ENG04 SMARTGRID

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1 Executive Summary

The “Metrology for Smart Electrical Grids” project has promoted the effective development of Smart Grids via the realisation of the necessary metrology infrastructure for monitoring grid stability and quality of supply. The new measurement tools developed in the project will help utilities add more renewable energy sources (RES) such as wind and solar to their electricity grids, and thereby support the European aim to have 20 % of the electricity supply generated via renewable energy sources by the year 2020.

The problem

The increase of decentralised energy supply by renewable energy sources forces the electricity grid to become a ‘smart grid’: an active system with bi-directional energy flows. In such active systems the stability of the grid becomes delicate and also the quality decreases as voltage distortions increase. Without the appropriate measurement tools and additional understanding of the behaviour of smart grids, our future electricity supply becomes at risk.

The solution

This project responded to this challenge by realising the necessary metrology infrastructure for monitoring the stability and quality of our electricity supply. The specific objectives of the project realised are:

- New modelling, simulation, and network analysis tools to assess system state of smart grids were developed these enable operators to design and implement stable and secure gird infrastructures.
- A measurement framework for reliable and accurate Phasor Measurement Units (PMUs) used to assess grid stability.
- Important new knowledge on the effect of renewable energy sources on power quality (PQ) of grids.
- New traceable on-site ‘smart’ energy measurement systems for electricity grids and households

The impact

More than 60 scientists active in the project worked in close cooperation with electricity grid operators, instrumentation manufacturers and other stakeholders in their realisation of the project aims. This resulted in extensive exchange of knowledge and experience, especially in the on-site measurement campaigns, and led to new long-term relationships. The project has clearly placed Europe at the very forefront of worldwide electrical grid related metrology research, among others reflected in series of invited keynote talks.

The project outputs are already being used by instrument manufactures to develop and improve product performance for smart grid applications. A number of grid operators are using and considering using the outputs in the design and upgrading of grids. This will lead to longer term impacts:

- For utilities, the new sensor placement tool will allow for a reduction in installation cost of grid monitoring sensors.
- Extension of the tool for PMU-based impedance measurements to dynamic line rating will allow grid operators to connect additional renewable energy sources to heavily loaded grid sections without the need of costly grid reinforcements.
- Contributions to new standardisation including smart grid security, standards for PMU testing, and renewable energy related power quality standards will support technical developments and increase reliability of smart grids.

Together, the project outcomes constitute an accurate and reliable measurement infrastructure, that provides crucial support to the successful implementation of a Smart Electrical Grid in Europe.

2 Project context, rationale and objectives

2.1 Context

The electricity grid is the backbone of our modern society, with a high level of security of supply and quality of supply. The increase of decentralised energy supply from for example renewable energy sources forces the network to become a 'smart grid': an active system with bi-directional energy flows. In such active systems the stability of the grid becomes delicate and in addition the quality decreases as voltage distortions increase due to new types of equipment e.g. inverters required by renewable energy sources. This project responded to this challenge by realising the necessary metrological infrastructure for monitoring stability and quality of supply to support the effective development of Smart Electrical Grids.

2.2 Need for the project

Environmental issues and diminishing energy supplies are challenging the traditional model of electricity generation and distribution. Smart Grids are broadly seen as the crucial enablers for the future vision of clean, renewable, locally generated energy, which is required to meet society's energy challenges. However, Smart Grid systems are highly complex, difficult to optimise and vulnerable to instability. This leads to a paradigm shift in the instrumentation and control requirements for Smart Grids, such that stable high quality electricity supply can be assured.

When it comes to understanding grid behaviour, there is limited knowledge available both in understanding the grid state of low and medium voltage smart grids, as well as the actual stability of such grids. This lack of knowledge and information is problematic, as the need to integrate renewable generation has led to the development of active distribution networks where energy is fed in at the low (LV) and medium voltage (MV) levels. In such networks, the complex interactions between intermittent sources and sinks of power with multiple distribution links make Smart Grids vulnerable to instability and failure.

Phasor Measurement Units (PMUs) are ideally suited to improve the monitoring of the static state estimation as well as the dynamic behaviour of large transmission networks. In the future, PMUs will be essential for the monitoring and control of the stability of medium and low voltage Smart Grids. Differences between individual PMU performances are currently a recognised problem that undermines the usefulness of these devices in grid stability monitoring and control schemes.

The implementation of widespread renewable generation in distributed generation networks exposes issues related to the quality of the power as seen by the consumer. Power quality (PQ); the level of voltage fluctuation;, harmonic content and reliability of the available energy has significant impact on electricity consumers. PQ measurement and mitigation techniques are key to the realisation of effective Smart Grids and the integration of renewable energy sources.

In energy trade, the reliable and accurate measurement of energy flows is at the heart of ensuring fair trade in electrical energy markets, since bills issued between commercial parties are based on the measured amount of power and energy transferred (revenue metering). In smart electrical grids, the energy flows will increase due to the addition of renewable energy sources and at the same time more commercial parties will be involved due to liberalisation of the energy market. This requires integrity, authenticity and privacy of measurement data as well as increased accuracy and reliability in energy measurements throughout the whole grid.

In summary, at the start of the project in 2010, the actual development of smart grids was still in its infancy. The basic hardware elements for constructing a smart grid were partially available. However, very little theoretical and practical experience existed on the stability of the grids that would arise after implementation of these elements. In addition, the metrological infrastructure for measurement of the crucial monitoring and control parameters in smart grids was essentially lacking.

As a consequence, electric power utilities have posed a series of questions to the metrological community: What is the optimal smart grid instrumentation network required for adequately monitoring the grid at an acceptable cost? How can we achieve reliability and trust in grid phasor measurements that are critical for monitoring grid stability? What is the effect of the integration of renewable energy sources on the quality of the electricity supply? And how can we assure fair trade between the increasing number of commercial organisations exploiting the grid?

2.3 Scientific and technical objectives

Triggered by the needs expressed by the utilities, the joint research project "Metrology for Smart Electrical Grids" embarked on the development of measurement tools for monitoring stability and quality of electricity supply in Smart Grids. The project outputs are metrology tools for Smart Grid designers and operators to facilitate the observability and controllability of this new technology. In four technical areas, it aimed to develop, refine and apply new metrology to determine power flows, stability and power quality of these new grids. Fair trade will be assured through the implementation of revenue billing systems and cryptographic infrastructure for purposes of security. New design methodologies will be developed to optimise smart grid instrumentation networks for reliable and stable energy supply.

The specific scientific and technical objectives for the project were to:

a. **Development of a metrological strategy for the observability and controllability of smart grids.** Models need to be developed for low and medium voltage smart grids, with the aim to optimise observability, controllability, and overall design of these grids. Research concerns optimal number and location of sensors required for the reliable measurement of the smart grid system state at an affordable cost. The modelling methods are improved and validated by making measurements on actual laboratory and smart grids in the field. Additionally, the security and reliability of smart grid data needs to be addressed since tampering of the grid control data e.g. by hackers can have an enormous impact on society.

b. **Realise a measurement framework for reliable and accurate Phasor Measurement Units (PMUs)**. PMUs are unique instruments since they produce high-rate synchronised measurements of grid voltages and currents. They are ideally suited for monitoring stability of smart grids since they directly measure the voltage phase used in grid state estimation. For this critical application it is crucial that PMUs deliver accurate, reliable grid information. To bridge the gap between the need for traceable PMU measurements and the current lack of metrology related infrastructure within Europe, set-ups need to be developed for calibration of PMUs and a reference PMU needs to be designed and built. Present commercial PMUs will be evaluated and on-site measurements will be performed in electricity grids in order to prove and increase the applicability of PMUs in monitoring grid stability.

c. **Perform a series of on-site measurement campaigns of power quality (PQ)**. Widespread renewable generation in distribution grids negatively affects the PQ in the grid. Bad PQ, such as voltage fluctuations and harmonics, has significant impact on electricity consumers including failure of appliances and additional energy losses. Building on the knowledge and instrumentation from a previous iMERA+ "Power & Energy" project, portable systems and measurement routines for on-site power quality measurement will be developed dedicated to a series of specific applications. Subsequently, a series of on-site case studies will be performed covering 'pilot' smart grids, wind turbines, rail grids, distribution grids, and substations.

d. **Develop traceable on-site energy measurement systems** for ensuring fair energy trade. New, advanced metering techniques will be developed for consumers, such as next generation smart meters based on non-invasive load monitoring (NILM), a technique with which the energy consumption of consumer appliances can be monitored. To support utilities, two further on-site metering techniques will be realised, one for on-line monitoring and calibration of household energy meters, and one for on-site three-phase energy measurements in medium and high voltage grids. These techniques aim to reduce calibration cost and increase confidence of utilities in the calibration status of energy meters and grid revenue metering systems.

In total, 19 European national metrology institutes and 4 universities and research centres, bringing specific expertise to the project, have worked on complementary tasks realising the scientific and metrological challenges related to the successful implementation of smart electrical grids. Intensive contacts have been kept with transport system operators (TSOs), distribution system operators (DSOs), utilities, instrument manufacturers, electricity companies, and IEC technical experts (enabling of international standards development) to assure focus of the project on actual customer needs and assure a timely and smooth take-up of the research results.

Altogether, the project outcomes will provide a significant advancement in the accurate and reliable measurement infrastructure that supports the successful implementation of a Smart Electrical Grid in Europe.

3 Scientific and technological results and foreground

3.1 Smart Grid system state for stabilised power flow

Metrological strategy for the observability and controllability of smart grids – state estimation

The increasing number of decentralised generation units (typically from renewable sources of energy) located at the distribution level (a medium voltage level between high voltage transmission lines and the consumer level) of power grids causes new dynamics in the electric grid which need to be observed through measurement or estimation in order to ensure safe operating conditions. State estimation methods developed for the transmission grid level cannot be used for the distribution grid level without significant modifications for a number of reasons. Firstly due to the normal case of unbalanced conditions at the distribution grid level which often demands the use of three-phase-models, opposed to single-phase models often applicable at the transmission grid level. Secondly, at the distribution grid level, a high number of nodes has to be observed through a limited number of available measurements; whilst at the transmission grid level a high number of measurements is made for few nodes which allows for robust state estimation including the detection of low qualitydata.

In power system state estimation methods for unobservable grids, missing critical measurements are often replaced by pseudo-measurements such as load and generation forecasts, which differ considerably from the actual real-time values and therefore affect the accuracy of the estimated quantities. Special care has to be taken as to how to include these uncertain pseudo-measurements. During this project, starting from the original idea presented earlier, a method has been developed that estimates the grid state in medium-voltage distribution grids, especially for the case of an incomplete measurement infrastructure. The procedure, called „nodal load observer (NLO)", is based on measurements of voltage phasors at grid buses and forecasts of load and generation data.

The basic principles of the NLO are closely related to the Iterated Extended Kalman Filter (IEKF)-based dynamic state estimator for voltage phasors and the static weighted-least-squares estimation method for loads. However, it extends these methods by combining the benefits of both in order to achieve a better applicability in distribution grid setups.

Different from classical static or dynamic state estimation techniques for power system, the NLO does not use the magnitudes and phase angles of node voltages as state vector, but instead uses nodal active and reactive power. Based on the forecasts, a nonlinear dynamic model is built which describes the development of active and reactive power over time and how voltage magnitudes and phase angles depend on them. An Iterated Extended Kalman Filter (IEKF) is then applied to calculate corrections for active and reactive power forecasts based on the available measurements. During this iterative process, any missing voltage magnitude and phase angle values are reconstructed such that the overall estimation results fit the given measurements. Even if only comparably few voltage phasor measurements are made, major improvement of forecasts is achieved in the neighbourhood of the measurements and in addition, improvement in results for nodes further away from them will also be obtained. Simulation studies on medium-voltage distribution networks and validation on the laboratory test grid of the University of Strathclyde have shown the efficiency of the proposed method.

The development of the method has been carried out in close cooperation between the Energy Research Center of Lower Saxony (EFZN) in Goslar (Germany), the Clausthal University of Technology in Clausthal-Zellerfeld (Germany) and the Physikalisch-Technische Bundesanstalt (PTB) in Berlin (Germany). Fruitful discussions at the National Physical Laboratory (NPL) in Teddington (UK) have greatly enriched and inspired the work. Measurements for the validation on a laboratory test grid were carried out by the University of Strathclyde (UK).

Metrological strategy for the observability and controllability of smart grids – optimal sensor placement

The NLO state estimation technique builds on work in the literature to recover grid state in the absence of a complete measurement infrastructure. The method has proved highly successful at limiting the effect of pseudo measurements on the accuracy of the state estimation. In addition to this new state estimation concept, techniques were developed to increase the observability of distribution networks, whilst limiting the amount of costly new sensors.

An estimate of the accuracy of grid state estimation is required to assess if sufficient-quality information exists for adequate control of the network. Methods were sought to find methods of determining the uncertainty of state variables (i.e. nodal voltage magnitudes and angles obtained from the state estimation) given uncertainties in the input real and pseudo measurements. The relationship between the uncertainty in the state variables and different measurement strategies (sensor location, accuracy and number) was then used to determine optimum strategies to give the required uncertainty for effective network control.

Power flow calculations were carried out on models of the University of Strathclyde's experimental microgrid and several large simulated networks based on standard IEEE and UKGDS (United Kingdom Generic Distribution System) models using full published data sets. Results from the power flow analysis were used as trial input measurements to assess the ability of state estimators to estimate the state of the grid at non-instrumented locations. To help in this analysis, a graphical user interface was written in the open source MATLAB based analysis software, which greatly improved the efficiency of the process and enabled greater insight into the sensitivity of the estimates to the model parameters and measurements.

A thorough sensitivity analysis included the construction of a sensitivity matrix relating the state estimates to the input measurements. This matrix can be used to determine the most important measurements for estimating the grid state when a full set of measurement information is unavailable. This matrix forms the basis of a method to select the best minimum set of measurements to give an accurate picture of the system state for the least cost.

The uncertainty in the state variables (voltage magnitudes and angles) recovered from the state estimation was calculated using the sensitivity analysis based on the uncertainty of the input measurements. Good agreement was achieved in comparisons between the uncertainty evaluated using the analytical sensitivity analysis and that evaluated using monte-carlo methods in all cases.

With the validated uncertainty calculation, an algorithm to find the optimal sensor placement strategy for grid observation could be developed. Such a method was realised by first reducing the number of measurements to the minimum required for observability by ranking the measurements in order of importance using the sensitivity matrix. Once the optimum minimum set of measurements has been found, the sensors which lead to the greatest reduction in overall state estimation uncertainty can be made more accurate and those which have a lesser influence can be made less accurate. It is necessary to replace some measurements with pseudo measurements, derived from consumer demand based past usage, to further reduce the number of required real measurements. The sensitivity matrix can again be used for this and the optimum number of sensors can also be found by observing the relationship between number of sensors and overall uncertainty.

The sensor placement algorithm was tested with a variety of different simulated networks and has been shown to give close to the minimum achievable overall uncertainty for a given number of sensors.

Testing with real measurements was then performed on the laboratory microgrid at the University of Strathclyde. The ability of the algorithm to choose the optimal subset of measurements was tested by comparing the estimated power flow from reduced measurement sets with the measured power flow of a fully instrumented grid. The subset chosen by the algorithm was found to have the close to the lowest overall error and all estimates agreed with the rejected measurements within the calculated uncertainties. The results from the applied sensitivity analysis algorithms illustrate that the method provides the optimum minimum observable set of measurements or close to this in all tested cases. So far this method has only been tested with one state estimator, but it is theoretically applicable to any type of state estimation algorithm, including the nodal load observer concept developed by EFZN. The results show that both the uncertainty calculation and optimal placement methods are working as expected. The performance with larger networks has been verified in simulation but still needs to be validated on full-scale real working networks.

The experiments that have been conducted with the microgrid available at Strathclyde University, also provided more information regarding the measurement uncertainty in the techniques of power flow management (PFM). The objective has been to assess the PFM technique performances when they are subjected to different levels of data uncertainty, in order to show how the security margins adopted by the distribution network operators (DNO) are dependent on data uncertainty and consequently how its reduction and control is important for network operators. The effect of the choice of the measurement position and the use of a state estimator (SE) has been evaluated as well.

Until now, the studies presented in literature on the impact of uncertainty for the problem of power flow management have investigated the effects determined by the absence of measures (lack of measurement points, communication problems or instrumentation failure at the measurement point) during the monitoring phase of the system. Then they have investigated the effects determined by the unpredictability of loads or sources during the planning phase of the system. In this work, the measured data uncertainty has been taken into account by the studies on the techniques of state estimation.

The scenarios considered during the experimental work simulate the situation in which the DNO must decide whether the transport capacity of the network can allow a part of the network to export the excess energy produced by distributed generators (DG) or if it is necessary to curtail the generators. Under these conditions, the adoption of an excessively prudent set of security margins potentially leads to the inability to exploit all the DG generated power.

The starting point was a calibration of the measurement system in order to achieve the same precision level that is found in real systems. Using this calibration, the uncertainty of the measurements collected on the micro-grid has been reduced to 4% for power flow measurement.

The grid has been fully instrumented in order to be able to choose different sets of measurements. Thanks to the use of a state estimator (SE) and a methodology based on the application of the sensitivity analysis, described above, it has been possible to identify a set of data for the SE that guarantees the observability of the network, and calculates the uncertainty of the estimated data. The methodology for the estimated data uncertainty calculation works with a linearised formulation of the problem so that the calculation can be executed quickly without convergence problems. The reliability of this methodology has been proved by comparing it with the results obtained with a Monte-Carlo simulation on different grid topologies.

In order to simulate the effects of increasing uncertainty in the measurements (due for example to a possible loss of calibration of the instruments or the worsening of the conditions of the communication channel), Gaussian signals with zero mean and increasing variance were added to the measures coming from the grid. The choice of adding an artificial signal to simulate the uncertainty of the data has been made in order to replicate the unpredictability of the noise that can afflict the real data. It has been not possible to find in literature an alternative way to simulate noise.

Increasing the variance, the number of wrong decisions made in media from the PMT was measured and it was evaluated how the DNO should set the security margin to ensure the security of the network. It has been shown that the effect of the increased uncertainty is to force the DNO to adopt higher security margins and consequently reduce the contribution of power from distributed generation more than is necessary.

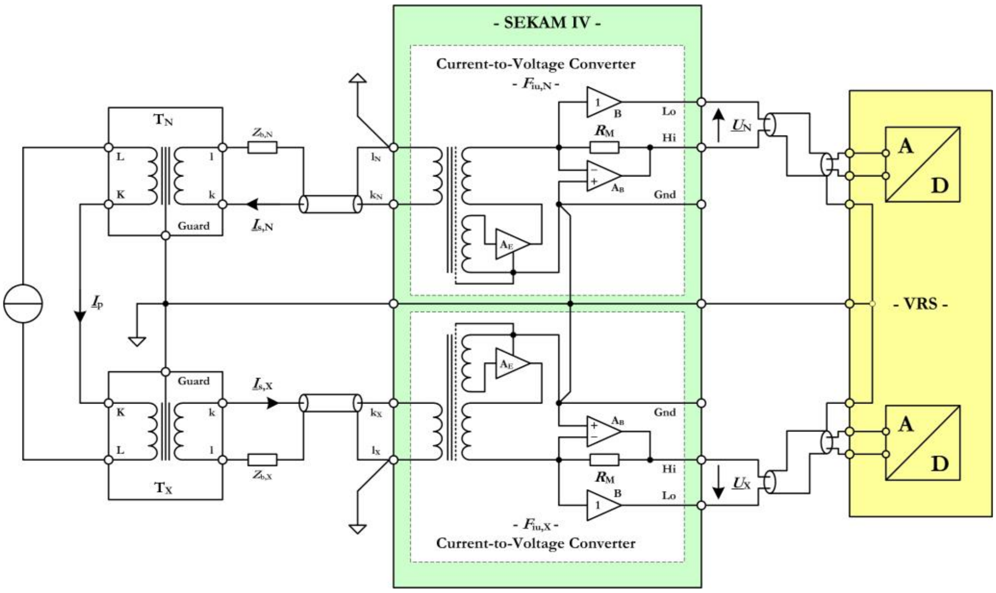
Optimised vehicle-to-grid concepts

An additional topic is the research into optimised vehicle-to-grid concepts. Traditionally, electricity distribution systems represent centrally managed passive grids. However, the need to integrate renewable generation has led to the development of active distribution networks where the energy is fed in at the LV and MV levels. In this context, electrical storage management as one of the players within an active distribution network is investigated with special focus on battery powered electric vehicles (BEV). The results of the research activities from the Technical University of Braunschweig were used to analyze the effects of the grid. In summary, a targeted integration of electric vehicles charging management is necessary. The technical and regulatory requirements are described in the project documentation in detail. The early adaptation of the temporal requirements for the development of electric mobility has shown that there is a long way to go to enter mass market. However, the progress of standardisation is a rapid progress. The current charging stations already meet the main technical requirements of DIN EN 61851. Furthermore, the intelligent communication with power line communication is being developed (ISO 15118). This standardisation is the basis for uniform roaming processes.

Metrology-Grade Calibration System for Current Transformers to Measure Polluted Grid Currents

Another research topic was to develop a current transformer bridge with a current-to-voltage converter module, a voltage ratio measurement system, and the necessary minimum information of the mathematics inside the LabVIEW software. In particular, the ratio measurement system is based on the work performed in collaboration with CEPRI, the China Electric Power Research Institute. From this work a metrology grade system to measure polluted grid currents in current transformers was developed. Two equal front-end modules and software for a two-channel digitiser were constructed and are now in operation in the laboratories of CEPRI and PTB.

The next figure shows the setup of the CTTS for calibrating the CT TX against the standard CT TN using the high accurate dual current-to-voltage converter module with the sampling-based two-channel ratio measurement system VRS. A waveform generator with a high power amplifier and associated range transformers is used to generate the test current Ip. The output of the current source is connected to the reference standard TN and the CT under test TX. Each secondary of both CTs is connected to a calibrated current-to-voltage converter of the subsequently arranged bridge.



Beyond the original objectives of the project, a very important activity was carried out. As the bridge was only capable of handling ac currents up to 10 A, a high quality generation system for higher currents was needed. The report therefore deals with the generation of arbitrary current waveforms. METAS developed a software control module for a commercial two-channel signal generator with 16 bit resolution. Additionally, collaboration between two industrial partners (Ritz Instrument Transformers GmbH and ROHRER GmbH) and PTB led to the construction of a customised range transformer, and an adaptation of a high-power amplifier for the needs of an instrument transformer test laboratory (soft-start as a necessary feature).

Finally calibration results with different types of possible transformers were described. First, a two-stage standard transformer with an accuracy level in the order of ppm was tested in order to compare the attained accuracy of the new system, compared to the PTB primary standard for current transformer measurements. The second transformer is a wideband reference transformer with an accuracy level of 10… 30 ppm - an ac-dc current transformer (LEM PSU 200 HF) with a defined ratio of 100 A / 100 mA. The third transformer is a class 0,5 instrument transformer (from Ritz) with several ratios from (25 A… 100 A) / 1 A. The calibration certificates of the latter two current transformers were uploaded as an intermediate progress report to the project public website.

Cryptographic infrastructure for electrical smart grids

A further objective for the research work was to design a cryptographic infrastructure for electrical smart grids. Due to the scope of the ENG04 project the MV and LV grid elements were the focus of the analysis. The problems in each grid region are very similar. Electrical grids consist of critical elements and components which need to be protected against manipulations and threats. Any cryptographic infrastructure has to take into account that in sum many single elements of the same kind (e. g. simple measurement sensors, state indicators, ..) have the same influence on the grid security as one complex one (e.g. data acquisition systems, grid control center). Firstly, these elements of the smart grid were identified. The main focus was on sensors and actors for measurement and control of the grid and energy management systems with information databases about the grid state and control strategies. An analysis of grid architectures was performed, during which all components, actors, roles, methods, effects/influences, interactions were taken into account. The main result was the realisation that manipulations of many apparently insignificant components probably has the same influence on security as only one significant component. Beside the theoretical concepts, the international standardisation efforts at the European level were actively supported by active participation in the meetings of EC Task Force Smart Grid (DG Energy) and the CEN/CENELEC/ETSI Smart Grid Information Security group. Also the results of research work in security for measurement and control on e-mobility projects was taken into account for the proposed concept of a cryptographic infrastructure for smart grids..

A possible control model for the secure integration of electric vehicles into the electrical grid has been developed. This will be analyzed in detail in further studies at the TU Braunschweig. In this model, the focus is on the customers of the electric vehicle, who require both security and cost benefit with respect to a conventional vehicle.

A security concept and a cryptographic infrastructure for smart grids was proposed. It takes into account an analysis of sensitive components and data flows (critical elements) in smart grids with special attention to safety and security. The active participation in standardisation and the practical work finding security solutions for distributed measurement systems were important for the research work. The concept is not limited to architectures of simple test grids because real grids are much more complex. The system architectures of the Smart Grid Interoperable Project (SGIP) and the European Smart Grid Reference Architecture (SGRA) were investigated and discussed. It showed the general problems, (e. g. mass of communication standards, high complex architectures) getting homogeneous smart grid architectures and usable security solutions for measurement infrastructures. It has been seen that secure smart grids have to fulfill a multiplicity of requirements. The security concept deals with standard strong cryptographic algorithms like Elliptic Curve Cryptography and Advanced Encryption Standard and a cryptographic infrastructure which is a precondition of the successful implementation of the concept. An important result of the research work was the set-up of a test certification authority (CA) for measurement systems and the implementation of secure prototypes for measurement purposes.

3.2 Measurement framework for reliable and accurate Phasor Measurement Units

The aim of the phasor measurement unit (PMU) research of the project was to develop a PMU metrological infrastructure in Europe with the aim of making PMU measurements traceable to the SI system of units. PMUs are used in Europe primarily for wide area monitoring so that transmission networks can be monitored more globally and at a much higher rate than with traditional SCADA systems. Similarly to the USA and China, the rate of acceptance of PMU technology is likely to gain momentum over the coming years. It is also expected that PMUs will find their way into distribution networks in which they will act as sensors for the control of grids with distributed generation.

The role of the NMIs is to provide a metrological infrastructure which can ensure that PMUs measurements are both traceable and conform to standards. While such infrastructures exist in the USA and China, the European NMIs undertook the challenge to establish such an infrastructure and close the gap within the framework of this project. This would have been a difficult task for a single NMI; therefore a common approach was adopted. This project work on PMUs is made up of four parts: design of a PMU algorithm simulator, the realisation of a reference PMU, a PMU calibrator as well as field and laboratory tests with commercial PMUs. Together, this provides the expertise and knowledge to develop the tools necessary to establish the traceability of PMU measurements.

PMU simulation platform and PMU algorithms

A software platform has been developed to evaluate the behaviour of PMU algorithms under different power system conditions. In order to have a flexible simulator to be shared among the project partners, the main variables in the PMU platform were discussed and a commonly accepted data structure was selected. Matlab was chosen as the language for implementing the platform and the design is organised around “structures”, which, in the Matlab language, are sets of co-ordinated variables data type. These “structures” are the connecting links between the various "functions", which perform their tasks in a fixed and expected way and are supposed to be unchangeable within a given version of the platform.

The PMU algorithms under test are built as Matlab "functions" and connected to the platform by putting them in the same directory. In the simulation they receive the sampled data and the sampled times and return the frequency, amplitude, phase and rate of frequency change estimations at the specified time frames. So, by means of the application of the proper input parameters, their behaviour can be simulated and their response analysed.

The software platform was built on the basis of the existing standard and, by means of the application of the proper input parameters, the behaviour of a PMU algorithm can be simulated and its response analysed. The positive characteristics of the platform are the compliance to the existing standards and the simplicity and the modularity of its set-up. The tasks separation permits an easy testing and maintenance of the software.

The main "functions" of the platform have been implemented for the following purposes:

- *The waveform generator* produces the signal (the set of samples and the relevant time values) that is supplied to the PMU algorithm under test from the parameters selected. In addition, this function computes the reference parameters of the waveform as a time function and, at the suitable times (frames), the values of the theoretical PMU parameters to be compared with those returned by the PMU algorithm under test. This function comprises also other sub-functions like the modulator, which give a wide possibility for defining the signals produced by the simulator, including sweeping input signal with sinusoidal amplitude and phase modulation and with a linear ramp for both the amplitude and the frequency.
- *The TVE calculator* receives the parameters derived by mathematical expressions from the signal and compares them to those estimated by the PMU algorithm. The differences, such as the total vector error (TVE), the frequency error (FE), and the ROCOF error (RFE) are evaluated and the TVE (total vector error) is computed.
- *The Graphic User Interfaces (GUIs)* controls the data flow. One of them is used for the acquisition and signal parameter definition and the other for performing calculations and displaying the results of the processing. These programs can be used sequentially or independently. For the second one, which generates the samples to be sent to the PMU algorithm and the instantaneous parameters considered as the "ideal PMU" response, the present definition of the signal parameters, based on the IEEE standard C37.118.1™ - 2011 has been assumed. However, the software platform can be easily modified for other definitions based on future standards.

By means of the software platform developed, algorithms published in technical literature and developed for the purpose were tested on their applicability for use in PMU were studied. A set of 7 algorithms was investigated for their applicability and their implementation was unified to provide a common calling structure for inclusion into the PMU platform: 2-point interpolated Discrete Fourier Transform algorithm (DFT2), 3-point interpolated DFT algorithm (DFT3), Four parameter sine fit algorithm (4PSF), Multi-harmonic sine fit algorithm (MHFE), Spectrum leakage correction algorithm (SLCA), Phase sensitive frequency estimation algorithm (PSFE), Interpolated phase sensitive frequency estimation algorithm (iPSFE).

The algorithms were checked for parameters such as speed of execution (the algorithms need to run in real-time), frequency, magnitude and phase deviation, harmonic components, inter-harmonic components, phase and amplitude modulation, magnitude and phase step.

During the project the algorithm developed by SIQ in EMRP project Power & Energy (PSFE algorithm) was further improved in terms of harmonic distortion insensitivity and amplitude / phase estimation accuracy. Comparison of total vector error and phase error calculation based on numerous simulations shows that the improved PSFE algorithm is more efficient for highly distorted signals that are expected on power lines.

PMU algorithms were analyzed with the signals according to the PMU standard IEEE Std C37.118.1-2011. Steady-state and dynamic compliance of power signals were verified with *TVE* (Total Vector Error), *FE* (Frequency Error) and *RFE* (ROCOF Error). The static tests included fundamental harmonics or inter-harmonics. In the parameter estimation results the different effects produced by the distortion in the algorithms considered become evident for distortions larger than 0,1 %, and it also depend on sampling parameters used, especially on the number of signal periods taken into consideration.

All required steady-state and dynamic power signals according to the PMU standard were programmed and generated in MATLAB. These signals were sampled and by using different algorithms, the PMU parameters (*TVE*, *FE* and *RFE*) were determined. Complete analysis of the simulations resulted in a table containing the suitability of different algorithms for specific signals that can occur on power lines.

The results of the harmonic showed similar error propagation as a function of the harmonic amplitude for both TVE and phase error. The sine fit algorithms (for example 4PSF) are generally sensitive to increased harmonic distortions, because they compensate the harmonic presence by adjusting amplitude and phase away from the actual fundamental amplitude and phase to find a minimum fit error. As expected, MHFE resulted insensitive to harmonic distortion because it effectively evaluate all harmonic components used within the model, even if the computing burden is high. In the PSFE, when the distance between the two points considered in the evaluation is chosen as close as possible to the integer number of periods of the fundamental, there is an effective cancellation of harmonic components influence, despite the use of a simple sine wave model. The effects given by the harmonic distortions are attenuated also by the 3pDFT, while the SLCA algorithm is quite sensitive to them.

The results given using inter-harmonic distortions show quite different behavior. SLCA performed with smallest estimation errors followed by 3pDFT algorithm. This can be explained by the fact that these algorithms operate in the frequency domain which effectively separate the inter-harmonics from the fundamental, minimising their interference on the estimated parameters.

From thee performed tests it could be concluded that algorithms PSFE and iPSFE are suitable for all tested signals. Algorithms MHFE and SLCA perform very well except for determination of *FE* at harmonically distorted signals. Other algorithms shall be used only for specific signals in order to get relevant results.

<u>Reference PMU</u>

The development of the metrology grade reference PMU was carried out at LNE according to the requirements of the IEEE C37.118-2005 standard (in relation with steady-state conditions). The hardware architecture was derived according to information in recent literature. For practical reasons (transportability, ruggedness, modularity, scalability,..) the hardware architecture was implemented based on National Instruments solutions. This implementation consists in a PXIe-8133 platform (embedded in a PXIe-1082 chassis) provided with high speed analog to digital converters (PXIe-6366 and PXI 7852R) and Timing and GPS synchronisation modules (PXI 6674T PXI 6682H). An active GPS receiver is coupled with an external antenna. From the signal received, a 10 MHz clock is generated in order to have all the data points time stamped according to GPS.

The software platform was implemented in the LabVIEW Real-Time environment. It consists in two parts: one running on a laptop and the other one embedded in a real-time target (RT Target). Communication between the two sub-systems was made via an Ethernet connection. The laptop host the graphical user interface (GUI). This part was implemented in order to fit (in terms of data structures) with the GUI implemented for the simulation platform.

As built, the RT target acquires (continuously, with a determined jitter) the waveforms from the grid. These waveforms are then processed via an embedded signal processing module (developed by SIQ) which calculates the actual frequency (f), magnitude (X_{mag}, X may be voltage or current) and phase (X_{phi}) of the signal from the grid. This calculation is performed over a determined number of cycles depending on the reporting rate.

The parameters *f*, *Xmag*, *Xphi* and the rate of change of frequency (*ROCOF*) constitute a frame. This frame, according to the IEEE C.37.118.1 standard [iii], must be reported at a rate depending on the grid nominal frequency (10, 25 or 50 frames per second for a 50 Hz grid and 10, 12, 15, 20, 30 or 60 frames per second for a 60 Hz system). The choice of the reporting rate determines the length of the window over which the calculation is made for one frame.

The as-built system was characterised under steady-state conditions at METAS using the PMU calibrator. The results obtained for a pure sine waveform seem to indicate that the measured phase is steadily varying instead of remaining constant. This is the signature of a loss of synchronisation during the measurement process.

Another remark which can be stated here is the fact that ROCOF is not equal to zero as it should have been expected in this situation for a perfect sine waveform. This may be due to the algorithm implemented for the ROCOF calculation. In fact the SIQ algorithm on which it is based, needs at least two cycles to produce significant results but in some cases, for some reporting rates, this condition is not fulfilled. However the value of ROCOF, even though not equal to zero, remains constant over the duration of the measurement, indicating a somewhat stable behaviour of the SIQ algorithm, for steady-state conditions. Moreover both frequency and magnitude are relatively stable (~2 ppm and ~40 ppm of variation around the mean values for frequency and magnitude respectively).

The characterisation of the reference PMU according to the IEEE C37.118-2005 standard lead to the application of different test scenarios: frequency range (from 45 Hz to 55 Hz), magnitude range (from 10% to 120% of nominal magnitude), phase range (from - 180° to + 180°), harmonics and interharmonics tests (at three different frequencies: 47.5 Hz, 50 Hz and 52.5 Hz).

The results obtained show that the signal processing algorithm behaves as expected only when the signal frequency is close to the nominal value (50 Hz), the TVE value is within the limits of the standard. In such a case the values reported in the corresponding frame are in the same order of magnitude that those obtained for a pure sine wave at nominal frequency. However, when the signal frequency differs significantly from the nominal value the frames reported become very different from those around 50 Hz. This observation is also made for the other test scenarios.

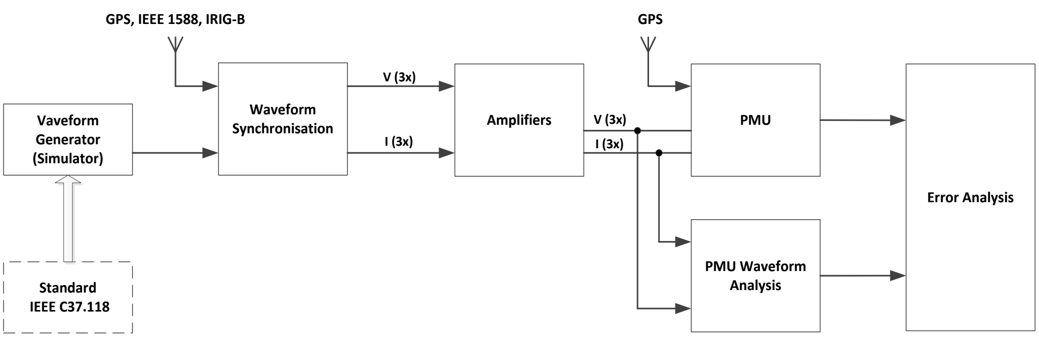
PMU calibrator

The PMU calibrator has been designed primarily as a test bed for the purposes of conducting compliance testing of PMUs against the standard IEEE C37.118.1-2011. This standard consists of both static and dynamic tests. However only static tests have been implemented since IEEE C37.118.1-2011 was no yet published at the time of the planning of the project. The implementation of the dynamic tests would have not been possible with the resources allowed to this project. The dynamic tests will be implemented in a follow up project.

The PMU calibrator was built using a combination of off the shelf components and proprietary hardware. The core functionally of the calibrator consists of generating three phase (voltage and current) waveforms that are synchronised to UTC. These signals are applied to the inputs of a PMU after amplification. The waveforms are those described in the standard IEEE C37.118.1-2011 for steady state tests. Steady-state conditions are where the magnitude, frequency, phases of the test signal, and all other influence quantities are fixed for the period of measurement (Section 5.5.5 of Standard). The following tests were implemented:

- Signal frequency range
- Signal magnitude – Voltage
- Signal magnitude – Current
- Phase angle
- Harmonic distortion
- Out of band interference

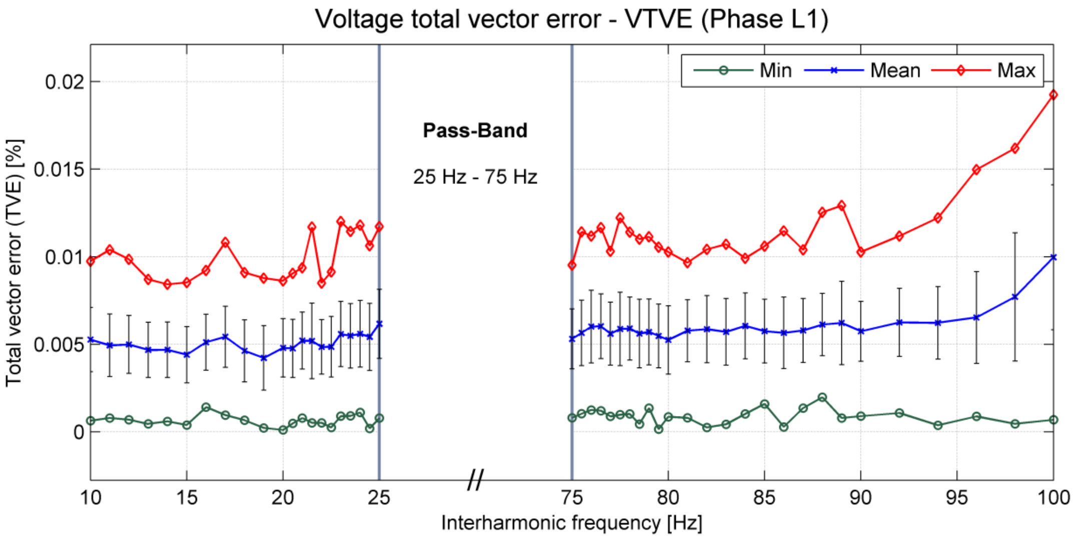
The following simplified schematic diagram shows the key components of the calibrator



The waveforms generated in the PMU simulation platform are also used in the calibrator. The waveform are stored in files and played back during the test. This provides a test of the PMU using the exact same waveforms that have been used during the simulation. During a test, the waveforms are read out and buffered before being applied to DACs. The synchronisation of these waveforms to UTC is achieved with a local event generator whose internal timer is synchronised to GPS, IEEE 1588 or IRIG-B selectable by the operator. Once generated, these waveforms are amplified with the two three-phase amplifiers designed and built by INRIM to transform the signals generated at low voltage into signals suitable to be applied to the input of one or more PMUs. The nominal voltage has been set to 110 V and 1 A for the current.

The first amplifier is a three-phase voltage amplifier with the three channels having a fixed nominal gain of 20. The output voltage is between –190V and +190V (in order to be able to produce, with moderate distorted sinusoidal signals, up to 120 V RSM. Its frequency band on resistive load is over 300 kHz at 20 V RMS and, in the full range, the band is limited by the slew-rate of the amplifier (about 100 V/μs) and by a possible capacitive load. The second amplifier is a three-phase transconductance amplifier. The gain of the three channels is 1 Ω^{-1} and the output voltage is between –5 A and +5 A to be able to produce with moderate distorted sinusoidal signals up to 2.5 A RSM with a bandwidth on resistive load of 20 kHz. The frequency band and the signal amplitude are limited if inductive loads are applied. A series of possible solutions have been investigated for the input transducers of the voltage and current channels of reference PMUs. These transducers were based on coaxial shunts and resistive dividers, alone or in conjunction with single stage or double stage active transformers to separate the input ground from the digitisers ground. In the experimental circuit, specific problems were encountered in particular for the insufficient stability of the coaxial resistive dividers.

For each of the PMU tests mentioned above, the PMU reports time-stamped values for the phasors, frequency and ROCOF (Rate of Change Of Frequency). The time stamps correspond to the selected reporting rate. To evaluate this data, they must be compared with those of the waveforms present at the input of the PMU. To this end, these waveforms are resampled and analysed. The analysis consists on a best fit of the waveform with the theoretical waveform that is being generated. Once the waveform parameters have been extracted it is possible to determine what the PMU should report. A direct comparison can then be made and the TVE (Total Vector Error) computed. Frequency and ROCOF can be directly compared. The graph below shows an example of TVE obtained on a commercial PMU during an out of band interference test. The test results can be directly compared to the limits set by the IEEE standard.

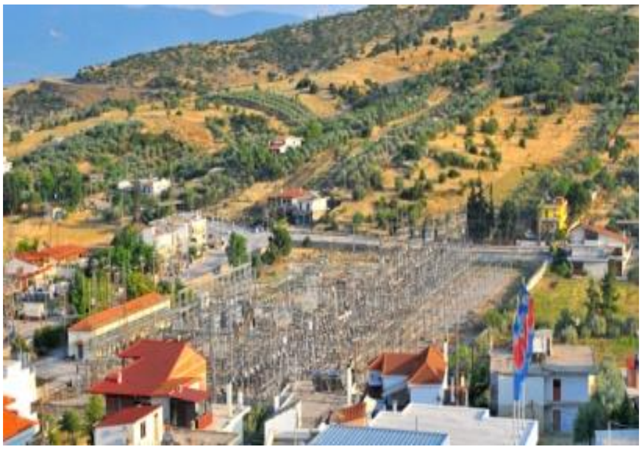


As the amount of data generated during any test is very large, it is important to have software allowing a high degree of automation. This software is responsible for the sequencing of the waveform data during the generation and reacquisition of the waveform applied to the PMU, and the output from the PMU. As these real time functions handle a large of amount of data, the actual data analysis is made off line after the completion of the test.

PMU field measurements

A series of on-site PMU measurements were performed in Greece and Sweden.

Effective cooperation between the partners EIM and SP and exchange of experience was achieved by performing two on-site measurements together in two high voltage substations in Athens and Thessaloniki, Greece. The results of a well-characterised PMU from SP have been compared to that of an installed commercial PMU, the device under test (DUT). The results gave significant insight in on-site aspects affecting the uncertainty of PMU measurements in real grids. This among others included the effects of secondary wiring, grounding circuits, and settings of the DUT. It appeared crucial to have full documentation of the DUT and of the connections to the current and voltage transformers.



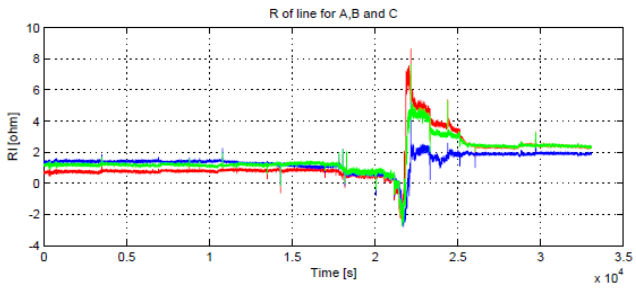
The table below shows the results of one of the tests, which indicates that the differences in both voltage magnitude and voltage phase between the reference PMU and the installed PMU (the DUT) are negligible.

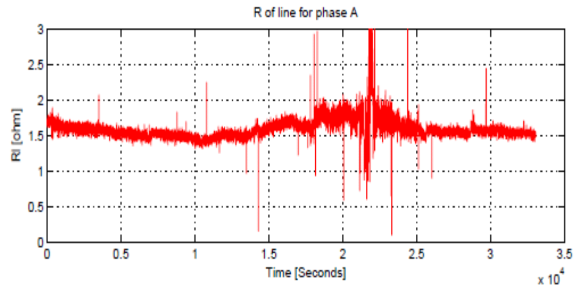
Date: 5 September 2012

EIM (PMU Connection Tester)					SP (ARBITER)					COMPARISON EIM-SP		
Date-Time	Phasor U1 (deg)	Phasor U1 (V)	Freq (Hz)	Delta freq	UTC Time	Phasor U1 (V)	Phasor U1 (deg)	Freq (Hz)	Delta freq	Diff angle (°)	Diff volt (%)	Diff Hz
9:35:32.000	-135.7889412	59.24047	49.979	-0.01	9:35:32.000	58.406292	-135.416183	49.9793	-0.0013	-0.03	-0.02	-0.0003
9:35:33.000	-142.7392937	59.27370	49.984	0	9:35:33.000	58.408279	-142.359863	49.9807	0.0053	0.01	-0.01	0.0033
9:35:34.000	-147.4909393	59.28245	49.989	0.01	9:35:34.000	58.433929	-147.117584	49.9868	0.0043	-0.02	-0.01	0.0028
9:35:35.000	-152.1380688	59.26387	49.987	-0.01	9:35:35.000	58.421711	-151.761948	49.9871	-0.0014	-0.03	-0.01	0.0019
9:35:36.004	-156.9764633	59.25621	49.987	0	9:35:36.004	58.409988	-156.505432	49.9868	0.0000	-0.03	0.05	0.0002
9:35:37.000	-161.5112902	59.24176	49.988	0	9:35:37.000	58.400471	-161.138855	49.9871	0.0012	-0.04	-0.01	-0.0001
9:35:38.000	-166.153174	59.24049	49.986	-0.01	9:35:38.000	58.403606	-165.78038	49.9871	-0.0022	-0.05	-0.01	0.0009
9:35:39.000	-171.4392799	59.22798	49.986	0	9:35:39.000	58.384396	-171.066727	49.9853	-0.0006	-0.04	-0.01	0.0007
9:35:40.004	-176.6350992	59.24152	49.986	0	9:35:40.004	58.378258	-176.160278	49.9859	0.0010	-0.01	0.05	0.0001

The second series of on-site measurements were performed in Sweden by a team of project partners, consisting of SP, EJPD, BRML, LNE, and VSL. The on-site PMU measurements were performed on both ends of a 97-km 400-kV overhead line: one PMU was installed at each end of the power line and measured both voltage and current phasors. The total on-site campaign lasted three days and in two consecutive runs, measurement data was collected over around 10 hours.

In a collaborative effort by IMBIH and VSL, the acquired PMU phasor data was subsequently analysed. The analysis focused on the determination of overhead line impedance parameters. Accurate knowledge of these parameters helps the transmission system operator to improve accuracy in relay settings, post event fault location, and transmission power flow modeling. The results of the analysis showed that the overhead line impedance is very sensitive to errors in the voltage phasors. Such errors are inevitable in practice and not only include the deviations of the PMU, but also the current and voltage transformers (VT) used to connect the PMU to the electricity grid. Since the PMUs used in this experiment were calibrated and found to have insignificant errors, the main contribution to the errors originated from the voltage transformers. Using two methods, a sensitivity analysis and an independent least-squares method, both the line impedance parameters and the errors of the voltage transformers could be determined. A typical result of the initial line impedance determination without VT error correction and the final analysis with VT error correction are shown in the two graphs below (left and right graph respectively; note the different y-axis scales in the graphs). The inadequacy of the initial analysis is clearly proved by the large variation of the calculated line resistance R over time, which corresponds to variation of grid current.





It appears that the voltage transformers had a small deviation from their known value, of 0.1 % in amplitude and 1 minute in phase, which is well within their specifications and well within their calibration data. Given the results of this analysis, PMUs appear to be ideally suited for both accurate determination of grid line impedances as well as provide a method for calibrating voltage transformers in the grid.

Best Practice Guide for PMU testing and calibration

The PMU test protocol Best Practice Guide has been prepared, which is freely available at the Euramet research publications repository. Each participant has added his part and SIQ has revised and finished the whole document. PMU test protocol Best Practice Guide consists of the following sections: Laboratory testing of Phasor Measurement Units, Field measurements of Phasor Measurement Units, Application of PMU in electricity grids, and two annexes with a reference algorithm selection guide, and information on the selection of window types in the Arbiter 1133A PMU respectively. With this information, the Best Practice Guide forms a useful reference document to utilities and test / calibration laboratories for measurement and testing of PMUs, and for performing phasor measurements in actual electricity grids using PMUs.

3.3 On-site measurement campaigns of power quality (PQ)

Distribution Network Operators (DNOs) and Transmission Systems Operators (TSO) are each responsible for ensuring that new renewable generation equipment and other smart grid technology can be accommodated without detrimental effects to the energy supply power quality such that electricity safety, quality and continuity regulations are met.

Hence there is a keen-interest in the effect of renewables on a network such that DNO/TSO can predict the impact of planned large-scale installations and if necessary make provisions for network reinforcements to mitigate any detrimental effects they have on power quality or network reliability.

In order to determine the effects of large-scale installations, the most reliable method was to undertake on-site measurement surveys that spanned several weeks or even months. This period encompassed a wide variation in weather conditions and seasonal load changes, such that comparisons of the network behaviour with and without new generation could be compared.

This part of the project was set out to make three such surveys in a variety of networks, however due to the level of interest from network operators, finally six such surveys were completed across Europe. This work involved 4 distribution networks and 1 transmission network and one for a wind-turbine manufacturer, details of which are given below.

Each campaign required considerable preparation and planning. To assist with this task an *on-site measurement questionnaire* was prepared and used in each campaign, during the initial site-surveys. Issues such as connection access, safety regulations, required measurement parameters/Standards and site logistics were all covered in the questionnaire (the questionnaire is included as an annex in the Best Practice Guide – see below). A mixture of commercial and project built power quality analyser equipment was used to conduct the measurement campaigns. Details are given for each case below.

Distribution Networks

Distribution networks exist in localised areas feeding domestic, commercial and light industrial consumers with power at low and medium voltage (LV and MV) levels. These networks are the backbone for future

SmartGrids and will the point of connection for distributed renewable generation. A variety of distribution network scenarios were considered as described below.

Retro-Fitted Solar PV

An example of distributed generation is the ever increasing amount of photo-voltaic (PV) panel generation that is retro-fitted to domestic dwellings. This mostly occurs on an ad-hoc basis, however the proliferation is causing PQ concerns, particularly as any disturbances will be correlated and aggregated as utilisation increases.

The retro-fitting of a relatively large cluster of PV generation provides an excellent opportunity to study this aggregated effect at substations that feed such installations. Such an example was a PV cluster located in Anglesey, North Wales connected to a distribution network owned and operated by Scottish Power Energy Networks plc who collaborated with NPL to undertake a 9 month survey on this network using project-built analysis equipment and software. Control of the equipment and regular data download was completed using the internet.

The effect of the PV cluster generation on local power quality was assessed and parameters including current and voltage harmonics, flicker, active and reactive power, voltage unbalance were all measured and compared during periods of generation and no generation and solar radiance. The results have been reported in a full paper submitted to the premier industry conference, CIRAD 2013.

The most significant effect seen during the study was a rise in voltage associated with PV generation. The analysis of the results presented shows that the voltage at the substation transformer increased by about 1 V during periods of generation. The rise in the middle of the feeder was more significant, showing a voltage change of about 4 V during PV generation. There was no detectable evidence of significant harmonic, interharmonics or flicker disturbance form the type of invertor used in this installation.

It was observed that the voltage on this network was at the high end of the statutory limits, which is typical of the UKs traditional 240 V infrastructure. Such mid-feeder voltage rise maybe of some concern to the networks operators when planning to add substantial PV to LV systems.

It is noteworthy that on average the PV units are generating at approximately half capacity on the sunniest days during the survey, which was conducted in the summer months. It is interesting to speculate as to effect of this finding on cost-benefit and CO_2 savings estimates that maybe used in such projects to justify investment.

Renewable Generation Technology Park

The future integration of different renewable generation sources into the same electrical grid is a great challenge both for network planners and Smart Grid researchers. The Walqa technology park in Spain is a good example of a distribution network with mixed renewables including wind turbines, solar panels and hydrogen production. A 9-month on-site measurement campaign was undertaken by CEM in collaboration with Fundación del Hidrógeno en Aragón, the owner of the Walqa installation. The campaign was undertaken with several GPS synchronised digitisers/PQ analyzers designed and built by CEM. The large data sets generated were downloaded and managed by a specially written SQL data base to ease the analysis and find trends and events in the 9 months of data.

The campaign has resulted in several important findings which will be of benefit to the operator in under-standing the grid's behavior and to the wider electricity community when planning and operating this sort of mixed renewable network. The findings are summarised as follows:

Wind turbine failures are common at weekends; results from the PQ study indicated increased overvoltage events at weekends due to the relative light grid loading. These changes on voltage levels were often found to trip the turbines leading to loss of service. This is particularly prevalent in older wind turbines with less sophisticated power control circuits. Having measured and understood the apparent cause of these trips, it is recommended that the installation of MV auto-reclosers at generation busbars should be carried out in order to reconnect the turbines following these false voltage trips.

Flicker is an important PQ parameter related to public health and the annoyance of electric lighting disturbance. Wind-turbines must conform to international limits on flicker (i.e. IEC 61400-21). During the measurement campaign excessive levels of flicker were observed at the customers' buildings. The renewable generation sources (especially wind turbines) were the prime suspects for these disturbances. However, after analyzing the recorded campaign data, it was found that the flicker levels were associated with the high-level of non-linear loads (i.e. computers, lighting, etc.) installed inside the buildings. Conversely, the flicker levels at renewable sources were always beneath the EN 50160 limits.

Similarly, the measurements showed that the levels of the voltage harmonics produced by the renewable generation were not a significant contributor to the measured levels of harmonic content measured at the customers' building, this again was a consequence of the high-level of non-linear loads. However, it is recommended that further investigation should be made to confirm this by separating the contribution of the network loads from the generation.

The relatively small geographical distances within the Walqa's distribution network, makes it impossible to relate voltage event propagation from renewable sources to the customers' side. However, the GPS synchronised multiple measurement point scheme used in this campaign is a prototype for future PQ propagation campaigns on larger distribution networks.

Urban Distribution Grid, before and after PV installation

SMU in collaboration with the Slovak DNO (ZSE Distribucia a.s.) performed an on-site PQ campaign over a six month period which included the installation PV panels. The measurement location was in the western part of Slovakia in a LV 3-phase, 4-wire urban distribution network. The first period of the campaign was conducted in June 2012 prior to the installation of the PV. Following the PV installation, a second period of measurements was made between July and Nov 2012.

A commercial PQ analyzer, the Fluke 1760 PQ1, and associated transducers were used in the campaign. This instrument has 600 V range voltage inputs and 50A/5A clamps were used for the current inputs. The PQ Analyzer was calibrated prior to making on-site measurements.

The measured parameters were according to the standard EN 50160. The measurement procedure was according to the standard IEC 61000-4-30, Class A.

A summary of data analysis is presented below in Fig. 1, Fig. 2 and in the Events Table. It can be seen that the number of events increases after the PV panels were installed (July 2012). Some PQ parameters measured during the July and August 2012 campaign exceeded the limit values according to the standard EN50160.

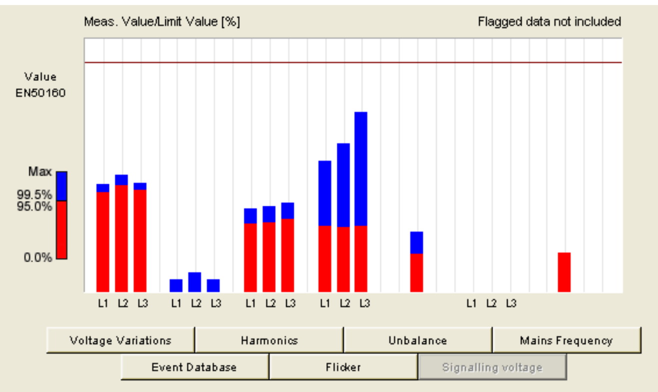


Fig.1 Statistics Charts for DNO - June 2012 (before the PV panels were installed)

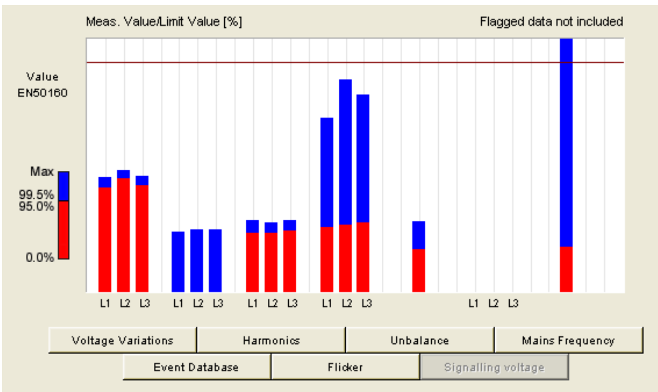


Fig. 2 Statistics Charts for DNO - July 2012 (after the PV panels were installed)

The y-axis of the charts is the ratio of measured value to limit value. The a-axis shows the various PQ parameters measured with a set of three bars situated above each parameter indicating the PQ levels for each of the respective phases. Legend for the charts:
RED: at least 95% of the values of one week have to be within the 95% tolerance range.
BLUE: 100% of the values of one week have to be within the 100% tolerance range.

Events/Months	June				July				August				September			
Designation	L1	L2	L3	L3ph	L1	L2	L3	L3ph	L1	L2	L3	L3ph	L1	L2	L3	L3ph
Overvoltages	0	0	0	0	4	4	4	4	3	4	4	4	2	2	2	2
Voltage dips	4	6	4	5	16	17	17	19	9	10	9	13	5	7	5	7
Short interruptions	1	2	1	2	1	1	1	1	1	1	1	1	0	0	0	0
Long interruptions	0	0	0	0	5	5	5	5	4	4	4	4	2	2	2	2
TOTAL	5	8	5	7	26	27	27	29	17	19	18	22	9	11	9	11

The events table shows an increase in over-voltage and dip PQ events following the installation of the PV panels. This is consistent with the trend seen in the Anglesey campaign where PV generation was seen to cause voltage regulation difficulties, although these results are much more significant and beyond the statutory limits. The total events reduction in September could be related to reduced sunshine, alternatively the high July/August count could be explained by the general degradation of the quality of the network due to summer period system maintenance outages and changed load types. Correlation of events to solar radiation should ideally be included to strengthen these conclusions.

MV Distribution Network with Large PV Park.

Large PV generation plants often operate in tandem with industrial sites connected to the public MV network. PQ assessment gives useful information on the impact of large PV generation on the network, in relation to the structure of the network itself and on the PV plant operating conditions. A measurement campaign was performed by INRiM at a private MV/LV 15 kV/400 V, 40 A private substation. The substation is connected to the public MV distribution network and supplies a factory equipped with a PV generation plant, respectively rated 200 kW and 800 kW. The private network can absorb up to 800 kW from the DNO and supply up to 1 MVA. Voltage and current were measured on the MV line connecting the 800 kVA step-up transformer to the main MV substation busbar. Two series of measurements were carried in autumn 2012 and late spring/early summer 2013 respectively.

Measuring systems equipped with a characterised INRiM MV resistive voltage dividers and commercial Rogowski coil current transducers were used in association with a digitiser based on an NI Compact RIO embedded real-time controller. Prior to the campaign, accurate laboratory characterisation of the sensors was made under conditions reproducing the measurement site, thus reducing the associated PQ parameters measurement uncertainty. Since the generated current is related to the solar conditions, a passive pyranometer was installed close to the solar panels and its output voltage was simultaneously measured.

The daily behaviour of the generated current was measured under different weather conditions and different maximum irradiance conditions. The highest rms current measured in late autumn days under full solar irradiance was found to be half of the maximum values (30 A rms) measured in late spring/early summer. Under changeable weather conditions, even on an early summer day, the generated current varied by more than one order of magnitude down to a few amperes.

The current Total Harmonic Distortion (THD) is found to significantly increase for values lower than about an ampere. However, the corresponding measured voltage THD remains relatively unchanged (<1%). No harmonic component at the PV invertor switching frequency was detected. Daily and weekly analysis of data, shows a slight voltage increase during the night.

The voltage frequency content over the week includes significant contribution from the 5th, 7th and 11th harmonic. Unexpected decreases of the 5th harmonic amplitude were found every work day between 8 am and 12 am; however, this effect is not evident during the weekend. A deeper investigation of this behaviour will include an analysis of the correlation with the factory working cycle.

In general, with reference to the PQ limit indicated by the IEC 50160 for the public network, no significant PQ problems were detected for the considered plant. A few overvoltage events were found (no more than one over a week) with reference to the observation period.

Transmission Networks

Transmission systems are used for bulk-power transfer over long distances and operate at high voltage (HV) levels. Power quality is also important at HV and the connection of large disturbing loads or major renewable farms could have an impact.

Transmission System Substation

SMU performed on-site PQ measurement campaigns in collaboration with the Slovak Transmission System Operator (TSO), SEPS a.s.. The measurements took place in a HV/MV substation in the central part of Slovakia, for a 6 month period between June 2012 and November 2012. The system under investigation: 3-phase 4-wire.

Installed transformers were used for the measurements; the current transformers ratio as 1600 A/1 A and 10 A/1 A current clamps were used in association with the PQ analyser current channel. The voltage transformers ratio was 110 kV/100 V, the secondary being connected to the 100 V range of the PQ analyser. The accuracy class of the installed transformers was 0.2.

The parameters were measured in accordance with the standard EN 50160. The measurement procedure was according to the standard IEC 61000-4-30, Class A.

A synthesis of data analysis is presented below in Fig. 3, Fig. 4 and in Events Tables. As we can see in figures, the PQ parameters are better kept under control by the TSO, to avoid the problems which might occur at the final users, if the transmission system has events (voltage swells, dips, short/long interruptions, harmonics, etc.).

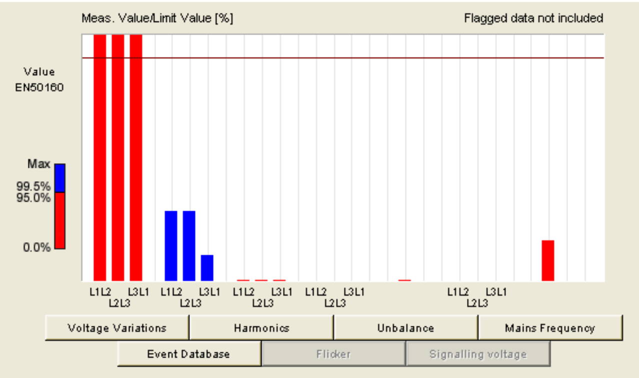


Fig. 3 Statistics Charts for TSO - July 2012

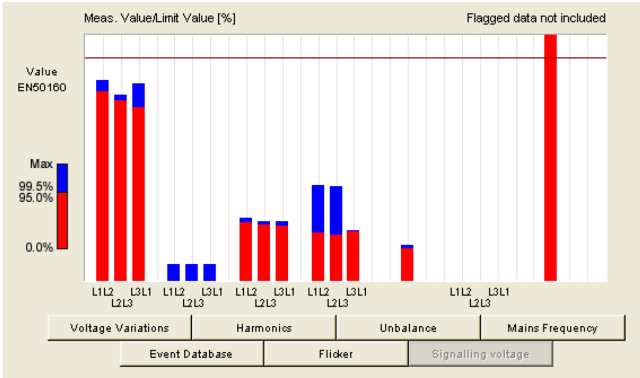


Fig.4 Statistics Charts for TSO - Sept 2012

The y-axis of the charts is the ratio of measured value to limit value. The a-axis shows the various PQ parameters measured with a set of three bars situated above each parameter indicating the PQ levels for each of the respective phases.

Legend for the charts:
RED: at least 95% of the values of one week have to be within the 95% tolerance range.
BLUE: 100% of the values of one week have to be within the 100% tolerance range.

Events/Months	June				July				August			
Designation	L1L2	L2L3	L3L1	Lpp	L1L2	L2L3	L3L1	Lpp	L1L2	L2L3	L3L1	Lpp
Overvoltages	4	4	2	2	17	17	9	1	1	1	1	1
Voltage dips	0	1	0	1	12	13	1	14	2	2	2	2
Short interruptions	0	0	0	0	0	0	0	0	0	0	0	0
Long interruptions	0	0	0	0	0	0	0	0	0	0	0	0
TOTAL	4	5	2	3	29	30	10	15	3	3	3	3

Events/Months	September				October				November			
Designation	L1L2	L2L3	L3L1	Lpp	L1L2	L2L3	L3L1	Lpp	L1L2	L2L3	L3L1	Lpp
Overvoltages	2	2	2	2	4	2	3	1	3	3	2	2
Voltage dips	2	2	2	2	2	2	2	3	2	2	1	2
Short interruptions	0	0	0	0	0	0	0	0	0	0	0	0
Long interruptions	1	1	1	1	0	0	0	0	0	0	0	0
TOTAL	5	5	5	5	6	4	5	4	5	5	3	4

It can be seen from the events table that there are regular overvoltage and dip events on this network. These maybe caused by lightning strikes, system faults or other operational issues. It is interesting to note the significant increase in events during July. It is speculated, that this increase is a result of a weakening of the network capacity associated with the summer maintenance outage period.

Renewable Manufacturers

Manufacturers of renewable plant must ensure that their generation equipment does not introduce PQ disturbance when connected to the network. International standards are emerging that place limits on the levels of particular types of disturbance and the manufacturers must test and certify their designs to ensure that they comply with these limits. In the case of new normative standards the details of how to test are not given and the methods must be devised such that compliance can be guaranteed in a rigorous manner.

Wind Turbine

A test centre for large wind turbines is located in the western part of Denmark. Five different wind turbine manufactures perform type tests of new turbine models. One of the project partners was asked by one of the major wind turbine manufacture to perform traceable measurements of flicker emission of a fictitious grid according to given standards. According to these standards this is a procedure-based task, but according to newer literature the presence of harmonics and inter-harmonics in the measured signals complicates the measurement process.


Wind-turbine on-site measurements; Rogowski coil current sensors installed on wind turbine outputs.

In preparation for this measurement, a series of algorithms were developed and implemented to simulate a fictitious voltage based on voltage and current measurements and a total uncertainty budget for these measurements were presented for the first time. The wind turbine manufacture have collaborated with Trescal and NPL to undertake a 6 month survey on their test wind turbine using project built analysis equipment and software. As in the case of the North Wales site measurement mentioned above, the control of the equipment and regular data download was completed using the internet. All measurements have been compared to measurements made by the wind turbine manufacture and acceptable agreement has been found.

Best Practice Guide for On-Site Power Quality Measurement Campaigns During the planning, execution and analysis stage of the on-site measurement campaigns, many lessons were learnt by the partners and collaborators involved. In order to ensure that future surveys performed by NMIs, utilities or consultant companies benefit from the learning outcomes of this project, a Best Practice Guide has been produced. This is freely available at the Euramet research publications repository.

3.4 Traceable energy measurement systems for revenue metering

The measurement of power and energy flows in the electrical grid is at the heart of ensuring fair trade in electrical energy markets, since bills issued between commercial parties are based on the measured amount of power and energy (revenue metering). In smart electrical grids, the energy flows will increase due to the addition of renewable energy sources and at the same time more commercial parties are involved, due to liberalisation of the energy market. This requires integrity, authenticity and privacy of measurement data as well as increased accuracy and reliability in energy measurements throughout the whole grid.

Under this objective, new metrological revenue metering applications were realised in three areas. The first activity related to smart meters and focused on smarter meters that not only record the total household energy consumption, but also record how much each appliance is contributing to that consumption. To realise this, non-invasive load monitoring (NILM) techniques have been developed for use in the next generation of smart meters together with a dedicated testing facility.

A second activity concerned the verification of the calibration status of energy meters after their installation in distribution grids in houses and apartment buildings. Smart meters with automatic meter reading (AMR) allow for the comparison of their cumulated readings with a summing meter placed ‘upstream’ in the electricity grid. Supported by a meter manufacturer and a distribution grid operator, a special algorithm was developed for deriving the individual smart meter accuracy from the AMR data and the data of the summing meter. This will allow utilities to monitor the calibration status of smart meters in between formal calibrations, and possibly to extend the re-calibration interval of these meters.

The third metering activity concerned the measurement of energy flows in medium and high voltage distribution and transmission grids. The calibration and verification of the accuracy of energy measurement systems in these grids is important for fair trade between the commercial parties exploiting the electricity grid. New set-ups were developed for traceable on-site three-phase electrical energy measurement that, among others, can be used for system calibration of revenue metering systems in the transport and distribution grid.

<u>Smart meters with non-invasive load monitoring</u>

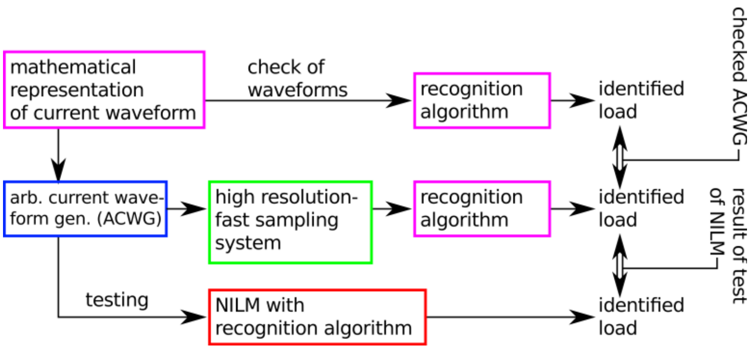
Non Invasive Load Monitors (NILM) are devices that have been in development for the last few years. These devices should be able to identify a load in the home power network without install additional sensors to every electricity plug. The load can be a refrigerator, washing machine, notebook etc. NILM should be able calculate consumption of electricity for a particular load.

The first part of the work concerned the development of an improved NILM algorithm by AUTH. Based on existing methodologies found in published literature, the effort focused on the formulation of distinct and robust ‘appliance signatures’ since it has become clear that they could ensure efficient load identification. From a large series of home appliances the characteristic current signals (‘signatures’) where acquired and analysed. Based on the evaluation of these signals, AUTH has proposed a novel approach for the detection and distinction of different appliances based on the spectral distribution of the current waveform. Special coefficients along with some heuristic rules are used in order to structure the database containing the reference appliance signals. From the evaluation of the proposed algorithm it appears that its benefits are simplicity together with an excellent efficiency level. The simplicity of the algorithm assures easy implementation in smart meters without high computational power requirements. The efficiency of the new algorithm is demonstrated in the effective categorisation of unknown appliances.

In the second stage of the work, a new system for calibration of NILM smart meters has been constructed. The system is designed to calibrate electrical characteristics of the NILM as well as to test the ability of NILM to identify loads. The design of the system is based on the electric characteristics of particular loads typical for the home power network as acquired in the first stage. Only current waveforms are relevant for load identification tests because voltage waveforms do not contain information important for load distinguishing. For every sampled current waveform, the following procedure was carried out. First, the waveform was checked by load identification algorithm developed by AUTH. Next, a mathematical representation of the waveform was generated. During this process, the waveform was up sampled to use full possibilities of the arbitrary current waveform generator (ACWG). The mathematical representation of up-sampled waveform was again checked by the load identification algorithm. Next, the up-sampled waveform was loaded into ACWG and current waveform was generated. This was achieved by newly developed LabVIEW software. To check ACWG, the current waveform was sampled by an analog-digital converter (ADC) with very high resolution and sampling frequency. Sampled data was processed to convenient format and the waveform was checked by the load identification algorithm. This was achieved by applying a script written in GNU Octave to the measured data.

The current generated by ACWG was at the same time measured by NILM. If all load identifications of the previously sampled current waveform, of the up-sampled waveform and the waveform generated by ACWG and sampled by high resolution ADC was successful, the generation of current waveform is considered as correct and the result reported by NILM is counted into the statistics of the load identification test. A full load identification test of NILM meters contains 18 waveforms for every of 15 loads.

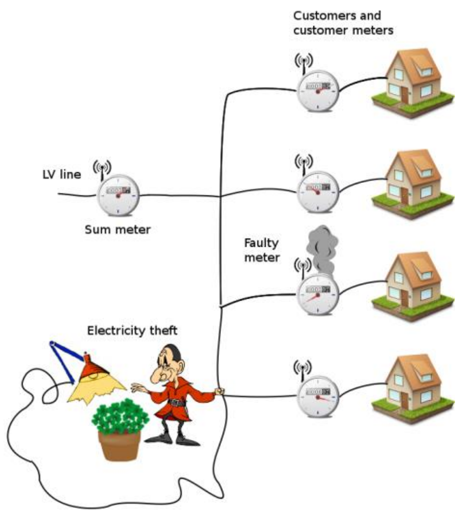
The figure below shows a schematic of the full load identification test. The result of the load identification test represents a ratio of successful load identifications to the total number of measured test waveforms. The system can reproduce current waveforms in the range up to twenty amperes and with frequency content up to 20 kHz.



Scheme of the load identification test.

<u>Use of Automated Meter Reading (AMR) for monitoring smart meter calibration status</u>

MIKES, with support of a smart meter manufacturer and a metering provider, studied a method for using AMR data for on-line verification and calibration of consumer electricity meters. The conventional way of taking the energy meter from the consumption point to laboratory for calibration is costly and inefficient. Therefore, a method was developed for verification of electricity meters using automatic meter reading data. An approach where a calibrated sum meter is used to measure the sum energy consumption of a group of customer meters was used (see picture). When placed in a tree-like grid, the traceable calibration of the sum meter in the trunk of the tree can be transferred to the customer meters in the branches. The customers turn their appliances on and off in uncorrelated sequences, and in this case the correlations of sum meter and all customer meter readings can be solved. A mathematical basis for the method has been derived and the related assumptions studied. Using simulations based on the real consumption data, the applicability of the approach was assessed.



The conclusion of the study is that AMR data indeed can be used for remote monitoring of the calibration status of energy meters, provided that the main verification meter has sufficient resolution and that the energy registrations of the energy meters are not correlated. The process was applied in a real-life scenario using data from a field experiment. In the small scale study an uncertainty well below the required 2% was achieved.

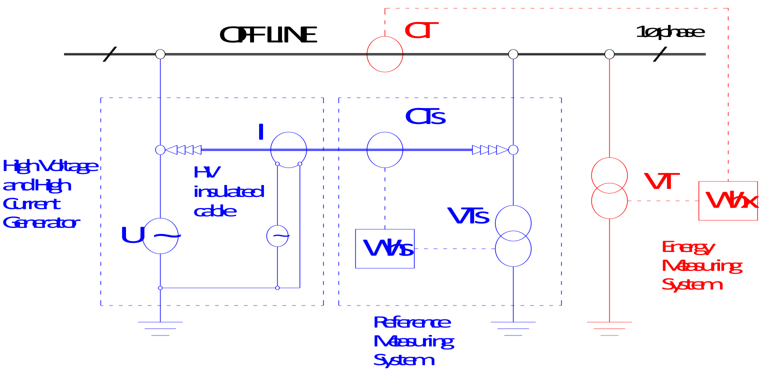
<u>On-site revenue metering in medium and high voltage grids</u>

Three different energy measurement set-ups were designed by FFII and VSL for traceable on-site energy measurement in medium and high voltage grids. These systems are suitable for performing system calibration of existing revenue metering systems in the transport and distribution grids with an uncertainty of less than 0.1 %, which is at least a factor 5 better than the grid metering systems.

Collaboration between FFII, VSL, SP, and stakeholders involved in this part of the project was key in order to identify real needs concerning calibration of installed energy measurement systems and also specifications and requirements of the reference energy measurement set-ups to develop.

As a result of the research and analysis work carried out by FFII and VSL and the feedback from electrical utilities in charge of transport and distribution grids in Spain and The Netherlands the following set-ups were designed:

- Single-phase energy measurement set-up for off-line calibration of energy measurement systems in MV networks up to 66 kV with current levels up to 1 500 A, according to circuit diagram in the figure below.
- Single-phase energy measurement set-up for off-line calibrating energy measurement systems HV networks up to 400 kV with current levels of 4 000 A. A schematic circuit diagram is provided in the figure below.



Set-up for traceable on-site off-line calibration of energy measurement systems

- Three-phase energy measurement system up to 150 kV and current lines up to 5 000 A for on-line calibrating energy measurement systems.

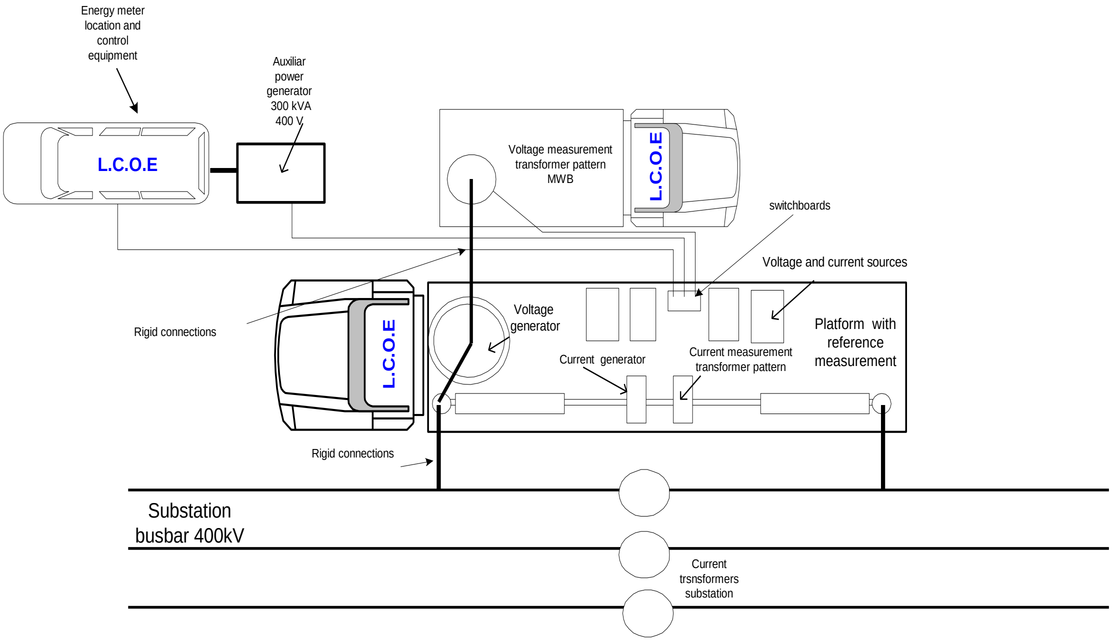
The main advantage of an off-line system is that the calibration and verification can cover the complete range of operating voltages and currents. The disadvantages are that separate voltage and current generation is required (see the “high voltage and high current generator” in the figure above), and that the calibration requires the grid to be taken off-line for a relatively long time, especially in the case of a single-phase setup. A three-phase on-line system places the reference system in parallel with the grid system and compares readings during normal grid operation. It does not suffer from the disadvantages of the off-line system, but on the other hand only verifies the grid energy measurement system at the currents and voltages occurring in the grid. This is partly compensated for by extending the evaluation over an extended period of several weeks.

The research activity developed by FFII and VSL in close cooperation enabled both institutes to properly select the main components of the designed set-ups such as standard current transformers (CTs), standard voltage transformers (VTs), energy meters, high current source, high voltage generator and the current-voltage phase displacement control unit. Characteristics and specifications of substations and devices (CTs and VTs) currently installed were taken into account. Some of these devices were already owned by FFII and VSL and others were bought to become part of the developed systems. Since an overall target reference system uncertainty of better than 0.1 % was aimed for, the individual components should be at least accurate to 0.05 % and preferably better than 0.03 %.

All the main measurement components of the reference systems were calibrated by National Metrology Institutes (CEM, VSL) or Designated Institutes (FFII) with their best measurement capabilities in order to achieve the best calibration uncertainty. The results of the calibrations showed that all CTs, VTs, and energy meters were according to manufacturers' specifications and that the obtained calibration uncertainties were compatible with the uncertainty targeted for the whole energy measurement system.

In order to build the designed reference systems it was necessary to define the auxiliary elements required. Some of them were already owned by FFII and VSL and others were bought to complete the systems (truck platform, high voltage insulated cable, high voltage terminations for insulated cable, tailored connections and etcetera).

Both FFII and VSL worked together in order to better define the most suitable and convenient layout of their corresponding set-ups. Different solutions were investigated taking into account the characteristics and bulk of the equipment. As an example, the figure below shows a drawing of the FFII's layout.



Layout of the FFII grid revenue metering calibration system

The final part of the work concerned a series of tests with the aim to analyse the influence of different identified error sources which could affect the accuracy of the developed energy measurement set-ups. The objective was to keep these error sources under control and/or consider them on the uncertainty budget of the systems. The following tests were scheduled:

- Temperature influence on the accuracy of the measurement transformers (CTs and VTs) and the energy meter between 0 ºC and 40 ºC.
- Influence of high voltage / high current generator performance on the accuracy of the standard measurement transformers (FFII system)

- Dielectric tests of the standard measurement transformers: withstand voltage tests with power frequency and lightning impulse tests.
- Frequency response of the standard measurement transformers.
- Influence of harmonics on the energy reading of the reference energy meters

All the tests were carried out by FFII and VSL in their own laboratories except dielectric tests on measurement transformers which were done by the manufacturer of the considered device. The performance of this set of tests required important specific metrological developments in order to accomplish the targeted accuracy in all the considered scenarios, with such bulky systems and also electrical high voltage involved. This was the case in the study of the influence of temperature on the accuracy of the measurement transformers, and to determine their frequency response in order to have a quick estimation of influence of harmonics by using an in-house resonant circuit.

The characterisation tests were very useful and led to a better understanding of how to streamline the measuring systems and provided useful information about how the systems have to be used in order to achieve the best accuracy.

The tests provided a set of uncertainty contributions which together with the calibration results of the measurement equipment made up the uncertainty budget of the whole energy measurement set-ups developed. The results show that the reference systems developed in the project are suitable to calibrate a broad range of the current energy measurement systems installed in outdoor substations with uncertainties better than 0.08 % for the FFII system and 0.03 % for the VSL system. In both cases this is well below the target uncertainty objective of 0.10 %.

<u>Best Practice Guide for on-site calibration of energy measurement systems</u>

A best practice guide was produced aimed at NMIs, utilities and consultant companies that summarises the revenue metering experiences and practices gained through the project research. This guide pays particular attention to on-site measurements and is freely available from the Euramet research publications repository. The guide covers both practical aspects such as check lists for on-site campaigns and safety issues, as well as specific on-site measurement issues such as influence of environment (temperature, electromagnetic interference).

3.5 Summary of scientific and technological outputs

The project has resulted in new instrumentation, calibration facilities, modelling tools and extended insight in monitoring the stability and quality of electricity supply in smart electrical grids.

The first major scientific outputs of the project are two new tools for modelling and analysis of power flows in smart grids. The tools are unique in that they are able to derive key grid values in distribution grids with an incomplete measurement infrastructure, and support finding the optimal location of grid measurement sensors based on an uncertainty propagation analysis.
A risk assessment of the data flow in grid monitoring and control systems has resulted in a proposal for a cryptographic infrastructure for smart grids.

A metrological infrastructure was developed for calibration and application of PMUs in smart grids. This infrastructure consists of a PMU calibrator for calibration and testing of PMUs, a reference PMU that facilitates evaluation of commercial PMUs, and a set of new PMU algorithms for determining phasors from grid signals. In addition, a series of on-site traceable PMU measurements were performed in Greece and Sweden, which among others led to a new PMU-based method for accurate determination of grid line impedance values.

The six on-site PQ measurements that were performed in transmission and distribution grids and at a wind turbine site have led to increased insight to utilities in the origin of bad grid power quality and more generally in the effect of renewables on grid power quality. One campaign, for example, showed that PV panels raised the grid voltage in a domestic area to close to the maximum allowed value, and another campaign in an industrial area with several renewable energy sources showed that an older-design windmill was the main cause of bad PQ.

Two high-voltage revenue metering systems have been designed and subsequently built, for off-line and on-line verification and calibration of grid revenue metering systems respectively. The uncertainty budgets of the two set-ups showed overall uncertainties in electrical power of 0.03 % and 0.08 % respectively under on-site conditions of up to 150 kV and 5 kA, well below the 0.1 % project aim.
Excellent results were achieved in a study on the use of automatic meter reading (AMR) data for verification of the calibration status of household energy meters. An algorithm was developed and successfully applied during a practical trial in an apartment housing, showing that if the required summing meter has sufficient resolution and accuracy, the accuracy of the individual household meters indeed can be verified well within their 0.5 % accuracy class.

Three best practices guides summarise the project findings and scientific progress in PMUs, on-site PQ measurements and on-site revenue metering respectively. The guides provide useful information and detailed guidance to utilities, consultancy companies, test laboratories and NMIs that aim to be active in on-site grid measurements. All three guides are freely available from the Euramet research publications repository.

4 Actual and potential impact

4.1 European leadership

The ENG04 Smart Grid Metrology joint research project has developed outputs that have placed Europe at the very forefront of worldwide electrical Smart Grid related metrology research. The leading role of Europe is reflected, for example, in a series of invited keynote talks at the CPEM2010 conference (South Korea), ISGT Europe 2010 conference (Sweden), Metering China Conference & Exhibition 2011 (China), the X Semetro conference (Argentina), APMP Smart Grid workshop (Taiwan), i-PCGRID 2014 workshop (USA), World Metrology Day symposium (Belgium), and CPEM2014 conference (Brazil).

The special Smart Grid sessions organised at the leading electrical metrology Conference on Precision Electromagnetic Measurements (CPEM) were dominated by European presentations on research and results of the ENG04 SmartGrid Metrology project, making Europe the leader in this area of research.

4.2 Stakeholder interaction

The Smart Grid Metrology research of this project relates to significant stakeholder needs, as reflected by the attendees at the two stakeholder workshops organised within the project in March 2012 and June 2013. Each workshop was well attended by around 70 participants, among others from utilities, equipment manufacturers and non-European metrology institutes (US, South Korea, China). The effective interaction between the stakeholders and project partners helped to keep the project research focused on stakeholder needs and has led to new long-term relationships. In the course of the project, the initial 20 members of the project stakeholder committee increased to 45 members by the end of the project.

At the first stakeholder workshop, an open brainstorming session was held with all workshop participants resulting in a complete overview of key future metrology research needs in the area of power and energy, and specifically for Smart Electrical Grids. This overview served as the basis for the subsequent Euramet "Power and Energy" road map developed for guiding future grid metrology research under the new EMPIR program.

One of the most relevant project impacts was achieved via the on-site measurement campaigns in power quality and phasor measurements. In total 8 on-site campaigns were performed in the UK, Sweden, Denmark, Slovakia, Italy, Spain, and Greece. Already, in the iMERA project (Power and Energy) that paved the way for the present EMRP project, stakeholders had indicated that knowledge transfer and actual impact is best achieved via close collaboration between metrology researchers and stakeholders. The experience in the SmartGrid project indeed is that contacts between NMI researchers and technicians from utilities are very effective in achieving knowledge transfer. Whereas the contacts between NMI partners and the utilities in their respective countries was limited at the start of the project, this has significantly changed during the course of the project and new long-term relationships have resulted from the research and on-site measurements performed in the project.

The AMR (Automatic Meter Reading) for monitoring smart meter calibration status was performed in close cooperation with a meter manufacturer, metering service provider and local utility, all in Finland. They now have a good understanding of the new method and its potential benefits. The new approach has a potential for large savings in the cost of periodic verification of customer energy meters. Successful application of the new approach would significantly reduce the need to go on-site for un- and re-installation of energy meters.

In establishing a new ratio measurment system for instrument transformers, PTB has worked with a number of institutes and companies. The new system itself is the result of a collaboration with the China Electrical Power Research Institute. Additionally, there was collaboration with two industrial partners (Ritz Instrument Transformers GmbH and the ROHRER GmbH) and PTB for the construction of a customised range transformer, and an adaptation of a high-power amplifier for the needs of an instrument transformer test laboratory.

In addition to a strengthened relationship with the universities having research grants in the project, new academic links have been established during the life of the project. Italian Universities of Trento and Padova have worked with INRiM on PMU algorithms development and assessment. The University of Lausanne has collaborated with METAS on PMU calibration. The University of Strathclyde in addition to their contract within this project has developed some world leading PMU algorithms and have shared many technical discussions with the project team. Further a new strong connection has been created between PTB and EFZN, the department of electrical power engineering and the control system's department of TU Clausthal. PTB also took part in instrument transformer comparisons with TU Dresden.

4.3 Scientific impact

The scientific results achieved in the project have been widely disseminated via publications in scientific journals and journals for the wider public. A total of 49 papers describing the achievements in the different Smart Grid research areas have been published and up to now already 100 presentations have been given at national and international conferences and workshops such as CPEM, Métrologie, IEEE ISGT Europe, IEEE PES General Meeting, with at least 8 more to follow in the course of 2014.

Without excluding the traditionally instrumentation and measurement audience for electrical metrology based publications, the project has sought from the outset to target electricity industry conferences and journals in order to maximise the exposure of the project's outcome to that user audience. Presentations to premier industry conferences such as CIRAD, IGST, IEEE PES have resulted from this policy. Introducing the metrology community to this industry community has resulted and the development of a mutual understanding between the communities will be essential in ensuring good measurement practice in future smart grids.

The project outcomes were presented to national electricity industry conferences. At national conferences in Slovakia, Spain, Germany and the UK, the importance of measurements for Smart Grids was emphasised to industry and technical audiences. Results from the project were presented across the technical subjects covered in the project such as PMUs, PQ, security, transducers and instrumentation networks.

4.4 Standardisation

Many partners of the project have actively contributed to new and improved standardisation. Meetings and workshops of the CEN/CENELEC/ETSI Smart Grid Coordination Group (SGCG) were attended by project partners and information on the project results was shared with the SGCG members. More specifically, the research results of the grid cryptography research work was directly integrated in the development of the smart grid standardisation process of the EU mandate M/490 and the Smart Grid Information Security (SGIS) work group. In addition, two national standardisation initiatives in Germany were supported, dealing with security in metering and measurement (DKE 1911.11) and e-mobility respectively.

In the area of PMUs, contributions were made to the 2014 revision of the IEEE C37.118.1 standard for PMU testing. This activity resulted in subsequent involvement in the definition of the Test Suite Specifications (TSS) of the IEEE conformity assessment program (ICAP) that laboratories and companies should follow in PMU testing.

In the area of revenue metering, a proposal was submitted to the Spanish legal metrology authority for legislation of on-site calibration of grid energy measurement systems.

AMR techniques developed in the project show significant potential benefit to utilities, however metering regulations do not fully support the new approach. MIKES has contributed to preparation of new Finnish legislation, ensuring that the AMR approach can be incorporated in to future metering regulations.

Concerning PQ measurements, the on-site campaign conducted in collaboration with a major wind-turbine manufacturer in order to verify meeting the new IEC 61400-21 standard, entailed the development of new techniques and procedures in order to test to the new IEC standard. As is often the case, the new standard gave little detail on how the measurement might be conducted and the project team in association with the manufacturer was successful in developing and implementing the new method to meet the standard. This is an example of how metrology can turn committee-written standards into workable and practical measurements.

New techniques developed in the project will also feed into future standards activities. For example, the IEEE PMU standard is highly evolutionary and measurements and analyses performed in this project have informed the debate of the relevant committees. An example of this is the analysis of sources of discrepancy in the performance and accuracy of different PMUs, and the impact of the various power quality disturbances on the parameters measured by the PMUs. This has improved the knowledge of the state-of-the-art of the

PMU algorithms, which is an essential element of the future of this type of instrumentation and its standardisation.

The PMU experience gained in the project not only resulted in a “Best Practice” Guide, but also is fed into a new Technical Brochure that CIGRÉ committee C4.34 is preparing on PMU applications for electrical grids.

4.5 Stakeholder take-up of project results

Many outputs of the project were already picked up by utilities, instrument manufacturers, and other stakeholder communities. These are:

- The PMU calibration service developed in the project was used for evaluation of commercial PMUs. The results of these tests helped PMU manufacturers to identify weak points in their present designs and to develop improved products.
- The on-site PMU measurement campaign in Sweden has led to unprecedented accuracy in grid impedance measurements. This has paved the way for a serious application in Dynamic Line Rating (DLR), where the rating of overhead lines is made dependent on the actual line temperature, e.g. derived from impedance measurements, instead of fixed line rating. This application has already raised the interest of transmission system operators of Sweden, Netherlands, and France. DLR allows these grid operators to connect additional renewable energy sources to heavily loaded grid sections without the need of costly grid reinforcements (new, additional overhead lines).
- Stimulated by the results of the on-site PMU campaigns, one of the distribution system operators (DSOs) in the Netherlands has started a project together with VSL concerning installation of PMUs for monitoring a heavily loaded 50 kV ring. Based on the experience of the SmartGrid project, measurement applications will be developed for monitoring the 50 kV ring stability and power quality. Data will be provided by the DSO to VSL and other partners in the new ENG63 GridSens project for refining and evaluation of state estimation methods for distribution grids.
- A major PMU manufacturer (Arbiter Systems) has collaborated with the project providing the loan of PMU instruments for field measurements carried out on the Greek transmission system. The stakeholder profited from the measurements in gaining data on the operation of their instrument, realising a visit and fruitful discussions with the Independent Transmission System Operator in Greece.
- The PMU experience gained in the project fed into a new Technical Brochure that CIGRÉ committee C4.34 is preparing on PMU applications for electrical grids.
- The success of the use of AMR for monitoring smart meter calibration status performed in Finland has triggered extensions of this pioneering work to Sweden. Smart meter data collected in Sweden will be evaluated with the newly developed analysis tool.
- The test set-up for testing smart meters with NILM functionality has been used for evaluation of commercial monitoring devices. The results of these tests will be used by the manufacturer MEgA to improvement of its product.
- A small start-up company in Belgium has expressed an interest in the NILM evaluation capabilities developed in the project for testing its new innovative smart meter. This meter aims to give insight in the energy consumption of small and medium-sized enterprises allowing them to save energy and cost.
- The high-voltage revenue metering reference set-ups were developed following needs expressed by utilities. In the meantime, E.On has shown interest in using the reference set-up for evaluation of the metering installation of one of their new power plants. The aim of this evaluation will be to prove the accuracy of existing metering installation and provide trust in the correctness of its metering data.
- The on-site PQ campaigns have provided direct insight in the effect of additional renewables on the grid. For example, the on-site PQ measurements in a Spanish industry park with several renewable energy sources showed that one of the older wind turbines in this park was the dominating sources of bad PQ. This indeed is very important knowledge if bad PQ is causing damage to electrical equipment connected to the grid.

- Several network operators have expressed interest in applying the sensor placement algorithms developed in the project to their networks. For example, a UK DNO is preparing to install sensors at 12000 substations at a large cost and is very interested in investigating ways of reducing this cost. This is also of interest to the UK electricity regulator, who sees the reduction of expensive instrumentation as necessary to lower the cost of electricity for the consumer.

4.6 New research needs

Even though a massive step forward was made by the research in the SmartGrid project, its results and new developments during the course of the project also revealed several new and further needs. In the area of PMUs requests for realising enhanced PMU traceability were driven by additional requirements on PMUs posed by written standards, the launching of the first commercial PMU calibrator, and the application of PMUs in distribution grids. In the area of PQ, the results of present project mainly indicated the level of PQ at a single measurement point which naturally led utilities to questions like “where is the source of this PQ” and “how does the PQ at this location affect customers further in the grid”. These challenges are presently being picked up by the ENG52 SmartGrid II project.

4.7 Technology Transfer / Exploitation of Results

It is anticipated that on-site PQ measurements performed in this project will form the basis of commercial on-site measurement services offered to network operators and manufacturers of renewable plant.

NPL further developed is on-site digitiser based on the outcomes of its field use during the project. This instrument will be available for commercial sale for use in PQ measurement surveys and other on-site calibrations.

Several NMIs have gained the capability and experience necessary to realise the traceability of PMU measurements in Europe. As the future deployment of PMUs gains momentum, the NMIs in Europe will be in a position to respond to the calibration and certification needs of the power industry at large.

A non-commercial voltage divider was used by INRIM for the measurement performed in the industrial site. It is now planned to improve the performances of the developed divider in collaboration with an instrument transformer manufacturer and, by exploiting the features of the used measuring instrument, to develop an integrated voltage measuring system, to be made available on the market.

4.8 Broader societal impact

The broader impact and wider societal implications of the research and results of the project is the support it provides to the integration of renewable energy sources (RES) to the electricity grids. There is a strong push from society and politicians for increased use of RES since it makes our energy supply more sustainable and environmentally friendly compared to the present use of fossil fuels. In addition, it makes Europe less dependent on energy from politically unstable regions. The project provides support to the increased uptake of RES via reliability in PMU and PQ measurements used for monitoring decreased grid stability and quality.

The key findings of on-site measurements campaigns carried out in this project will enable grid planners to anticipate and sidestep several potential pitfalls in the design of the future grid and, as such, should make a highly significant contribution to carbon reduction. For example, an independent UK evaluation study of one PQ measurement campaigns performed in the project[1] estimated a saving of 167k tonnes of CO_2 over the 10 year lifetime of the installation, via the improved voltage level measurement it provided. This would be valued at over £5 million euro each year at current prices.

By understanding the impact of renewables on electricity networks, operators will be able to incorporate RES more readily thus speeding the rate of deployment to meet carbon reduction targets. As operators have a better understanding of the impact of renewables, they will be able to plan and reinforce their networks to avoid a degradation of the quality of supply. This will smooth the public acceptance of renewables which otherwise would be compromised by supply disturbance, whilst maintaining the level of quality required for commerce and industry.

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[1] Available on-line at http://www.npl.co.uk/upload/pdf/ccm-impact-report.pdf, accessed 08/08/14

5 Website address and contact details

The address of the project public website: www.smartgrid-metrology.eu

Further information concerning the project can be obtained via the coordinator dr.ir. Gert Rietveld, grietveld@vsl.nl.

6 List of publications

Reports: (available in the EURAMET research publications repository https://www.euramet.org/research-publications-repository/)

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