Flexible smart metering for multiple energy vectors with active prosumers

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1. Executive summary

1.1. General

FLEXMETER project has the aim to develop and to install a flexible smart metering architecture for multiple energy vectors. An important step of the project is to integrate smart meters in the MV/LV substation, in order to perform algorithms enabling an energy balance in the subtended network, load non-intrusive monitoring (NILM), LV alarms testing in case of faults and outages or feeders’ overload.

1.2. Deliverable structure

Deliverable 3.1 has the objective to carry out an overview of the main objectives reached by the integration of the smart meters in the MV/LV substation.

The document is structured in 4 Chapters:

- Chapter 1 introduces the objective of the FLEXMETER project and the structure of the document.
- Chapter 2 and 3 will make an overview of the smart meter integration in the MV/LV substations in terms of smart meters characteristics, of the goals reached throughout their installation and of the application of NIALM technology, for the Italian pilot.
- Chapter 4 makes an overview of the meter data aggregation.
- Chapter 5 reports the different use cases about the installation of smart meters in the MV/LV substation.
- Chapter 6 reports the references of the document.

At the moment the project is at an early stage in which the meters, mainly in the Italian test site, have not yet been installed, so this document will be updated with the results achieved downstream installation of the meters or a new document will be drawn up which containing these results.

2. Smart meter integration in the MV/LV substations in Turin

2.1. Smart meters characteristics

2.1.1. Criteria for choosing the base technology for the smart meter

Based on D.1.1, that is giving the specification on the distribution network, it was decided to base the Smart Meters at substation level on the ST Comet technology. ST will provide the Comet evaluation board on which to build around the smart meter that will be used for the project. ST will provide, nevertheless, a firmware instance of communication while ST and POLITO will contribute to customize the provided firmware to match the technical specifications stated on deliverable D1.1. Further it is described the enabling technology offered by ST to the project, in order the achieve all the above specifications.
2.1.2. Smart meters overview

Starting from EVLKSTCOMET10-1, an evaluation board of STCOMET, which is actually a smart meter, ST will give schematics, project, Gerber files, and all is needed for the design of the final board of the Smart Meter. The STCOMET platform development environment is a set of SW, HW and FW tools and associated documentation available from ST or third parties, conceived to ease the evaluation and development flow of an STCOMET based smart meter design. The EVLKSTCOMET10-1, shown in Figure 2.1, is a development kit for the STCOMET platform, exploiting the performance capability of the full-feature STCOMET10 device. The STCOMET10 is a single device integrating a flexible power line communication (PLC) modem with a fully embedded analog front end (AFE) and a line driver, a high performance 3-channel metrology function and a Cortex ™-M4 application core.

From the functional point of view, the STCOMET development kit (EVLKSTCOMET10-1) is composed by a main board implementing a complete smart meter with power line communication (PLC) and metrology functionality and a separate power supply board based on the VIPER26H AC-DC converter. With a complete access to the STCOMET GPIOs and peripherals and the on-board SEGGER® J-Link® probe it is specifically designed to facilitate HW/SW development. In Figure 2.2 is shown the STCOMET development kit.
2.1.3. STCOMET smart meter and power line communication system-on-chip description

The STCOMET is a device that integrates a narrow-band power line communication (NB-PLC) modem, a high-performance application core and metrology functions. The metrology sub-system is suitable for the EN 50470-1, EN 50470-3, IEC 62053-21, IEC 62053-22 and IEC 23 compliant class 1, class 0.5 and class0.2 AC metering applications. With its multi core fully programmable architecture, the STCOMET platform can support a range of PLC standard protocols. The PLC line coupling interface is designed to allow the STCOMET device to transmit and receive on the AC mains line using any narrow-band PLC modulation (single carrier or OFDM) up to 500 kHz, mainly for automatic meter reading (AMR) applications. The default configuration of the PLC line coupling targets the G3-PLC (ITU G.9903) and PRIME (ITU G.9904) CENELEC A-band protocol standards., The STCOMET development kit can be also adjusted to fit other narrow-band PLC protocols in CENELEC A-band or FCC band (e. g.: S-FSK IEC61334-5-1, IEEE 1901.2, G3-PLC FCC, METERS AND MORE®). If necessary, a specific customer’s module can be designed and placed instead of the LCD module, for a different peripherals configuration. In Figure 2.3 is shown the STCOMET block diagram.
2.1.4. Safety recommendations

The STCOMET development kit must be used by expert technicians only. Due to the high voltage (85 - 265 V ac) present on the non-isolated parts, special care must be taken in order to avoid electric risks for people safety. There are no protections against high voltage accidental human contact. After disconnection of the board from the mains all the live part must not be touched immediately because of the energized capacitors. It is mandatory to use a mains insulation transformer to perform any tests on the high voltage sections, using test instruments like, for instance, spectrum analyzers or oscilloscopes.

One should not connect any probe to high voltage sections if the board is not isolated from the mains supply, in order to avoid damaging instruments and demonstration tools.

When configured for metering evaluation, the STCOMET development kit is not isolated and ground will be tied to the line. On should not connect instrument probes that can bring the earth connection to the line, thus potentially damaging the STCOMET development kit and the instruments and creating electrical risk.

2.1.5. Three-phase metrology evaluation

The STCOMET development kit provides an SPI/UART interface (J2 connector) and general purpose signals (J3 connector) on the LCD module (Figure 2.5) to connect STPMxx metrology boards in order to build a three-phase meter development kit. Figure 2.4 reports the J2 and J3 pinout plus the configuration jumpers to select between the UART and SPI connection to the external STPMxx board. Table 1 describes the jumper configuration to select SPI or UART configuration.
Figure 2.4: Three-phase metrology evaluation - digital connections to STPMxx evaluation boards

Table 1: Three-phase metrology evaluation - SPI/UART configuration

<table>
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<th>UART configuration</th>
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<tr>
<td>J15</td>
<td>Close</td>
<td>Open</td>
</tr>
<tr>
<td>J35</td>
<td>Open</td>
<td>Close</td>
</tr>
<tr>
<td>J36</td>
<td>Close</td>
<td>Open</td>
</tr>
<tr>
<td>R50</td>
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Figure 2.5: LCD module drawing with indication of the various sections
2.2. Objectives of the integration of the smart meter in the MV/LV substation

Throughout the integration of the smart meters in the MV/LV substation, chosen for the project, it is possible to reach the following goals:

- disaggregate transformer load in order to carry out the load balancing of the network;
- analyze the abnormal energy flows in order to detect energy thefts almost in real time;
- detect and locate faults and outages in the LV network, throughout appropriate alarms;
- analyze the possible losses in the grid;
- supply information about the monitored substations and the power quality;
- monitor in quasi-real time and more optimally the system.

2.3. Application of NILM technology

The project requires the installation of measurement equipment on each LV derivation, namely upstream of all LV costumers supplied by the derivation.

Through the analysis of data gathered the objective is developing algorithms able to:

- disaggregate transformer load;
- automatically detect and locate faults and outages in the low voltage distribution grid;
- provide information about the monitored substations and power quality.

Algorithms will be developed on a Matlab simulator, once the algorithms will be sufficiently reliable they will be converted into an on-line tool.

Referring to the disaggregate transformer load, load disaggregation will be obtained applying NILM-based (Non-Intrusive Load Monitoring) signal processing techniques at the data gathered by power meter installed on the LV derivation of the MV/LV transformer. Nowadays NILM is widely studied at household level: it allows the energy disaggregation and the loads recognition through the analysis of the aggregate power consumption measured in a single point. The load recognition is possible thanks to load signature which is defined as the electrical behavior of an individual appliance/piece of equipment when it is in operation. Similar to any human’s signature, each electrical device contains unique features in its consumption behavior.

For the purpose of the Flexmeter project the extension of these techniques to higher levels in the distribution grid becomes necessary.

Energy disaggregation allows, for each transformer derivation, to breakdown the loads among each type of consumers. By knowing the percentage respect to the total it is possible to identify, for each type of load, the daily, seasonal and yearly consumption trends. The knowledge of load trends allows to make further considerations about the substation capability to meet demand and planning corrective actions in order to upgrade components to ensure systems long-term ability to meet demand (e.g. if in a certain substation the demand is becoming greater than the transformer capacity, it is possible to take corrective action before fault happen). It is also possible to correlate load trends with environment variables (at least temperature) to forecast the variation of loads behavior in case of external changing. Load disaggregation
also allows to highlight the portion of demand manageable load and the effect of demand side management on power system performance.

From Figure 2.6 you can notice that each final costumer owns a certain quantity of individual load type, i.e. the individual device. As the number of individual load types far exceeds the reasonable level which can be considered for the application of NILM, it is not practical disaggregating the consumption among all the individual load types installed at the consumer level, consequently we decided to subdivide them in a small number of load categories.

A load category is defined as a group of electrical devices which may have different end-uses but, for our purpose, devices belonging at the same load category have the same, or similar, electrical characteristics [1]. At the moment, for the purpose of the study it was decided to consider the load categories showed in Figure 2.7.

![Figure 2.6: organizing individual load types into load categories](image)

![Figure 2.7: main Load Categories [1]](image)

Electrical loads in all sectors of electricity consumers (industrial, commercial, and residential) are typically a mix of linear (e.g. resistive heaters, directly connected motors, incandescent lamp) and non-linear loads
(e.g. adjustable speed drives, power electronics, compact fluorescent lamps). The latter are all sources of current harmonics hence we will consider a combination of the time domain signatures normally used for domestic NILM with frequency domain feature.

The load harmonic spectrum could be obtained by applying Fourier Transform at the measurements of current. This information constitutes a signature useful to identify load composition. In order to identify the harmonic spectrum it is necessary to also use the sampling frequency for current and voltage to several kHz. A minimal quality of the measurement set-up, including the reporting rate, is mandatory in order to have meaningful results. Flexmeter will ensure this by using the proposed smart metering platform

Harmonic containment is used for NILM also in context more complicated i.e. industrial buildings. In [2] is stated that the harmonic distortions provide a tremendously improvement in recognition capacity.

However, it is necessary verifying the feasibility of extending this approach also at the secondary substation level. In fact literature review allows highlighting some issues related to the properties of harmonics when a lot of non-linear load are working at the same time. These properties could make difficult to go back to the actual load composition (in terms of load categories) by the only means of harmonic measurement at the beginning of LV feeder. These issues are summarized below:

1. The harmonic current produced by aggregate non-linear loads is usually significantly smaller than the arithmetical sum of the harmonic currents produced by the individual non-linear load, mainly due to phase cancellation. Consequently information about the operation of certain loads could be lost due to the harmonic cancellation.
2. The number and power rating of devices connected to the feeder are important parameters which have an impact on the harmonic composition of aggregate load, but these parameters could not be easily available.
3. Under polluted voltage condition, prochanges in the device current spectrum may happen.

Finally, considering the above mentioned points, in order to utilize the information contained in current harmonics as load signature for the load identification, it is necessary, for each load category, to determine the shape of the current spectrum at the MV/LV transformer level.

It is necessary to investigate the possibility of overcoming the above mentioned issues, in order to realize a reliable load signature for each load category. Starting from the harmonic behavior of single devices, a study on the modified current harmonic content when multiple devices, belonging to different load categories, are operating simultaneously becomes necessary.

3. Smart meter integration in the MV/LV substations in Malmö

3.1. Smart meters characteristics

The electricity grid of the pilot area in Hyllie today essentially consist of two 10 kV radials with interconnection possibilities, see figure below.
Substation nr 4 and 10 is used for the Flexmeter project with a total of approx. 350 metering points connected to these two substations. It is residential customers and small commercial customers.

In the substation nr 4 and 10 there is installed Echelon CT meter that measure the energy data in the LV network. These meters will register measurement data every 10-20 seconds and sends the data to the Flexmeter MDM database communicating via GPRS.

The quantities that are provided by the Echelon CT meter include meter energy (summation of phases, totals, or per individual tariff), instantaneous RMS values such as voltage and current, and pulse inputs. All values are updated within the meter once per second for usage such as viewing, data logging, or communications.

The measured electrical values are:

- Active power (kW), summation: forward, reverse;
- Active energy (kWh), summation: forward, reverse, forward + reverse, forward – reverse Note: “forward – reverse” is limited to zero at the bottom of the range, negative values are not accumulated;
- Reactive power (kvar), summation: import, export;
- Reactive energy (kvarh), summation: import, export;
- RMS voltage, per phase;
- RMS current, per phase;
- Power factor, per phase;
- Frequency;
- Sine of phase angle, per phase;
- Pulse counts from pulse output devices;
- Apparent power (VA), summation.

Due to the limitation in the communication module that sends the data to the E.ON Flexmeter MDM system the resolution will be values every 10-20 seconds in the MDM database.
3.2. Objectives of the integration of the smart meter in the MV/LV substation

The objectives of installing a smart meter in the substation are the following:

- Measure the total active energy in the LV network and compare it to the sum of all the energy for the end users. The result of the comparison is to analyze energy losses and find energy thefts.
- Measure and monitor the phase and total currents in the LV network to be able to act (send demand response commands) if the current reaches the higher limitation of the transformer in the substation.
- Measure and monitor the frequency in the LV network to be able to act (send demand response commands) to preserve the proper frequency.
- Measure and monitor the voltage in the LV network and compare it to the end users to be able to determine if a power failure is located at the end customer or in the LV network cable.

4. Meter data aggregation

4.1. Introduction - data aggregation as information compression

The presently emerging power systems—intrinsically included in the smart grids paradigm—reflect the synthesis of an unique technological evolution: on one side, the increased complexity of the active distribution grids are demanding the use of more elaborate models of the grid infrastructure: intermittent generation, prosumer-type loads with patterns highly variable in time (constant impedance, constant active power, profiled reactive power), and mobile storage units require new control algorithms, which have to rely on different models for the energy transfer itself. A relevant example is given by hybrid (ac/dc) active distribution grids. On the other side, the evolution of the ICT-enabled solutions has a direct impact on both the customers and signal-processing techniques embedded in commercially available data acquisition systems. Active distribution grids exhibit several differences from active distribution grids: firstly, low inertia due to the power electronics interfaced generation units and rectifier based loads translates into one order of magnitude lower constant times associated to power transfer in both steadystate and dynamic operation and secondly: a higher control flexibility and potential acceptability of different levels of quality of supply according to customized energy contracts.

State estimation is one of the main applications that can be used in distribution networks, for providing the best estimation of the voltage magnitude and phase for all network nodes based on the network topology information, the network parameters, and available measurement data. Further, a specific task of distribution networks is the power flow management providing direct benefit on deferral of investments due to network congestions. The advent of smart metering and associated services like demand response and demand side management will contribute to the development of a quasi-real time responsiveness scheme for monitoring and control of the distribution networks. It is expected that features like automatic alarming of low voltage network outages will improve low voltage network reliability.

Active distribution grids operation will require new formulation of optimal energy transfer and therefore it is needed to analyze in greater detail the LV network. Further, a specific task of microgrid control is the power flow management. Smart meters and associated services like demand response (DR) and demand
side management (DSM) contribute to the development of a quasi-real time responsiveness scheme for monitoring and control. The measurement reporting rate associated with these control schemes is usually 10 minutes. Monitoring the steady-state power transfer in LV and MV networks is mainly done in the power quality (PQ) framework. Monitoring (and control) is to be equally determined by the quality of measurement system and by the processing techniques of the measurement results (acting as information retrieval). Standards [3] are silently assuming steady state operation with nearly constant frequency. The upper limitations for deviations of frequency and voltage (rms values) are applied to values obtained from a successive aggregation of measurement data available from long-term observation. A compromise between the end-user needs for information and the amount of data resulting from averaging over one period of the observed quantities waveforms (i.e. rms values) has been up to now done by data aggregation over the time axis.

In the following, we use ac combination of the Business Intelligence definiton of aggregation:

*Data aggregation is a type of data and information mining process where data is searched, gathered and presented in a report-based, summarized format to achieve specific business objectives or processes and/or conduct human analysis.*

With the classical one used by Statistics:

*Aggregated data are data combined from several measurements; groups of observations are replaced with summary statistics based on those observations.*

In Power Systems, aggregation algorithms have been promoted for the consideration of:

i. information concentrator, data compression;

ii. noise filtering

iii. dc-ac energy transfer models equivalence.

Further, the data concentrator paradigm –especially for WAMCS applications considers data aggregation as the activity of *forming a set of data from multiple inputs*. The later approach is corresponding to an aggregation in space, a function relevant for modern deployment of smart meters.

A first example of formalizing the information concentrators in power systems – in the sense of data compression -is given by the use of rms values for describing quantities with [quasi-] sinusoidal variation (currents, voltages, active and reactive powers): 

$$ X = \sqrt{\frac{1}{T} \int_{t_0}^{t_0+T} x^2(t) dt} $$

(1)

where $x(t)$ is the periodical (period T) quantity mapped into a single point $X$, its rms value. For discretized signals, the rms algorithms can be implemented in either synchronous way or using a moving window with pre-defined width (usually one period of the original signal). The algorithm of computing rms values on non-overlapping windows with fixed length (N samples) is a powerful compression method. In [4] it is shown that such algorithms are equivalent to low-pass filtering; if the required response time of the monitoring process is less than tens of milliseconds, more information on the actual implementation is needed. This type of data compression can be seen as a moving-rms process applied to the discrete signal $g[n]$ where the components are the rms values obtained from sampled values $x[n]$ followed by decimation with factor $N_k$, where $N_k = 10, 15, 299, 12,...$ according to the aggregation level proposed in [3].
Figure 4.1 shows the signals involved in the time aggregation process [5].

![Diagram of time aggregation process](image)

Figure 4.1 - Time aggregation process represented as rms filtering followed by decimation [6].

For example, the first level of aggregation is performed on a time period corresponding to 10 cycles of the initial waveform (N1=10) resulting d[n], the output of the decimation applied to g[n] over exactly N=N1 samples and for which the z-transform is:

\[
D(z) = \sum_{k=0}^{\infty} d[k]z^{-k} = \sum_{k=0}^{N_1} g[kN]z^{-k} = \sum_{k=0, N, 2N, \ldots} g[k]z^{-k/N} = H(\sqrt{z})
\]  

(2)

In (2), H(z) is the z-transform of an additional signal h[n], defined such as:

\[
h[n] = \begin{cases} 
g[n] & \text{when } n \text{ mod } N = 0 \\ 
0, & \text{otherwise}
\end{cases}
\]

It can be shown [5] that

\[
D(\omega) = \frac{1}{N} \sum_{k=0}^{N-1} G\left(\frac{\omega}{N} + \frac{2k\pi}{N}\right)
\]  

(3)

For the moving-rms filtering [4] applied to the discrete signal

\[
G_{rms} = X^2_{rms}
\]

where

\[
\Omega = 2\pi \frac{f}{f_s}; \quad f_s = 1
\]

one can write [6]:

\[
G(\Omega) = \frac{1}{N} \left(1 - \left(\frac{1}{N_1}\right) e^{i\Omega}\right)^{N-N_1}
\]

\[
D(\Omega) = \frac{1}{N^2} \sum_{k=0}^{N-1} \frac{1}{1 - \left(1 - \frac{1}{N}\right) e^{i\left(\frac{\Omega}{N} \frac{2k\pi}{N}\right)}}, \quad \Omega \in [0, \pi)
\]  

(4)
4.2. Aggregation in time domain

According to the standard [3], the aggregation method related to voltage measurement is the root mean square (rms) algorithm performed on quantities describing energy transfer under stationary conditions. The aggregation method uses 4 different time intervals: 200 ms (10 cycles for 50 Hz system frequency – as basic interval for the measurement process), and 3 s, 10 minutes, 2 hours as aggregation intervals. Aggregations are performed, with one exception for the frequency, using the square root of the arithmetic mean of the squared input values [3]. Figure 1 shows the theoretical structure of the aggregation process.

Typically three categories of aggregation are encountered: package aggregation, cycle aggregation, and time-clock aggregation. The package aggregation is the 10-cycle time interval aggregation.

According to the standard, the time tag is the time at the end of the 10-min aggregation [3]. The 2-hour intervals measured data should be computed from twelve 10-minute time intervals. In consequence, the formula for the first aggregation level (0.2 s time interval) is [7]:

$$v_{(0,2)} = \sqrt{\frac{1}{10} \sum_{k=1}^{10} v_k^2}$$

where $v_k$ is the quantity associated with one fundamental period of the quasi-sinusoidal waveforms; usually this quantity is the rms value of voltages or currents, which already is the result of an second-order filter [4]. In order to assess a stationary process, which has the same probability distribution for all times and positions, parameters like mean and variance should not change over time. It is expected that some of the quantities describing the power system operation and observed during 0.2 s time intervals meet the stationarity condition. With this assumption we can make the hypothesis that the 10 values could be treated as measurements over the same measurand [3]. Similarly, data aggregated in the next step should include the associated uncertainty form the previous step. The formulae used for the further three time aggregation intervals (3 s, 10 minutes and 2 hours) are [7]:

$$v_{(1)} = \sqrt{\frac{1}{15} \sum_{k=1}^{15} v_{(0,2)}^2} ; \quad v_{(10\text{min})} = \sqrt{\frac{200}{10} \sum_{k=1}^{200} v_{(1)}^2} ; \quad v_{(2\text{h})} = \sqrt{\frac{12}{10\text{min}} \sum_{k=1}^{12} v_{(10\text{min})}^2}$$

Although stationarity is always assumed, recent studies show that this condition is not always met for the 3 s time interval. Moreover, stationarity for a 10-minute period in power systems is already a questionable hypothesis [8]. Because frequency measurement did not need an aggregation method as that defined for class A instruments [3], the proposed data concentrator is practically a simple arithmetic averaging over adjacent approximately 500 waveform time periods.

Figure 4.2 shows [9] the two aggregation algorithms proposed by the power quality series standards IEC 61000-4-30 [1].
Presently there is a gap between (i) the level of approximation used for modeling the current and voltage waveforms which is implicitly assumed by most of the measurement devices deployed in power systems and (ii) the capabilities and functionalities exhibited by the high fidelity, high accuracy and high number of potential reporting rates \([10]\) of the newly deployed synchronized measurement units (SMU). This gap can determine a significant depreciation of the information mediated by the control systems which are relying on real-time measurements delivered by equipment with heterogeneous aggregation and reporting rates \([7]\). Moreover, real-time definition is evolving following changing patterns of energy transfer: for example, the increased use of power electronics converters as the interface for both generation and loads results in lower system inertia and consequently requires a faster control.

Several applications, among which of increased importance is the class of state estimators, need both types of measurements: the so-called “classical” one, adapted for a de facto steady-state paradigm of relevant quantities and the “modern” one, i.e. with fewer embedded assumptions on the variability of same quantities. Measurements in power systems are physical measurements, which embed the two independent features (objectivity and intersubjectivity) directly in the structure of the measuring instrument \([11,12]\).
The main constraint so far is put by the power quality (PQ) standards [3] where several aggregation algorithms are recommended, with specific focus on the information compression. The further processing of $rms$ values (already the output of a filtering algorithm) results in significant signal distortion [13].

### 4.3. Measurement Quality and Reporting Rate

The need of merging measurement data made available with different reporting rates and/or embedding standard aggregation algorithms requires an evaluation of the quality of measurements. Therefore it is needed to consider definitional uncertainty, which is strongly dependent not only on measurement data post-processing but also on the physical model of the energy transfer in the considered grid section.

Let us consider a classical measurement equipment $E_1$ which fulfills the IEC 61000-4-30 recommendations [3] for measuring the parameters of a signal $x(t)$. Let be $T_N$ the averaging window, which for most of the PQ measurement equipment is identical to the reporting period. According to [3]:

$$T_N \in \{200 \text{ ms}; 10 \text{ s}; 10 \text{ min}; 2 \text{ h}\}, \text{ for frequency}$$

$$T_N \in \{200 \text{ ms}; 3 \text{ s}; 10 \text{ min}; 2 \text{ h}\}, \text{ for all other quantities}$$

The algorithm embedded in $E_1$ can be [3] either the simple average of the information provided by $N=\lfloor T_T/T_0 \rfloor$ samples (for frequency data, where $T_0$ is the inverse of the reported (average) frequency), or the $rms$ average for other quantities. Moreover, for the in-use reporting rate, $E_1$ is certified with an accuracy class $c_1$ (class A, B or C instruments) or, in general, has associated the measurement standard uncertainty $u_1$. For example, considering a uniform distribution of measurement errors, for the measurement range $X_{max}$ and for most analogic instruments, the corresponding standard uncertainty is:

$$u_1 = \frac{c_1 \cdot X_{max}}{100 \sqrt{3}}$$

Now let’s consider a synchronized measurement device $E_2$ (for example PMU) for which the maximal relative error is $e_{PMU}$ usually $e_{PMU}$ is derived from the maximal uncertainty associated with the local measurement channels, which for frequency is less than 1 ppm (0.0001%) of reading, plus time base error; while for the time stamp is 1 $\mu$s plus time base error; time base error is less than 1 $\mu$s, when locked to at least one satellite with correct position. This device is deployed with a $R_N$ reporting rate. According to [14]:

$$R_N \in \{50, 10, 1, \ldots\} \text{ frames/s.}$$

The question is how to assess (and compare) their measurement quality equivalent accuracy when such two devices $E_2$ and $E_1$ are simultaneously used in a common application. To this, we distinguish two scenarios [15]:

**First scenario**: The application requires the information to be processed in the power quality framework. This translates into an approximation of the energy transfer process through either simple or quadratic averaging algorithm applied to the monitored quantity (voltage, frequency etc.). PMU data is available with highest reporting rate which has to be further aggregated following the same averaging algorithm (over the window $T_T$). The reference information in this case is represented by the $E_1$ data. Equipment $E_2$ will have associated a standard uncertainty $u_2^{\text{Case1}}$, derived from the $E_2$ standard uncertainty $u_2$ (made available for the maximal reporting rate) and the standard uncertainty associated with the signal processing unit which
computes the required average over $T_N$. In this case, the error derived from model approximation (PMU measures the “true” data series of measured quantities, while $E_1$ reports an approximation) is to be accounted by $E_1$ only as a definitional uncertainty and its contribution to the measurement uncertainty is already taken into account by the accuracy class of $E_1$. Therefore the two sets of measurements become compatible by referring to the same approximation where $E_1$ has standard uncertainty $u_1$ and $E_2$ has [16]:

$$u_2^{\text{Case 1}} = \sqrt{\frac{u_2^2}{N}}$$

(9)

Taking this into consideration, the relative standard uncertainty can be computed for all quantities and reporting rates.

**Second scenario**: in this case $E_2$ is used at lower reporting rates, with the goal to emulate a synchronous information merging from $E_1$-type of equipment; i.e. the “real” information is made available after a decimation process (for example, 1 frame/s selection for an equipment $E_2$ able to deliver information with a maximal reporting rate of 50 frames/s would result in a decimation factor of information =50).

Data fusion of the information provided by $E_1$ (reporting period $T_N$ following an approximation algorithm applied to $N$ instants of the “theoretical” data stream) and $E_2$ (actual information provided at instants separated by a time window $T_{N2} =T_{N1}$, i.e. information decimation) has to consider the standard uncertainty of $E_2$ as provided by the manufacturer (for example, TVE=1%) and for $E_1$, a compound uncertainty derived from both definitional uncertainty and the equipment $E_1$ standard uncertainty:

$$u_i^{\text{Case 2}} = \sqrt{u_M^2 + u_1^2}$$

(10)

Here the model (definitional) uncertainty $u_M$ is a measure of “distance” between the actual descriptor implicitly used for the variation in time of a quantity and its single values resulted from applying the embedded aggregation algorithm. This distance is dependent not only from the time aggregation formula and length of the time interval but also from the phenomena described by the quantity in use. This latter component cannot be derived theoretically, as it is dependent on the actual power network operation conditions. An extensive monitoring campaign needs to be pursued in order to quantify this component. The following section presents specific cases where the information is fused from PMUs installed in four different nodes of the Romanian power system and set on the highest available reporting rate (50 frames/s).

### 4.4. Randomenss Power – a measure of heterogenous reporting rates [15]

Let’s consider a linear (resistive) circuit. For this circuit $U$, $I$ are evaluated (rms) over each $T_1$ interval (rms aggregation) and corresponding $P_k$ measured (first level of aggregation according to IEC 61000-4-30). Doing a simple summation we obtain the average power corresponding to $T_A$ observation time. For the purpose of this exercise $T_1=200\text{ms}$ and $T_A=3\text{s}$ the observation interval; $T_A=15T_1$. The challenge is to compare this result with a direct measurement over TA. As it can be seen in the table below the obtained results are different.

For $T_A$, the equivalent voltage (aggregated on first level), the current and the apparent power are:
\[ U_A = \sqrt{\frac{1}{15} \sum_{k=1}^{15} (U_k^2)} = 229.9984 V; \quad I_A = \sqrt{\frac{1}{15} \sum_{k=1}^{15} (I_k^2)} = 10.4849 A \]

\[ \Rightarrow \quad S_A = U_A \cdot I_A = 2411.5 VA \]

\[ \overline{P}_A = \frac{1}{15} \sum_{k=1}^{15} P_k = 2405.7 W < S_A \]

\[ \Rightarrow \quad D_R = \sqrt{S_A^2 - \overline{P}_A^2} = 166.8528 VA \approx 0.07 \cdot S_A \]

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<td>2530</td>
<td>2475</td>
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### 4.5. Aggregation of wide area measurements

*Aggregation in space* denotes an algorithm to encode information provided by sensors located in various nodes of a network for which accurate models are available. Applications based on measurement information retrieved from several nodes of the system to be controlled need a synchronization protocol. The required clock precision is dependent on the application, the standards maturity and available technology.

In several control applications (for example, active distribution grids operation), which are based on power quality assessment, both time and space data aggregation is needed. A good model of such dual aggregation is given by synchronized measurements. Such a platform should allow the connection of measurement equipment from different vendors, full control over the measurement chain and its associated uncertainties, a reliable communication infrastructure, and a data hub (cloud) as the underlying layer for concentrating the data and the environment for extracting, managing and processing the data. Such an environment can be seen as a complex coding application (in space and time) for which a minimal standardization effort is required. Data hug related standardization (space-related data aggregation) is at the beginning [14], while for time aggregation only the PQ algorithms are standardized. Moreover, the measurement equipment-data hub communication layer should be governed by standardized communication. Integration on the same platform of PQ-information simultaneously delivered by measurement devices with different reporting rates is still under development [18]. Difficulties rely in the different type of information compression in case of time aggregation of phasor – and PQdata, which is not always possible to relate to the steady-state grid operation.
4.6. Aggregation paradigm and Smart Metering technology [19]

Smart meters (SM) deployment, as basis for Smart Grid support as well as for flexible energy and energy services markets are becoming the most present installed equipment in LV distribution networks, in line with the aim of European Union for 80% SM in 2020, as a politically endorsed target which shows the society engagement towards more efficiency and sustainability.

Distribution networks and especially the LV networks are also living a dramatic change in the era of Smart Grids deployment, through high penetration of distributed generation, in an environment which ask for both high network efficiency and flexible local markets, including neighborhoods markets of energy and energy services such as demand response.

The new meter chips are more and more performant and use in the latest solutions architectures complex architectures such as dual-core ARM Cortex processors with DSP functionalities, allowing intensive digital computations for measuring the energy but also additional quantities based on voltage and current computations, such as Power Quality (PQ) monitoring.

The main PQ areas of interest for the DSO as well as for the user are:

- Voltage level, which is currently described by EN 50160, giving legal limits in a statistical approach based on P95% levels [20, 21];
- Voltage harmonic level, through the synthetic THD and through individual harmonics up to 50, with the same statistical approach of P95% [3,21] and with norms for the statistical level
- Current harmonic level, analyzed with the same algorithms [3,21], but without a legally required limit
- Non-symmetries of voltage and current, calculated for the fundamental or for the RMS value, within a statistical approach;
- Flicker effect, meaning low frequency deviations of voltage, with the same statistical method [22],
- Voltage dips, as short voltage depreciations, to be classified e.g. according to Unipede rules;
- Energy continuity in supply, through number and time-lengths of outages, to be used for calculating SAIDI and SAIFI.

Particularly PQ aspects a), b) and e) have standards with high requirements in terms of computation, which ask for high cost specialized equipment.

Existing power quality (PQ) standards [3,21] use several aggregation algorithms in order to retrieve statistical results P95% of different harmonics.

According to current standards and PQ practice, statistics of harmonics is based on a complex statistical methodology, with the following steps:

- harmonic level for each set of 10 periods is continuously calculated through DFT computations and are mediated each 3 seconds (15 sets considered for exact 50 Hz, but 14 up to 16 sets for frequency deviations under or over the 50 Hz) or each 10 minutes (15x600 sets); moreover, overlapping windows can bring the necessity to make 2 different DFT/FFT analysis in the same time, to be covered by the computational power of the PQ analyzer; this may request, for class A, a double computation power in some cases and requires corresponding microprocessor based platform (usually including a DSP part) in the measurement equipment;
• an additional 2 hours interval is also mentioned in the standard, by aggregating 12 time intervals of 10 minutes;
• Finally, a week of such 10 minutes results, meaning $1440/10 \times 7 = 1008$ values are analyzed in terms of distribution of probability, in order to get a 95% level of probability, to be used as informative limits for the harmonic distortion level.

This procedure has been recently questioned and more efficient solutions are to be addressed in the project NobelGrid [23]:

The statistical Light PQ Assessment Method is not challenging the today standards, but is intended to bring a method for PQ assessment which has acceptable errors comparing with today standards but allows cost-effective implementation in each piece of a new generation of Smart Meters to be connected in LV networks. In the Smart Grid oriented PQ framework, this method is desired to become a standard to complement today standards, applicable in Smart Meters designs and recognized as practical method of PQ assessment at low voltage level, dealing with small consumers, prosumers and active LV networks.

5. Use cases related to the integration of smart meters in the MV/LV substations

Distribution networks, because of their geographical dispersion in urban and rural areas, can be significantly affected by faults arising from different sources such as adverse weather conditions, and equipment failure. In order to minimize outage times and improve the continuity of supply, development of practical method for detection and location of outages is mandatory. Power companies normally depend on customer trouble calls for outage mapping. However, in modern distribution networks, smart meter data would be an available option to determine the impacted part of the network.

5.1. The use cases for outage detection and outage location in LV networks

At the moment usually DSOs use customer calls to detect the LV network outages, this process has the following disadvantages:

1. During the nights there would be a little number of customer calls which makes the outage location process difficult or impossible.
2. False or fake reports are hard to realize.
3. The whole process is time consuming and inefficient.

On the LV grid, several monitoring devices will be installed, in the Flexmeter project, which would prepare the following data:

• RMS values of Voltage, Current, Reactive and Active Power;
• Load profiles from LV customers and production points;
• Status of remote-controllable elements in secondary substations (RTU1-IED2);
• Alarms related to events and faults (IED-PQM3-RTU).

1 Remote terminal unit
2 Intelligent electronic device
An outage detection and location platform (Figure 5.1) can use these LV measurement and data collected from different sources to detect and locate LV outages in a fast and efficient manner with no or little human interventions.

In case of outage, all the meters in the outage area detect the absence of voltage and send a “last gasp” signal to the cloud system. No particular stringent requirements are needed from the point of view of the communication network. The main issue is that the communication network should work also in a power outage condition, thanks to a UPS system.

5.2. The use cases for fault location in MV networks

After the detection of a fault in the MV distribution network and reaction of the protection system, it is possible to design an algorithm, to identify the fault location on the MV lines (Figure 5.2).

\[^{2}\text{Power quality meter}\]
The HV/MV substations are already equipped with voltage and current measurements for the purpose of protection. MV network fault location is an additional feature which could be implemented in HV/MV substations or in the main control center. In the first case just the fault location is reported, while in the second case the voltage and current waveforms or their (calculated during-fault) phasors should be sent from the primary HV/MV substation to the cloud. The requirements from the communication network point of view are the same of the previous point. Also in this case no particular stringent requirements are needed from the point of view of the communication network. The amount of data to be sent is quite small and there are no stringent latency requirements. Even if the data arrive to the cloud some seconds after the event, it would be much faster than with conventional fault location methods. Also in this case the main issue is that the network should work also in a power outage condition, thanks to a UPS system.

4.3 The use cases for Network management for load balancing

The use case about “Network management” aims to balance network load profile by using energy storages. The goal is to write an algorithm that manages the charge and discharge operations of a battery situated in the medium to low voltage cabins. In the sequel, we will call this algorithm storage manager. This tool will work by using real-time consumption and production power measurements from the database in the cloud, and by using the load profile scenarios generate from the ING. The output of the storage manager is, for each time step, the control of the energy storage. By using this tool, the energy network will gain stability and further renewable energy will be more competitive.
The use case diagram is shown in Figure 5.3.

![Use case diagram](image)

Figure 5.3– Use case diagram

In the use case diagram, we have called Storage management instead of Storage manager because we still do not know if we are going to use one or more algorithms. The information flow to the Storage Manager consists of:

- Real time consumption of the buildings connected to the medium to low voltage cabin where the battery is located.
- Real time production of energy of the buildings connected to the medium to low voltage cabin where the battery is located.
- A reasonable amount of load profile scenarios.

The information flow from the Storage Manager consists of:

- For each time step the action (charge - discharge - do nothing) that the battery must do.

6. References


[20] EN 50160, Voltage characteristics of electricity supplied by public distribution systems
[21] IEC 61000-4-7, Electromagnetic compatibility (EMC) - Part 4-7: Testing and measurement techniques – General guide on harmonics and interharmonics measurements and instrumentation, for power supply systems and equipment connected thereto

[22] IEC 61000-4-7, Electromagnetic compatibility (EMC) – Part 4-15 Testing and measurement techniques, Flickermeter – Functional and design specifications