers permanently installed at several TS allows analyzing both local and temporal aspects. Figure 5 shows the relative magnitude of the 2nd to the 25th voltage harmonic for 20 exemplary TS over a period of four weeks at the end of the year 2016.

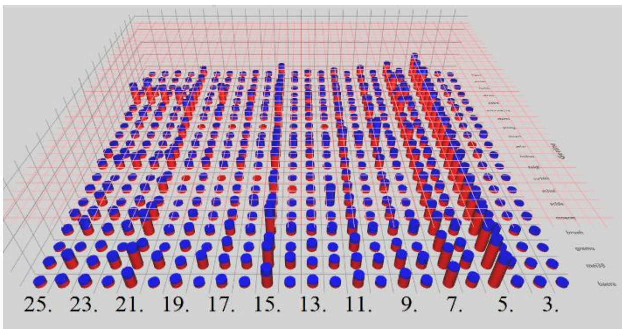

Figure 5: Voltage harmonics for 20 TS

The red part of the columns represents the 95% quantile. The EN50160 limit, indicated by the red ceiling grid, is not violated at any time. On the one hand, it shows a common and not surprising pattern of higher levels for the 5th, 7th, and 15th harmonic. On the other hand, the differences between the TS are visible. A more detailed investigation can be carried out taking into account the main customer types at each station.

The same kind of examination, only for one TS, but grouped by calendar week over a period of the last seven weeks of 2016 is shown in Figure 6.

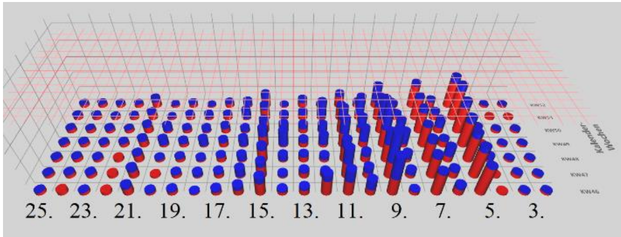

Figure 6: Voltage harmonics for one selected TS by calendar week

The particularity of this station is a higher level of the 9th harmonic especially during a very short time period. There, the blue part of the column representing the values above the 95% quantile is rather important. A photovoltaic plant is connected to this TS whose installed capacity of 80 kVA is more than half of the maximum loading of the transformer.

For this selected TS, the currents per feeder are further investigated. Due to the increasing number of appliances with single-phase rectifiers, it is of interest to compare the neutral currents of the different feeders. The neutral currents are normalized by dividing their measured value by the average of the three phase conductor currents. In Figure 7, they are displayed as a scatterplot depending on the corresponding active power flow, where positive sign describes the direction from the transformer to the customer.

It can be seen that in case of a higher power flow, the relative neutral current is smaller which indicates a more symmetrical loading. This is particularly visible in case of the PV unit, which is, due to its size, connected via three-phase inverters. The accumulation of spots around 1.0 for few kilowatts of active power in the household plot indicates the single-phase appliances. Furthermore, as the transformer current is measured with the higher accuracy of the PQ analyzer while the outgoing feeders are measured with a less accurate power meter, further investigations should follow which accuracy and measurement range is required and economically justifiable for different measurement tasks. This reflects the needs and strategy of a network operator as current measurement is not a compulsory part of PQ standards.

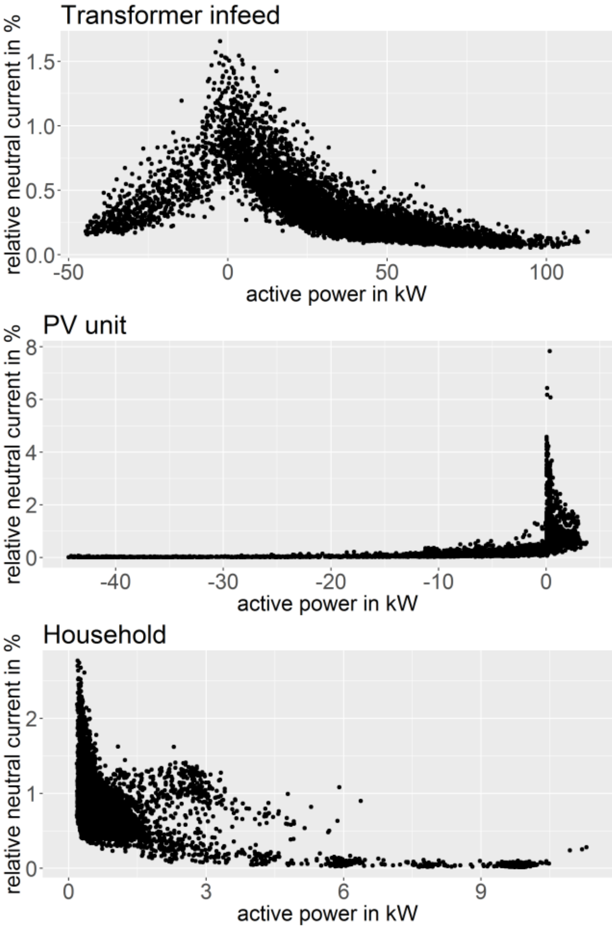

Figure 7: Relative neutral current depending on active power

Load profiles at end consumer level

The current standard load profiles available in Switzerland have not been adapted yet to today's consumption devices. Foreign load profiles are not representative for Switzerland, for example due to the use of electric boiling systems. Thus, in order to enable efficient planning and operation of the Swiss grid, updated load profiles are necessary. The first profiles have been received anonymously. Statistical analysis will include this update. These profiles together with the information on voltage band usage are a main input parameter for the network planning guidelines.

Data analysis

In order to get a better understanding of our distribution network, 80 key questions and 60 facultative questions have been identified. The questions have been arranged by thematic area as shown in Figure 8.

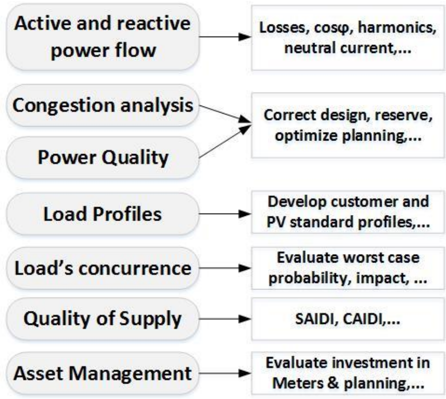

Figure 8: Seven thematic areas with exemplary questions

On the other hand, the required algorithms (i.e. load flow) for each question have been identified. These algorithms will generate new data that will be used by the data scientist to implement inference or prediction analysis in order to answer the questions.

As an example, one of the first questions that has been answered is the percentage of energy losses on the distribution network. For this purpose, a load flow algorithm (LF-A) has been implemented using the measured current on each smart meter and the voltage on each transformer. The LF-A will generate the current on each cable and transformer, then the energy losses E_{losses} on each component x will be calculated using the following equation:

$$E_{\text{losses.x}}(t) = \int_{\text{to}}^{\text{t1}} R_{\text{x}} * I_{\text{x}}^2(t), \qquad \text{[Eq. 3]}$$

where R_x represents the resistance for each component and I_x the current that flows through each component at a given time.
Then the results can be visualized directly via the Network Information System (NIS), as shown in Figure 9. These results would allow the network planners to know which components increase the amount of losses and plan new corrections or actions for a more efficient network.

Figure 9: Visualization of the energy losses

CONCLUSIONS AND OUTLOOK

This project is designed to quantify the benefit of measurements at different levels of the distribution grid. Particular interest is given to the question if power flow measurements from smart meters could be an economic solution to the enhanced demand of information or whether additional instruments or other measurement approaches will be necessary. Therefore, much effort was spent on an integrated architecture to combine existing and newly collected data on the same platform.

The rollout of the measurement devices and smart meters has started as scheduled. As it is a matter of retrofit, the main challenges are of mechanical nature to place the additional equipment in the existing TS and DC. After completion of the rollout in the second quarter of 2017, a two-year measurement campaign until middle of 2019 will follow. This increases the comparability and robustness of the evidences.

First results from different types of measurement devices are presented in a qualitative manner. A comprehensive list of questions has been prepared that will help the DSO to define new guidelines for a more efficient planning of future distribution grids.

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