Final Publishable Summary for ENG04 SmartGrid project
"Metrology for Smart Electrical Grids"

Overview

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 by 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 also the quality decreases as voltage distortions are increasing due to e.g. inverters used by renewable energy sources. This project responded to this challenge by realising the necessary metrology infrastructure for monitoring stability and quality of supply with the overarching aim to support the effective development of Smart Electrical Grids.

Need for the project

Environmental issues and diminishing energy supplies are challenging the traditional model of electricity generation and distribution. Smart Grids are the broadly seen as 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.

At the start of the project in 2010, the development of smart grids was in its infancy. The basic hardware elements for constructing a smart grid was 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, utilities were addressing the metrological community with a series of questions: 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 integration of renewable energy sources on the quality of the electricity supply? And how can we assure fair trade between the increasing number of parties exploiting the grid?

Scientific and technical objectives

Triggered by the needs expressed by the utilities, the joint research project "Metrology for Smart Electrical Grids" embarked on developing analysis and measurement tools for monitoring grid stability and quality of supply, and developing revenue metering systems for ensuring fair trade. The specific scientific and technical objectives of the project were to:

- **Perform modelling, simulation, and network analysis of the system state of smart grids.** Models need to be developed of low and medium voltage smart grids, with the aim to optimise grid observability, controllability, and overall design.
- **Realise a measurement framework for reliable and accurate Phasor Measurement Units (PMUs)**. PMUs are unique instruments in that they produce high-rate synchronised measurement data and thus are ideally suited for monitoring stability of smart grids. The project aimed to bridge the gap between the need for traceable PMU measurements and the completely absent related metrology infrastructure within Europe.
- **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. On-site measurement campaigns will provide insight in bad PQ, such as voltage fluctuations and harmonics that has significant impact on electricity consumers including failure of appliances and additional energy losses.

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- **Develop traceable on-site energy measurement systems** for ensuring fair energy trade. New, advanced metering techniques will be developed, to reduce calibration cost and increase confidence in the calibration status of energy meters and grid revenue metering systems.

Results

Modelling, simulation and network analysis of the system state of smart grids

Significant effort has been put into the modelling and simulation of smart grid networks aiming to find an optimized measurement and control strategy. One effort concentrated on expanding a “nodal load observer” (NLO) approach, previously successfully applied in gas grids, with time dynamics. The NLO method was validated via actual measurements in a laboratory environment using a UK laboratory microgrid. The NLO method was subsequently successfully applied for estimation of key grid values in medium-voltage distribution grids with incomplete measurement infrastructure, which is a significant advancement with respect to the state of the art.

A second approach used power flow analysis results to assess the ability of state estimators to estimate the state of the grid at non-instrumented locations. A comprehensive sensitivity analysis was performed in order to find the measurement locations that are most significant for estimating the grid state at all grid nodes. The work was completed by an uncertainty evaluation of grid state estimation with incomplete measurement infrastructure. The focus of the algorithms on uncertainty propagation through the state estimation is unique and has led to an effective and novel method of determining the optimal sensor placement and measurement strategy for a diverse range of grids.

A series of requirements for charging stations for electric vehicle were set up. Both technical and regulatory requirements were identified, where the former are based on the new standardization, such as DIN EN 61851. For a comprehensive charging infrastructure an all-encompassing e-roaming is necessary.

To enable traceability in current monitoring devices, a metrology-grade set-up for wideband calibration of current transformers was successfully realised and subsequently used for the calibration of several current transformers as used in electricity grids.

The research on cryptographic infrastructures for smart grid control focused on a risk assessment for measurement and control systems, based on smart grid architecture models and a use case analysis. The assessment took into account the expected changes in measurement and control strategies for medium and low voltage grids, and led to new insights in the critical elements of a smart grid control system.

Measurement framework for reliable and accurate Phasor Measurement Units (PMUs)

The first PMU-related activity in the project was to develop a software platform to evaluate the behaviour of PMU algorithms under different power system conditions such as described in the IEEE PMU standard C37.118.1–2005. Using this software platform, a series of existing and newly developed PMU algorithms were successfully evaluated. The results of the tests show that for different tests of the IEEE standard, different algorithms score best. The best overall performing algorithm was subsequently implemented in a reference PMU, that was designed and built using high-quality digitisers and a GPS-based time reference.

Very significant effort was put into the development of a PMU calibrator. This calibrator accurately generates the test signals described in the IEEE PMU standard and compares measured reference phasor values with those produced by the PMU under test. The test signals are generated using digitiser equipment, time-referenced to GPS, and specially developed amplifiers to reach current and voltage levels typical for electricity grids. In order to perform the tests effectively, a large amount of software was written for completely automated performance of the PMU tests described in the IEEE PMU standard. With the new calibrator, a commercial PMU and the reference PMU developed in this project were successfully evaluated.

A series of on-site traceable PMU measurements were performed in Greece and Sweden. The evaluation of the measurements in Sweden led to a new method for accurate determination of grid line impedance values. All experiences of both the PMU laboratory testing and the on-site PMU measurements were condensed into a PMU best practice guide.

On-site measurement campaigns of power quality (PQ)

A series of six on-site PQ measurements were performed in transmission and distribution grids and at a wind turbine site in order to determine the effect of renewables on the grid power quality. The campaigns lasted several weeks and even months to encompass a wide variation in weather conditions and seasonal load changes, such that network behaviour with and without new renewable electricity generation could be compared.

Each campaign required considerable preparation and planning. To assist with this task and to come to a coherent and generically applicable measurement strategy, a questionnaire was prepared to be used during the initial site-survey of each campaign. Issues such as connection access, safety regulations, required measurement parameters / standards and site logistics were all covered. A mixture of commercial and project-built power quality analyser equipment was used to conduct the measurement campaigns.

The results of the campaigns gave significant insight in the effect of renewables on power quality. For example, in one campaign it was found that PV panels raised the voltage in a domestic area close to the maximum allowed value. Another campaign performed in an industrial site with various renewable energy sources showed that an older-design windmill was the main cause of bad PQ in the site. All experiences of the 6 on-site PQ measurement campaigns performed within the project were brought together in a on-site PQ best practice guide.

Traceable on-site energy measurement systems

An improved non-invasive load monitoring (NILM) algorithm has been developed for determination of the energy consumption of individual household appliances. The algorithm is based on analysis of the current harmonics produced by these appliances. Using a series of 14 reference load 'signatures' of typical household appliances, it was found that the new algorithm was very effective in appliance recognition. In addition, a set-up was completed and tested for calibration of smart energy meters with NILM functionality. To prove the functionality of the set-up, a commercial PQ monitor simulating a NILM smart meter was calibrated and the results were presented in a certificate.

Research on the use of automatic meter reading (AMR) data for verifying the calibration status of smart energy meters has shown excellent results. The method relies on the use of a summing meter with sufficient resolution and accuracy for monitoring the total energy supplied to a number of households, and correlating its reading with that of the individual household meters. The algorithm developed for analysing the data has been successfully applied to real metering data from an apartment with several households.

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 components of the reference systems were calibrated, and the impact of typical on-site effects such as varying temperature and electromagnetic interference was evaluated. 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, well below the 0.1 % project aim. One of the set-ups has been compared to a similar set-up of NRC, Canada with excellent result: both systems agreed with each other within 0.003 % under the laboratory conditions during the test. The experiences achieved during the project were summarised in an grid metering best practice guide.

Actual and potential impact

The ENG04 Smart Grid Metrology joint research project has placed Europe at the forefront of worldwide electrical grid related metrology research. The leading role of Europe is among others reflected in a series of invited keynote talks at key international conferences. The special Smart Grid sessions organised at the leading Conference on Precision Electromagnetic Measurements (CPEM) were dominated by European presentations on research and results of the ENG04 SmartGrid Metrology project.

The fact that the Smart Grid Metrology research of this project relates to significant stakeholder needs is reflected in the attendance of the two stakeholder workshops organised within the project in March 2012 and June 2013. Each workshop was very well attended by around 70 participants, among others from utilities, equipment manufacturers, and non-European metrology institutes (US, South Korea, China). The vivid interaction between 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 at the end of the project.

On the occasion of the first stakeholder workshop, an open brainstorm session was held with all workshop participants resulting in wide overview of key future metrology research needs in the area of power and energy, and specifically 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 across the EU. Already in the iMERA project that paved the way for the present EMRP project, stakeholders indicated that knowledge transfer and actual impact is best achieved via intense 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 in the course of the project and new long-term relationships have resulted from research and on-site measurements performed in the project.

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 with at least 8 more to follow in the course of 2014.

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. 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. Concerning PQ measurements, the on-site campaign conducted with a major wind-turbine manufacturer in order to verify meeting the new IEC 61400-21 standard led to clarifications on how the measurement be conducted.

Many outputs of the project were already picked up by utilities, instrument manufacturers, and other stakeholder communities. Some examples of these include the following:

- 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 design 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 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 on 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.
- The PMU experience gained in the project not only resulted in a "Best Practice" Guide, but also is fed into a new Technical Brochure of CIGRÉ committee C4.34 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 a commercial monitoring device. The results of these tests will be used by the manufacturer for improvement of its product.
- 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 the grid metering installation and provide trust in the correctness of its metering data.
- A UK DNO has expressed interest in applying the sensor placement algorithms developed in the project to their network, since it helps reducing the cost of installation of sensors at 12000 substations. 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.

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 enhanced PMU traceability is needed given additional requirements on PMUs posed by new written standards. In the area of PQ, the results of the 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”. The research challenges posed by these questions are presently being picked up by the follow-on project ENG52 SmartGrid II.

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, and in addition 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 the decreased grid stability and quality. An independent UK evaluation study of one PQ measurement campaign performed in the project estimated a saving of many tonnes of CO_2, via the improved voltage level measurement it provided.

Reports

The project has resulted in three Best Practice Guides (available in the EURAMET research publications repository https://www.euramet.org/research-publications-repository/):

- B. Voljc et al, “Best Practice Guide for PMU test protocols and PMU field measurements”, 2013
- P.S. Wright et al, “Best Practice Guide for On-Site Power Quality Measurement Campaigns”, 2013
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JRP-Coordinator: Dr.ir. Gert Rietveld, VSL Tel: +31 15 2691500 E-mail: grietveld@vsl.nl JRP website address: www.smartgrid-metrology.eu	
JRP-Partners:	
JRP-Partner 1 VSL, The Netherlands	JRP-Partner 11 PTB, Germany
JRP-Partner 2 BRML-INM, Romania	JRP-Partner 12 SIQ, Slovenia
JRP-Partner 3 CEM, Spain	JRP-Partner 13 SMD, Belgium
JRP-Partner 4 CMI, Czech Republic	JRP-Partner 14 SMU, Slovakia
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JRP-Partner 7 INRIM, Italy	JRP-Partner 17 TUBITAK, Turkey
JRP-Partner 8 LNE, France	JRP-Partner 18 EFZN, Germany
JRP-Partner 9 MIKES, Finland	JRP-Partner 19 TUBS, Germany
JRP-Partner 10 NPL, United Kingdom	JRP-Partner 20 EIM, Greece
REG-Researcher 1 (associated Home Organisation):	Aggelos Bohouros, Greece AUTH, Greece
REG-Researcher 2 (associated Home Organisation):	Alberto Venturi, Italy STRAT, United Kingdom
ESRMG-Researcher 1 (associated Home Organisation):	Vladimir Milojevic, Bosnia and Herzegovina IMBIH, Bosnia and Herzegovina

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