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JRP-Coordinator	
Name, title, organisation	Dr Paul Wright, National Physical Laboratory, UK
Tel:	+44 (0)208 943 6367
Email:	paul.wright@npl.co.uk
JRP website address	www.smartgrid-metrology.eu
Other JRP-Partners	BRML, Romania; CMI, Czech Republic; IMBiH, Bosnia and Herzegovina; INRIM, Italy; LNE, France; METAS, Switzerland; MIKES, Finland SIQ, Slovenia; SMU, Slovakia; SP, Sweden; Trescal, Denmark; VSL, Netherlands; EIM, Greece; STU BA, Slovakia; UniNa2, Italy

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REG1-Researcher	Mario Paolone, EPFL	Start date: 1 June 2014 Duration: 36 months
REG2-Researcher	Vladimir Cuk, T-UE	Start date: 1 June 2014 Duration: 36 Months
REG3-Researcher	Andrew Roscoe, STRAT	Start date: 1 June 2014 Duration: 27 Months
ESRMG1-Researcher	Yljon Seferi, DPM-Albania	Start date: 1 June 2014 Duration: 7 Months

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1 Executive Summary

Introduction

This project has developed, demonstrated and validated measurement tools to enable electricity network operators to better monitor the quality and stability of supply against a background of growing inflow of energy from renewable resources that are variable in nature. These tools are based on GPS synchronised measurements of phase across wide areas and have led to a metrology infrastructure for these phasor measurement units (PMUs) and some key applications that will revolutionise network operations and improve network utilisation. This will make a significant contribution to the development of Smart Grids essential to meet carbon reduction targets.

The Problem

The increased use of renewable energy is vital to meet emission reduction targets and ensure security of supply in Europe. However, supply from renewables are intermittent and unless the energy flows are measured and controlled, the increased use of these distributed generation resources will cause costly power quality (PQ) degradation, leading to wide-spread blackouts. Smart Grids are seen as the only mechanism to reliably manage large amounts of renewable energy and they are specified in EU directives and regulations [1, 2] as the means to successfully accomplish this.

The problem is that Europe lacks the metrology infrastructure (instrumentation, and associated protocols) to firstly monitor Smart Grid stability and PQ, and secondly to develop and calibrate the necessary instrumentation (e.g. PMUs) needed to accomplish this.

Euramet project ENG04 SMARTGRID made significant steps towards establishing the necessary metrology infrastructure for monitoring stability and PQ to support the effective development of smart grids, however it also highlighted the lack of traceability and standards. This project aimed to address these issues as well as test the technology on real networks

The Solution

The project set out to solve the problem of monitoring the stability of Smart Grids over a large area by accomplishing the following:

- Recording PQ measurements at multiple measurement sites in real Smart Grids leading to an understanding of the level and propagation of PQ and a method to locate major disturbance sources.
- Providing a metrology framework, calibrators, protocols, etc. for PMUs and associated transducers, including dynamic calibration; new algorithms to improve resolution and immunity to noise; on-site calibration under operational conditions.
- Utilising PMUs to measure the impedance of the grid, a parameter essential to the planning, measurement and control of Smart Grid stability and PQ.

Impact

In planning and carrying out the measurement campaigns required for the completion of this project, the consortium have been engaged with seven network operators throughout Europe (Göteborg Energi AB, Energinet, Östkraft, Lilander, DNWG, Západoslovenská distribution, Hellenic Transmission System Operator S.A.). Utility engineers have had to work closely with the consortium and this relationship has exposed them to the objectives of this project as they have had access to all of the results generated on their respective sites. The information gained from these interactions is already available in three industrially relevant good practice guides (see section 5). Utilities have already gained useful insights to the way their networks and assets operate and they now understand the changing state of their network as loads and renewable energy power parks switch on and off throughout the daily, weekly and seasonal cycles.

For instance, the project has made available data concentration software to the Bornholm Network operator. This shows a map display of Bornholm with the live data from the six bespoke PMUs as well as weather data to correlate renewable generation and PQ events. The operator is able to see the voltage and power response at various locations on Bornholm such that events and operating conditions can be monitored.

Such information and displays will become increasingly important as future networks dominated by renewables will require constant vigilance to ensure stable supply.

A new method for ‘aggregation of harmonic current’ will be presented to the normative working group CIGRE/CIRED C4.40 in their autumn meeting of 2017. If accepted this method should lead to new Renewable Energy Source connections being accepted more readily without the need to reinforce the grid.

In the field of PMUs, the project has effectively provided all the metrological infrastructure for PMU manufacturers to supply reliable and accurate instruments under a full range of complex modulated signals. This will allow industry to purchase PMUs from multiple vendors, thus ensuring greater competition, and to use them interchangeably to ensure the stability and reliability of the electricity supply. Manufacturers of PMU calibrators will also now have a traceability infrastructure to assure the accuracy of their products. In the long term, the project results will be an essential input to Smart Grid measurement infrastructure for Europe that will be stable and reliable whilst ensuring that new Renewable Energy Sources can be added with the minimum amount of reinforcement of the network. This will lead to a significant environmental benefit relative to an absence of the infrastructure whilst keeping the price to the consumer, both industry and public, as low as possible.

2 Project context, rationale and objectives

2.1 Context

The increased use of renewable energy is vital to meet emission reduction targets and ensure security of supply in Europe. It is also mandated in the Renewable Energy Directive, 2009/28/EC1, that Europe achieves a 20 % overall share of Renewables by 2020. However, renewables are intermittent and unless the energy flows are measured and controlled, the increased use of these distributed generation resources will cause costly power quality (PQ) degradation, leading to wide-spread blackouts. Smart Grids are seen as the only mechanism to reliably utilise large amounts of renewable energy and they are specified in EU directives and regulations [1,2] as the means to successfully accomplish this.

Network operators need tools to measure the quality and stability of the electricity supply under the challenging dynamic conditions prevalent in networks with a high penetration of distributed renewable generation. Wide-area measurement systems using phasor measurement units (PMU) are increasingly seen as the “life-support monitors” for Smart Grids and they present many new opportunities to understand the complex dynamics of these networks. However, unless properly formulated and deployed, these new measurement techniques have many potential pitfalls that will give rise to misleading results that could ultimately undermine, rather than boost confidence in future-networks.

2.2 Objectives

The aim of this project was to develop, demonstrate and validate new measurement tools for the management of Smart Grid operational stability and power quality. Results and analysis of on-site measurements were undertaken during the project. The common theme to these tools is the use of multiple digitising instruments placed at geographically remote locations around an electricity grid. These instruments are time-synchronised to form a wide-area measurement system using GPS. The high level objectives of this project where to develop new synchrophasor-based tools and a metrology infrastructure to measure Smart Grid stability and quality. Namely:-

<u>To develop and implement wide-area tools to determine the propagation of PQ in a variety of distribution and transmission grids, developing new methods to locate sources of disturbance.</u>

On-site PQ measurements at renewable installations such as wind turbines, PV installations, a H2 production plant were extensively demonstrated in *SmartGrids1* to great benefit, however it rapidly became apparent that the wide-area consequences of distributed generation are largely unknown and of more

[1] COM(2010) 639 “Energy 2020 strategy for competitive, sustainable and secure energy”, available on line at: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:52010DC0639:EN:HTML:NOT
2 Directive 2009/72/EC, common rules for the internal market in electricity, available on line at: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:211:0055:0093:EN:PDF

significance from a network management standpoint. Wide-area measurement technology now presents a new opportunity to measure and analyse the propagation of PQ in distribution networks and more widely through different network levels. The project set out to demonstrate this. The ability to pin-point the source of serious PQ disturbances on their system is highly sought after by network operators. Such problems could be caused by unauthorised connections or by faults and it is clearly important to be able to identify the location of the disturbance in order to take the necessary action at the source. New opportunities are presented by PMUs and similar synchronous measurement equipment. Using the data from the on-site measurements accurately time-stamped PQ analysers to use phasor information to locate the origin of major disturbances.

To develop a metrology framework for PMUs including dynamic calibration, new algorithms to improve resolution and immunity to noise and on-site calibration under operational conditions.

PMU deployment and new applications of these flexible instruments are rapidly developing in response to emerging needs of Smart Grid management. Until recently, static PMU measurements over a large geographical distance in transmission networks have been the main application of PMUs; this was addressed by EMRP *SmartGrids1*. Commercial vendors are also addressing the needs of static PMU calibration in the laboratory, as are NIST. However, since the initial work on PMU calibration infrastructure, the flexibly of PMU has been widely appreciated by network operators and deployment in more-localised distribution grids is now planned. Moreover, recent changes to the PMU international standard IEEE C37.118 (2011) has proposed new and exacting requirements for PMUs to measure dynamic signals. These new aspects will be crucial to maintaining grid stability under all conditions.

Distribution system deployment brings new measurement challenges to improve phasor measurement algorithms and measurement techniques to account for much smaller timing accuracy, reaching the level of a few μs and below. Dynamic measurement is an urgent new requirement, linked to the accurate determination of 50 Hz phasors in the presence of time-varying disturbing signals, as more generally present in distribution grids than transmission grids. There is an industrial need to address these recent advances by developing, calibrating and on-site testing of this new generation of PMUs. The latter will ensure that the instruments and emerging algorithms are tested in real networks with realistic waveforms and disturbance levels. This is achieved by using readily modifiable PMU technology to implement and carry-out field trials on new dynamic algorithms, perform comparison testing of installed commercial PMUs and trial phasor measurements in distribution networks.

To utilise PMUs in a new tool to measure the impedance of the grid, a parameter essential to the planning, measurement and control of Smart Grid stability and PQ.

Wide-area PQ is inextricably linked to the network topology and impedance which also requires measurement. Network impedance measurements are notoriously difficult even in the laboratory and in the field, they are beset by noise and instrument transformer errors. The determination of network impedance at harmonic frequencies is further complicated by the need to energise the system at harmonic frequencies, which is far from trivial in a live electricity grid.

To provide a metrology framework for the PMU/PQ transducers; these devices convert the high voltage and current levels on the grid to measureable low levels, but introduce errors in the process.

Transducers are an essential part of the PMU and PQ measurement chain, yet surprisingly they are generally taken-for-granted when considering their installation in the field. For example, the phase errors on installed measurement transformers can be so severe, that they seriously compromise the usefulness of synchrophasor measurements required for reliable monitoring and control of the grid.

As CT/VTs are essential components of the electricity grid, they cannot easily be removed from the system for measurement. Characterisation of their wide-band behaviour is then most efficiently handled by characterising models that are typical for the instrument transformers installed in the grid. Capability and facilities are required to characterise the wideband performance of instrument transformers connected to PMUs and PQ analysers.

For PQ measurements where harmonics are of interest, the wide-band performance of installed CTs is often limited and non-invasive current transducers will be fitted if possible. These transducers represent the single biggest uncertainty in the measurement chain, with errors of some 1 % due to positional sensitivity being typical.

3 Research results

The top level objectives described in the previous section each incorporate one or more of the more granular 'Specific Scientific and Technical Objectives' of this research project. In this section the top level objectives are discussed and results presented, ending each sub-section with a summary identifying the technical objectives that have been met alongside the key results. Please note that the technical objective related to standardisation input*, 'Providing metrology input and undertaking pre-normative research toward the evolution of international (CEN, CENELEC, IEC, IEEE) standards concerning PMUs for network controllability and PQ in a Smart Grid context*, ran through all of the top level objectives and is mentioned where appropriate.

3.1 To develop and implement wide-area tools to determine the propagation of PQ in a variety of distribution and transmission grids, developing new methods to locate sources of disturbance.

The results of this part of the project are based on six independent on-site measurement campaigns in working electricity networks. This required considerable preparation and liaison with the operating utility companies and extensive cooperation with their engineering staff and the gratitude of the project team is extended along with a recognition that these results are fully dependant on this generous collaboration. The site measurements were performed by cooperation between NMI teams, each providing planning, utility liaison, modelling, instruments, software, campaign installation, data communications and data analysis roles in order to complete the successfully complete these long duration and complex campaigns.

Harmonics and poor PQ are detrimental to power system operation because they cause power loss, shorten the life of system assets, and cause malfunctions of grid controls and protection and cause interference and malfunction of consumer products. Large connections such as RES power parks can cause poor PQ as can the aggregated effect of many customers' connections.

For power system management purposes, network operators need to understand the level of harmonics in their networks so that they can take the most cost-effective measures to mitigate them. This may be in the form of tuned filters or the installation of new transformers and cables, all of which required significant investment in terms of civil and electrical engineering.

Network operators use on-site measurement surveys to plan for new connections of large loads or generators. These surveys determine the base level of harmonics, such that the effect of the new disturbance can be calculated to ensure harmonics will not exceed safe levels.

Whilst these and other surveys can be used to determine the local effect of a particular disturbing influence, its effect on the wider network remains unknown. For example, the generation of local harmonics by a large renewable installation could be significant, triggering the need for expensive mitigation equipment; however, if that disturbance had been "naturally" attenuated once at the wider grid level, the need for this mitigation can be relaxed. Conversely resonances in the network could give rise to an increase in the disturbance at the wider network level.

The nature of the harmonic propagation will depend on each specific network topology and impedance. Reconciliation of the results with the grid topology model is necessary to assess the system-level impact of various harmonic disturbances, leading to improved grid management/planning and appropriate constraints in future normative standards and grid codes.

In order to understand the nature of power flows in Smart Grid networks and the propagation of PQ events, six independent measurement campaigns were carried out in this project. Synchronised grid measurements using GPS enabled Waveform Measurement Units (WMUs) or Phasor Measurement Units (PMUs) were used in multiple locations within the respective networks. WMUs measure high rate samples of voltage and current waveforms at multiple sites synchronised to better than 1µs, whereas PMU measure amplitudes and phases (vectors or phasors). These instruments are used here for research into the power flows around the given networks and propagation of PQ events, in particular power system harmonics and their phase angles.

The remainder of this Section will describe the experimental set-up for each measurement campaign and a summary of the research findings and their significance.

Bornholm Island Distribution Network

Bornholm Island (Denmark) in the Baltic Sea was chosen for the site of this measurement campaign as described in [1]. This is an interesting site as it can operate as an electrical island (isolated from the wider grid) utilising over 50 % renewable energy sources (RES). It is essentially a test-bed for future EU power networks which will need to operate with at least 50 % intermittent RES by 2050.

In a collaboration between NPL and Trescal Denmark with the utility Energi & Forsyning, six measurement sites were selected on the island as shown marked in Fig. 1. These have been selected based on study of the circuit diagrams, the location of population centres and RES installations and modelling of harmonics using an industry standard proprietary tool *PowerFactory™*. NPL designed and characterised WMUs were installed at the sites using Rogowski coil current transducers (CT) and commercial voltage transformers (VTs) as required to transform the high working amplitudes to levels suitable for the inputs to the WMUs. The transducers were all characterised using facilities developed in WP4 and in previous Euramet JRPs. Full details of the experimental set up are given in [2].

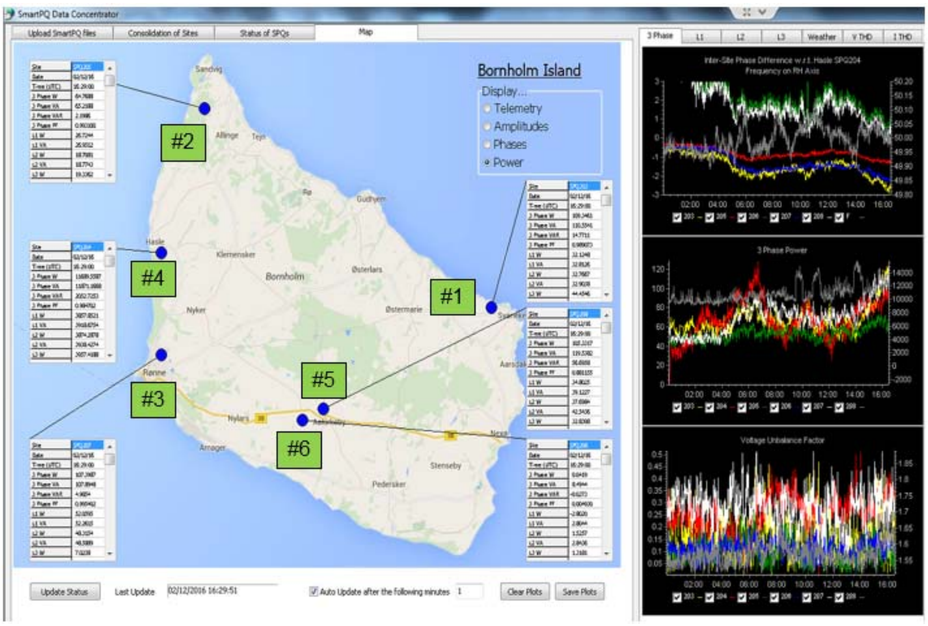


Figure 1: Screenshot of the live Dashboard display of measurments on Bornholm Island 60 kV MV distribution network. Measurement sites marked with # numbers for purposes of commentry in

Four sites were installed in May 2016 and the remaining two sites (#5 and #6) in February 2017. Referring to Fig.1, site #4 is a cross sea interconnector to mainland Sweden and is also part of the second measurement campaign on Bornholm Transmission. Data was continuously collected and regularly uploaded to a server for analysis. A "dashboard" status display of all six sites was developed (Fig.1) showing real time data about the network together with weather data (useful with RES). This was also provided to the network operator.

The measurement data for the campaign amounts to a significant data handling, analysis and presentation challenge, in-terms of the time taken to analyse the data. The philosophy used has been to collect data continuously and select data for analysis based on weather events, population events and an overview of the daily electrical values. Once data is selected there is then the matter of three separate phases on each of the instruments which all require separate analysis and presentation.

The results show expected power flow patterns associated with population induced load cycles (morning and evening peaks) particularly at sites #3 and #1 which are cities. The extensive RES adds particular interest and the effect of wind on the power provided by the cross sea link at site #4 is highly inverse-correlated to wind speed in some cases reversing the power flow and providing energy to Sweden. Site #5 and #6 are at a wind park and show obvious correlations.

The power system harmonics are measured up to the 40th harmonic in amplitude and phase relative to site #4. This allows the calculation of harmonic power flow around the island which are particularly useful for propagation studies. The use of the WMUs enabled the new observation that harmonic phase was correlated to the loading and RES generation patterns described above. This phenomenon was investigated by modelling the Bornholm network and it was found the relative phase can be used to predict load change at fundamental and harmonic frequencies [2].

The new inclusion of inter-site phase measurements, opens the possibility of locating areas of the grid where the harmonic generation is the highest. The harmonic voltage amplitude observed on Bornholm was generally seen at site #1. If this is assumed to be the site of highest pollution, a network planner may very well refuse to allow new connections of RES at this location, should the distortion be near the operational limit. However, harmonic phase measurements conversely predict the major harmonic source to be at site #3 with site #1 consuming the harmonics (most likely in linear heating type loads). It turns out this is entirely reasonable as site #3 is the major city with many harmonic generating electrical appliances, whereas #1 is a rural location. The inter-site phase information allows for the calculation of harmonic-power-flow. If this is measured at multiple locations in the medium voltage (MV) ring network, it seems likely that the location of harmonic sources could be predicted, which would greatly assist harmonic planning decisions and enforcement actions against of large harmonic polluters. Measurements made in low voltage (LV) spurs off the main ring grid do not allow for this, however the correlation of inter-site phase allows an inference to be made as to the local power flow, although this is complicated by resonances and the complicated nature the non-linear harmonics inducing loads. This is highly promising method and further work will be needed beyond the life of the project to take this feasibility work to a generic business as usual solution.

Transmission Campaigns.

Related to the above work, a transmission system measurement campaign was carried out on the cross-sea link between Bornholm Island and Sweden coordinated by SP working with NPL and Trescal collaborating with the utilities Östkraft and Energinet. This link provides bi-directional power flow depending on the prevailing levels of RES generation on Bornholm. Measurements were made either end of the cable with a WMU at location #3 in Fig.1 and a further WMU at a HV substation on the Swedish side of the Baltic Sea. A further campaign was carried out using commercial PMUs on a link to a Wind park in Gothenburg, Sweden in collaboration with the utility Göteborg Energi AB.

The purpose of these campaigns was to investigate the propagation, distribution, and damping of disturbances across cables. Cables may be divided in overhead cables, ground cables, and sea-cables. In this project, one short ground cable (Gothenburg 10 kV 3.4 km) and one long sea cable (Bornholm 60 kV, 49 km) have been measured and analysed. The effect that the cable parameters have on the harmonic RMS data is then examined for different loads. For the case of the 10 kV ground cable, the level of harmonics are examined in both ends and the propagation and dampening of the cable are modelled. For the case of the 60 kV sea-cable, the impact that the asymmetric cable have on the phase values are examined. Furthermore, there an attempt to model and verify the measured line losses are performed and the impact that an installed shunt reactor has on the measured phase values was examined. The results are fully reported in [3].

The results showed levels of voltage and current harmonics at both ends of the Bornholm cable were less than 1 %, relatively low in this installation compared with some grids. The largest distortion was in the 5th harmonic, followed by 7th and 11th. H3 and H9, are triple-N harmonics and their currents circulate in the delta windings of the 60 kV transformer, causing these measured values to be relatively low. Even harmonics and harmonics above the 11th harmonic are all relatively low.

The propagation of harmonics along the cable showed some interesting characteristics. Harmonics currents generated on Bornholm seem to be filtered by the cable and are reduced at the Swedish side. This may be due to the frequency response of the measuring transformer at the Swedish side, but simulation has shown how the cable and shunt reactor can act as a filter and at the same time explain the slight drop in the harmonic voltages at Bornholm relative to Sweden at higher frequencies.

The fundamental impedance of the cable was also computed from the measurements using two different methods. The results were in-line with engineering data for the cable at the time of manufacture. This analysis showed that the shunt reactor cancels the cable capacitance and overcompensates slightly leaving a net inductive shunt susceptance.

In the Gothenburg campaign, the highest levels of harmonics were found for the 5th, 7th, and the 11th harmonic, whilst the magnitude of the 3rd and the 9th harmonic were found to be significantly lower for both of the two levels of transferred power. A model of the harmonic dampening by the cable was developed, and the voltages of the examined harmonics were found to be accurately estimated. However, the measured currents in cable *End A* at the turbine were significantly higher than the measured currents in remote *End B*. Cables have in general high levels of capacitance due to the short distances between the conductor and the earthed sheath. The difference in the measured current indicates that the capacitive contribution from the cable could be significantly higher than the value from the cable manufacturer. However, an asymmetry of up to 4 % was also measured in End A. This asymmetry could also be the reason for the measured difference in current between the two ends.

The impact of perfect time synchronisation was also examined, both for the case of the analysis of the fundamental and for a chosen number of harmonics. It was found that the time synchronisation of PMUs significantly increased the accuracy of the analysis, and especially in the case when assessing harmonics. Since the variation of the magnitudes is so significantly higher in the case of the harmonics, time synchronized measurements were found to be essential in the analysis.

Alliander LiveLab and Enduris Measurement Campaigns.

TU Delft and VSL cooperated in two Dutch measurement campaigns in collaboration with the utility Liander were carried out with the aim of understanding the propagation of harmonic currents and specifically an investigation of the aggregation of harmonics which can be used to accurately and effectively assess the effect of major new grid connections on the grid.

The two networks chosen for the campaigns were located in the Netherlands; Alliander LiveLab is a 10 kV network in the Bommelerwaard, which is used to carry out live testing of innovative technologies, equipment and processes such that engineers can pursue various Smart Grid R&D projects. A further network operated by Enduris is a 60 kV ring network in Southern Holland.

Both networks were modelled using Digsilent Power Factory resulting in a measurement plan for the placement of instruments. A set of PMUs and with associated Current Transformer (CT) and Voltage Transformers (VTs) were installed at key locations in LiveLab and a further set of six PMUs were installed in the Enduris ring. Measurements were carried out over a period of two years on both networks.

The networks produced a wealth of data and R&D will continue beyond the life of the project. In line with the specific objective of this project, a new PMU method was developed using summation of harmonic currents which proposes an update of summation coefficients used in the assessment of emission limits of installations. A further method using stochastic harmonic modelling gives rise to a methodology for predicting harmonic distortion levels of residential loads based on measured load emissions and estimations of domestic load developments. Three relevant publications [4,5,6] have been prepared and the results of the summation methods will be presented to the Normative working group CIGRE/CIRED C4.40 in the autumn meeting of 2017.

Summary and Conclusions

The specific Scientific and Technical objectives that have been accomplished are:

- ***PQ Propagation***. Determination of PQ propagation mechanisms associated with a selection of disturbance sources in a variety of distribution and transmission networks. The results will be reconciled against network topology, drawing conclusions to support future network planning and standardisation.

- ***PQ Disturbance and Fault Location***. Amplitude and phase measurements for multiple GPS synchronised instruments will be used to determine power flows associated with major PQ disturbance / faults and their locations will be estimated.

And the key results are:

- A prototype harmonic location method was developed using a simulation of the Bornholm grid. Following the successful development of the location method in the simulation, significant challenges were overcome to implement the method using the six instruments on Bornholm. Location determinations of predictable cyclic harmonic disturbance has proved plausible and the feasibility of the technique looks highly promising, but will require further development and generalisation for routine use by utilities.
- On-site measurement using PMUs has resulted in a new method for the aggregation of harmonic currents which proposes an update of summation coefficients designed for use in the assessment of emission limits of installations. The results of the summation method could revolutionise the way that utilities assess the impact of new renewable connections and will be presented to the Normative working group CIGRE/CIRED C4.40 in the autumn meeting of 2017.

[1] J. Østergaard and J.E. Nielsen, “The Bornholm Power System, an Overview”, [Online]. Available: https://pire.soe.ucsc.edu/sites/default/files/denmark_the_bornholm_power_system_an_overview%20(1).pdf

[2] “Multiple-Site Amplitude and Phase Measurements of Harmonics, for Analysis of Harmonic Propagation on Bornholm Island”, P.S.Wright, A.Christensen, P.Davis, and T.Lippert, IEEE Transactions on Instrumentation and Measurement (Volume: 66, Issue: 6, June 2017, pp1176 - 1183), Published 01 March 2017, 10.1109/TIM.2017.2660019

[3] "PMU Measurements on Swedish and Danish Grid", S. Svensson, A. Lindskog, H. Hagmar, B. Larsson, P. Davis, P. Wright submitted for publication in the IEEE Transactions on Smart Grid, May 2017.

[4,5,6] – list TUD publications from the impact XLS….

3.2 To develop a metrology framework for PMUs including dynamic calibration, new algorithms to improve resolution and immunity to noise and on-site calibration under operational conditions.

The development of a metrology framework for PMU consisted of several aspects, namely the design of PMU algorithms (EPFL, INRIM, SIQ, Strathclyde), the realisation of a reference PMU (LNE) and of a PMU calibrator (EPFL, METAS) as well as the undertaking of several field trials (EIM, SP) necessary to gain the experience with the various metrological aspects of PMUs. Together, they permitted to develop a broad PMU expertise within the metrology community. The project focused primarily on the usage of PMUs in a distribution network and built on the results obtained in a previous project on the usage of PMUs in a transmission network.

As PMU algorithms are at the core of the process transforming waveform samples into phasors, a great deal of effort was placed to investigate the precision achievable by various PMU algorithms. To this aim the work consisted in the evaluation of at least six different PMU algorithms and finding the potential algorithm for implementation in the reference PMUs. To achieve this goal, a simulation platform in the Matlab environment was initially developed (INRIM, SIQ). In the platform static or dynamic (time-dependent) signals were defined in which amplitude, frequency and initial phase of the fundamental signal were accurately defined by the algorithms. Additionally different disturbances (noise, harmonics, missing samples, inter-harmonics, *etc.*) could be optionally added and/or varied. This final test signal is then sampled and divided into the smaller time intervals according to predefined reporting rate and the corresponding samples are then provided to six examined algorithms which give the estimation of the amplitude, frequency and initial phase from the samples. Finally the TVE, FE and RFE are calculated using the estimated and reference phasors.

Six PMU algorithms (INRIM, SIQ, Strathclyde) were examined based on different estimation principles: (i) the iDFT (three point interpolated DFT with Hann window) and MHFE (Multi Harmonic Frequency Estimation) estimates the phasor parameters in frequency domain, (ii) the 4PSF (4 Parameter Sine Fit) makes the estimation in time domain and (iii) three hybrid algorithms *i.e.* SLCA (Spectrum Leakage Correction Algorithm), PSFE (Phase Sensitive Frequency Estimation) and PSFEi (interpolated Phase Sensitive Frequency Estimation).

Several static and dynamic signals were tested (SIQ) that are required by the IEEE Std. C37.118.1-2014 (static amplitude/frequency/phase deviation, harmonically distorted signal, frequency ramps, *etc.*) and also other static and dynamic signals that are not included in the standard but are also of importance (amplitude step changes, ramps, frequency step changes, realistic frequency variations, missing samples, noise, inter-harmonic distortions, different realistic harmonically distorted signals (D2.1.3), *etc.*). Additionally, the numerical performance of the algorithms (minimum number of required samples, average estimation time) were tested. All simulation results are gathered in table below.

Figure 2. Summary of the algorithms.

The √ denotes agreement with the specification or good performance, the ► denotes that the standard limits are exceeded or bad performance of the algorithm. The ○ denotes the average performance of the algorithms compared to the others.

algorithm	**static**	**#samples/speed**	**harmonics**	***A* step/ramp**	***f* ramp/step**
4PSF	√	√ / √	►	√	√
iDFT	►	► / √	√	►	►
SLCA	√	○ / ►	√	√	√
MHFE	√	○ / ○	►	√	√
PSFEi	√	►/ ►	√	►	►
PSFE	√	√ / ○	√	√	√

According to the tests executed, numerical performance examination and reliability, the PSFE was found to have the best overall performance therefore this algorithm has been also implemented in NI LabVIEW and sent for further testing to LNE. The performance of the algorithms has been also presented at *Conference on Precision Electromagnetic Measurements* (CPEM 2016, Ottawa, 10-15 July 2016) as well as in a SCI paper entitled *Behaviour of different PMU algorithms under static and dynamic conditions* which was submitted to *IEEE Transactions on Instrumentation and Measurement*.

Complementary to the work on algorithms, it was important to verify if these algorithms were suitable for practical implementations where computing resources are limited. To this end a reference PMU was designed and built on PXI platform (LNE). Through the standardisation of the PMU algorithm interface, the loading of a PMU algorithm was streamlined and enabled the rapid verification of the algorithms with electrical signals. These signals were either provide by a PMU calibrator (METAS) or real world signals as this reference PMU could be used in the field (EIM, SP). The results of the algorithms could be either be logged in a file or streamed into IEEE C37.118.2 Ethernet frames. The reference PMU allowed to confirm the performances predicted by simulations.

A fully operational advanced PMU calibrator has been designed and implemented to permit the calibration of PMU designed around the standard C37.118.1 as well for PMUs used in distribution networks for which no standard exist (EPFL, METAS). These advanced PMUs are characterised by a TVE (Total Vector Error) between 0.02 and 0.05 % which is up to 50 times better than traditional PMUs used in transmission networks. This significant accuracy improvement in PMUs performances forced an even more important enhancement of the TVE of the PMU calibrator to 0.002 to 0.005 %. This demanded the simultaneous improvement of waveform timing as well as magnitude and phase precision. This translates into timing errors of less than 30 ns and 20 to 50 ppm or µrad respectively for the magnitude and phase accuracy.

The time accuracy was achieved by the replacement of a GPS based timing by the use of an atomic clock (METAS). For the calibrator designed by METAS, the clocking was directly connected to the atomic clocks used for the official time (UTC CH) while the calibrator from EPFL used a commercial atomic clock disciplined by GPS. This resulted in an improvement of the time jitter by over two magnitudes. The magnitude and phase precision was improved through the use of active calibration which recalibrated the PMU calibrator between two measurements. A further improvement was the use of equalisers to compensate the effect of the limited bandwidth of voltage or transconductance amplifiers. In effect phase shifts introduced by amplifiers could greatly complicate tests such frequency modulated tests.

A new waveform generator was also designed (METAS) to replace the original play back system of stored waveforms. This approach permits to create waveforms for non-normalised tests and renders the calibrator much more flexible. An additional benefit is the possibility to change the sampling frequency used for the generation and acquisition of the test waveforms. This flexibility has also the benefit to make the PMU calibrator useful for the calibration of power quality analysers where signals must have a known time relationship.

Another major achievement was the design of test software which permits to fully automate the calibration of PMUs (METAS). In effect, the calibration of PMUs is time and data intensive. The software must allow the user to inspect a large amount of data generated by PMUs so as to permit the detailed analysis of the behaviour of PMUs. Another important feature is the possibility to automatically generate test reports so that such measurements become cost effective for commercial calibrations.

A PMU calibrator is a system that enables us to validate the conformity of the PMU under test with respect to the current standard for synchrophasors, i.e., the IEEE Std. C37.118, in terms of synchrophasor estimation accuracy and measurement reporting latency. The former, is identified by the Total Vector Error (TVE), Frequency Error (FE) and Rate-Of-Change-Of-Frequency (ROCOF) Error (RFE). The latter, is defined as the time delay between the instant a specific event occurs in the power system and the instant the same event is reported by the PMU. In general, the TVE must not exceed 1 %. However, scalability of the PMU technology to Active Distribution Networks (ADNs) requires an increased level of PMU accuracy (TVE lower than 0.1 %). As known, a PMU calibrator must be characterised by a level of accuracy at least 10 times better than the one of the PMU under test.

Within this context, EPFL has developed and fully characterised a highly accurate calibration system for PMUs operating ADNs, capable of reproducing all the operating conditions defined by the IEEE Std. C37.118. The system is based on a non-linear least-squares (NL-LSQ) fitting algorithm. The optimization problem solved by the NL-LSQ algorithm was studied in terms of solution uniqueness and robustness against wideband Gaussian noise. The accuracy of the solution varying the amplitude, frequency and initial phase of the test signal generated by the PMU calibrator was characterised. Furthermore, to assess the dependence of the accuracy on the algorithm parameters (i.e., the observation interval length and the sampling frequency), a sensitivity analysis was carried out. The developed PMU calibrator produces reference synchrophasors characterised by a TVE lower $3.5*10^{-3}$ % in static operating conditions and a TVE lower $3*10^{-2}$ % in dynamic operating conditions (as expected, the algorithm performance degrades in the presence of dynamic test conditions).

In the proposed hardware configuration, the time synchronization of the PMU calibrator is guaranteed by a master atomic clock characterised by high short-time stability, disciplined through a GPS receiver, characterised by high long-term stability. In steady-state conditions, the timing error contribution to the phase angle uncertainty is equal to the standard deviation and it corresponds to 4 μrad.

Moreover, the developed PMU calibrator integrates a Phasor Data Concentrator (PDC), specifically designed to gather data streams coming from various PMUs under test, parse and de-capsulate C37.118 data frames and assess the PMU measurement reporting latency.

A third PMU calibrator was also developed at VSL. Following the experience of METAS, the calibrator proposed by VSL uses directly the UTC(VSL) (10 MHz and PPS) as a time source and trigger line. The major contribution to the TE uncertainty in the reference measurement is then due to the internal circuitry of the PXI and the wiring. Characterisation of TE was achieved by comparing the PPS routed out from the VSL calibrator (PXI-PPS), which is used as a trigger in the generation and acquisition stage of the calibrator, and the PPS of the UTC(VSL) (VSL-PPS), using a commercial frequency counter SR620. The 10 MHz clock of the SR620 was overridden with the UTC(VSL) one. When synchronized to UTC(VSL), in time interval mode, the SR620 has an uncertainty of about 25 ps. In order to ensure a stable synchronisation of the PXI, recording of TE was started after 48 hours of operation. Figure 2 shows the TE obtained during a 5 days measurement. The average delay is about 54 ns with a type-A experimental standard deviation of 70 ps. In the context of PMU calibration, after correction of the measured delay, the residual TE can be considered negligible.

A paper describing the calibration of PMU calibrators submitted to a peer reviewed journal. In collaboration with University of Padua and supervised by METAS, VSL wrote an article titled “Metrological Characterisation of a PMU Calibrator in the 25 Hz to 3 kHz Range“. The article has been accepted for IEEE PowerTEch 2017. In particular, the paper describes the metrological characterisation of a PMU calibrator currently being developed at VSL. At the moment, the calibrator can reproduce the static tests of the current IEEE Std with uncertainties way below the actual limits in the IEEE Std.

In order to investigate the performance of PMUs in real conditions, a comparison of a commercial PMU to a calibrated commercial PMU was performed by EIM and SP in the Greek Transmission Grid, within a high voltage substation. The two PMUs were a type ABB RES 521 unit, installed by the Greek Independent Power Transmission Operator and an Arbiter 1133A unit, calibrated by SP. Connections were made to one voltage phasor through 400 kV:100 V voltage transformers and one current phasor through 1600 A:1 A current transformers (interconnection line between Greece and Bulgaria). The results showed that the phase errors of the voltage and current fall inside the manufacturer specifications (0.1 %) and they also meet the precision criterion of 1 % set by IEEE PC37.118.1 Standard for Synchrophasor Measurements for Power Systems. It is significant to note that by performing the on-site measurements, effective cooperation and exchange of experience between EIM and SP was achieved.

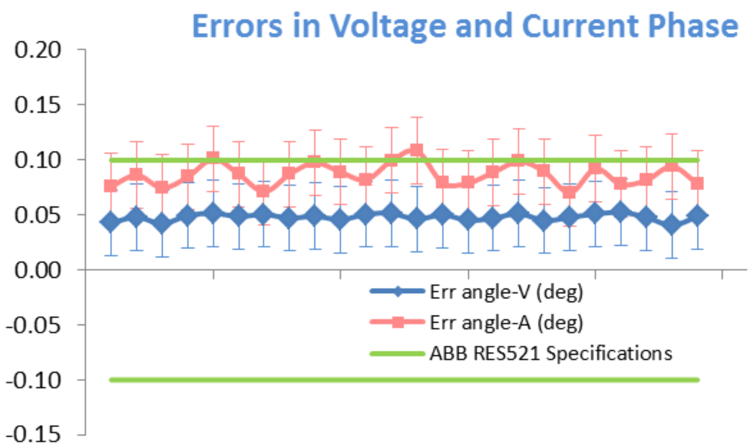


Figure 3. Errors in Voltage and Current Phase

Summary and Conclusions

The specific Scientific and Technical objectives that have been accomplished are:

- ***PMUs in Distribution Networks***. Selection, comparison and validation of new PMU algorithms suitable for use in LV and MV distribution networks. These networks are characterised by smaller distances and hence require higher phase sensitivity whilst at the same time accounting for a higher level of PQ disturbances.
- ***Dynamic calibration of PMUs*** . Develop extensions to a laboratory PMU calibrator to provide new calibration support for the dynamic performance of PMUs as proposed in IEEE standard C37-118.1 (2011).
- ***On-Site Calibration of PMUs.*** Undertake on-site measurements using reference PMUs, suitably modified to calibrate/verify the operation under realistic conditions including PQ disturbances.

And the Key Outcomes are

- With the help of the collaborator involved the PMU best practice guide for on-site PMU calibration has been revised and updated in section 4 “Field measurements of Phasor Measurement Units (PMU)” and section 5 “Application of PMUs in electricity grids
- A fully operational advanced PMU calibrator has been designed and implemented to permit the calibration of PMUs designed around the standard C37.118.1 as well for PMUs used in distribution networks for which no standard exist. These advanced PMUs are characterised by a TVE (Total Vector Error) between 0.02 and 0.05 % which is up to 50 times better than traditional PMUs used in transmission networks. This significant accuracy improvement in PMUs performances forced an even more important enhancement of the TVE of the PMU calibrator to 0.002 to 0.005 %.
- PMU algorithms are at the core of the process transforming waveform samples into phasors under the exacting PQ conditions and frequency deviations that exist in real networks. Six different PMU algorithms where investigated using simulations and a comparison guide was published. This will help manufacturers choose the best algorithms for future PMUs and will become a benchmark for new algorithms. These were implemented in reference PMU hardware for further lab and field testing.

3.3 To utilise PMUs in a new tool to measure the impedance of the grid, a parameter essential to the planning, measurement and control of Smart Grid stability and PQ.

3.3.1 Line impedance at the fundamental frequency

A new method for determination of three-phase transmission line impedances based on synchrophasor measurements was developed by IMBIH and VSL. The method uses a robust M-estimator to improve upon problems related to contamination of the synchrophasor data with unwanted spikes and complex noise which limits the accuracy in the line parameter determination, especially when electricity transmission lines (TL) are short. This estimator strongly reduces the influence of unwanted spikes (bad data or outliers) on the TL parameter determination, removing the need for a separate computational-intensive bad data analysis.

For determining the TL line impedance parameters, the classic three-phase two-port network model of Fig.4 is used. The algorithm itself, as developed by IMBIH, is described in detail in [1].

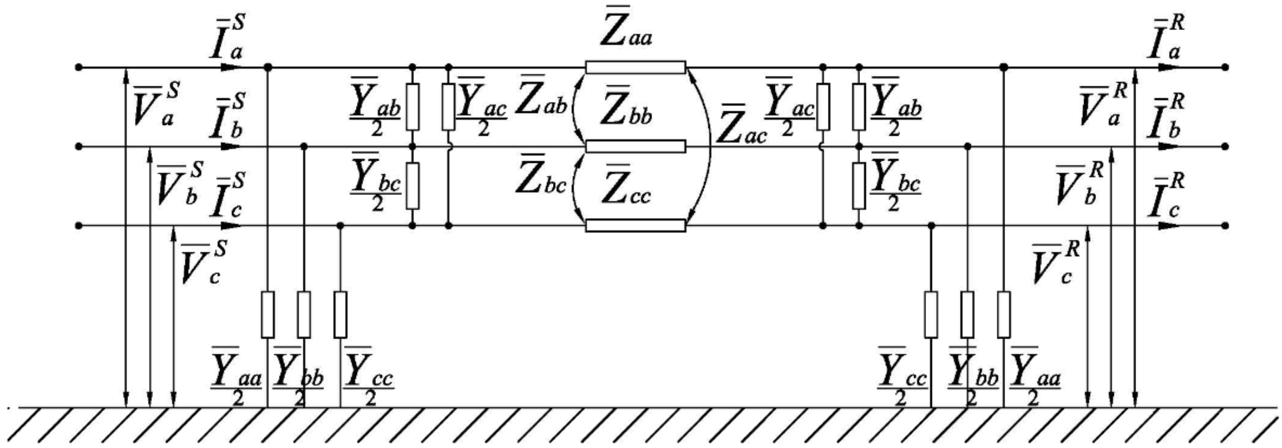


Figure 4: the classic three-phase two-port network model.

Equivalent three-phase transmission line model

An experimental setup has been developed by VSL, suitable for studying the characteristics of the proposed method as well as the necessary conditions for algorithm convergence at balanced and unbalanced loading of the transmission system. The parameters of the transmission line (impedance and admittance matrices) in the experimental setup are chosen such as to represent a real overhead 400 kV TL.

Fig. 5 shows the schematic of the laboratory measurement setup for verification of the new estimator algorithm. The TL emulation circuit is made using coils connected in series to achieve the required inductance, in combination with line-to-line and line-to-ground capacitors. In order to better represent the typical conditions in a transmission/distribution electricity grid, a return ground-path impedance was inserted in the laboratory model of the TL. The self-impedance of each phase of the TL consists of three air-core inductors connected in series, each with nominal inductance of 4.7 mH and nominal resistance of 0.77 Ω. The equivalent inductance per phase is $L_{aa} = L_{bb} = L_{cc} = 3 \times L_{coil}$ = 14.1 mH and similarly the resistance is $R_{aa} = R_{bb} = R_{cc} = 3 \times R_L$ = 2.31 Ω. The impedance of the return ground path consists of one coil and one resistor connected in series resulting in an equivalent inductance $L_g = L_{coil}$ = 4.7 mH and resistance $R_g = R_R + R_L$ = 7.97 Ω, where R_R is the resistance of the resistors inserted in the return ground path, R_L is the self-resistance of the coil and L_{coil} the self-inductance of the coil. The lumped capacitors used in the laboratory TL model have a nominal value of 470 nF, while the mutual capacitance consists of the natural capacitance between the coils of each phase.

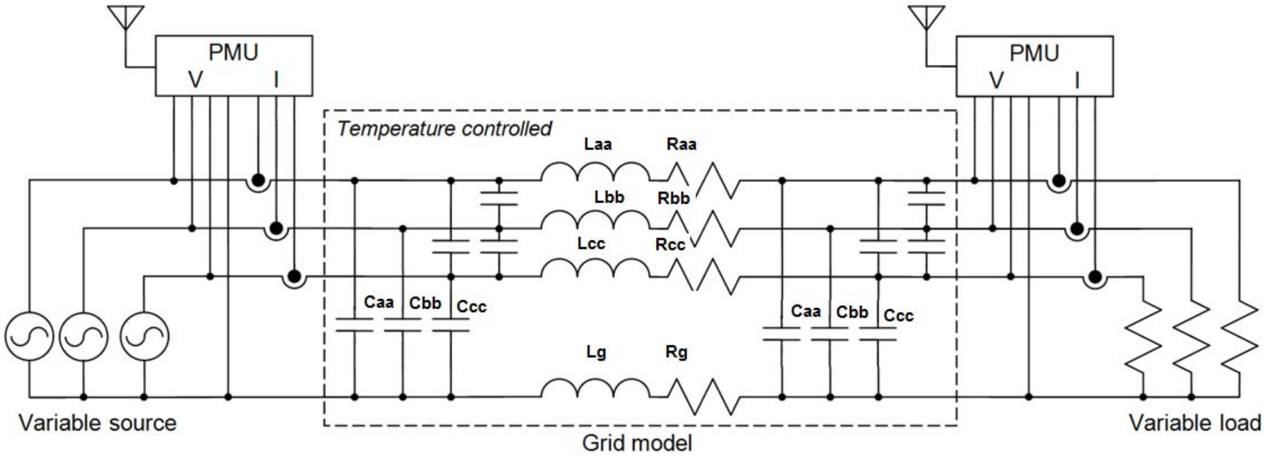


Figure 5: Electrical scheme of the laboratory measurement setup suitable for testing the TL impedance estimator algorithm.

The actual laboratory setup at VSL is shown in Fig. 6 The three-phase current and voltage synchrophasor measurements at both ends of the TL are obtained using two Arbiter 1133A PMUs. A three-phase amplifier (California Instruments 4500L-3) is used as power source on one side of the grid model, while the other side is connected via variable resistors to ground, simulating a symmetric or asymmetric load. The maximum voltages and currents generated by the three-phase amplifier in the equivalent circuit model were V_n = 60 V and I_n = 1 A respectively.

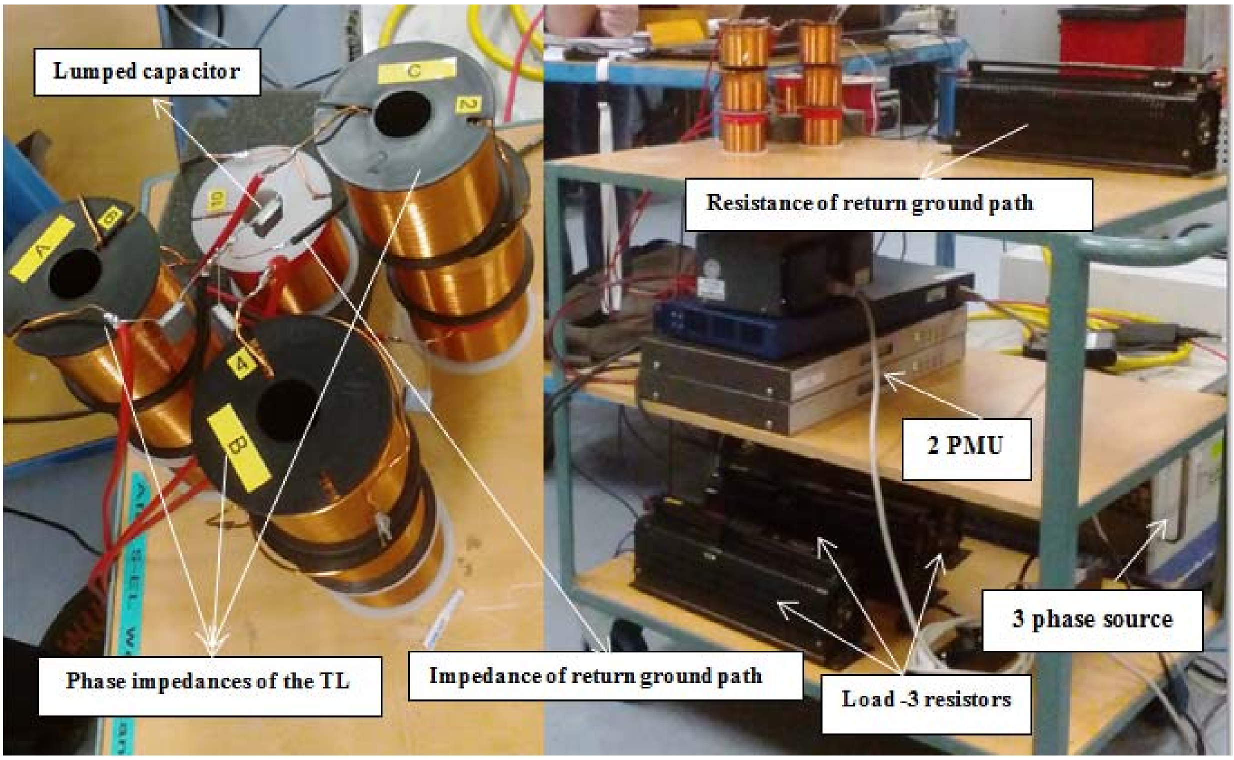


Figure 6: Three phase laboratory setup suitable for testing the TL impedance estimator algorithm.

Two cases are analysed. The first case takes into account a presence of large current unbalance while in the second case the current unbalance is small. Using the developed impedance algorithm, the parameters of the line were obtained, and the conclusions are presented below:

- By using the proposed algorithm, self and mutual parameters of impedance matrix are calculated successfully in the accuracy range of 5 %.
- Accuracy of the determined impedance parameters depends on the level of 3-phase current unbalance. The system of linear equations in the algorithm is easier to solve in case of a large current unbalance then in case of a small unbalance. Due to this fact, current and voltage errors (both magnitude and phase) have large contributions in errors of impedance parameters in case of bad conditioned linear systems.
- Results of series impedance are obtained without any corrections of current and voltage errors in the measurement chain. By calibrating PMUs and correcting for all errors in the measurement chain, the accuracy of obtained impedance parameters will be improved.
- Parameters of the admittance matrix are not calculated successfully. The reason for these results can be due to small capacitors used in the TL model. By comparing root mean square (rms) values of three phase currents on the sending and receiving side of the TL it can be noted that their values are close to each other because lumped capacitive currents are very small. Due to this fact, current differences between the sending and receiving side of the TL are up to 2 mA. Such low level of current cannot be considered as sufficient condition for calculating admittance parameters, because it can be corrupted with noise. This is especially the case with used PMUs, since the measurements were performed in the 5 A range, and taking into account the resolution of ADCs in the current measurement channel.

3.3.2 Instrumentation channel errors

Typical GPS-synchronized equipment-PMUs are very accurate devices. However, the inputs to this equipment are scaled down voltages and current via instrument transformers, control cables, attenuators, etc., collectively referred to as the instrumentation channel. The instrumentation channel components are typically less accurate. Specifically, voltage (VTs or CCVTs) and current instrument transformers (CTs) may introduce magnitude and phase errors that can be orders of magnitude higher than the typical PMU accuracy. Most of the currently existing high voltage power grids cannot provide information about real conditions of instrumentation channel errors (ICEs), especially errors of instrument transformers that have the highest contribution in the measurement chain. The most common case is that the information about the instrument transformers errors become known from laboratory tests carried out after factory production. However, these data are not valid after a certain exploitation time in the network, considering that the errors can be changed due to different factors.

A new PMU based instrumentation channel errors determination method is developed in this project by IMBIH and VSL. The method proposed in this project is relatively easy for implementation. Only three well characterised reference VTs and 2 calibrated PMUs are required. The proposed algorithm is employed to calculate a set of correction factors (CFs) based on the raw data obtained from PMUs installed on both ends of transmission lines and a measurement model. Instrumentation channel correction is then achieved by multiplying the raw PMU data with the calculated CFs. Once the PMU data are corrected, they can be used for further applications such as state estimation etc. The requirements for reference equipment as well as in comparison to the classical on-site calibration are significantly reduced by applying the proposed method.

The proposed algorithm is described in detail in [2] and uses a similar TL model as described above for line impedance parameters, but is based on ABCD parameters whereas the estimator is an ordinary least squares (OLS) technique. In order to verify the accuracy and reliability of the proposed method, at IMBIH the three-phase PI model of the TL was built in SimPowerSystems Toolbox of Matlab, while the algorithm is implemented in Matlab. The TL model built in simulation is 400 kV and 100 km long line with typical tower geometry. The resulting series impedance and shunt admittance matrices per unit length (Ω/km) of transmission lines built in SimPowerSystems model are obtained by applying a geometry approach. The proposed method requires redundant PMU measurements. These measurements are obtained by running the simulation multiple times with a different loading level. Variation of the load is achieved by adjusting each active and reactive power of the three-phase load model within a range bounded between 20 % and 80 % of the TL's capacity. The system is simulated in steady-state operating conditions and therefore the outputs of the CTs and VTs are ideally sinusoidal. During each run, the outputs from each Potential Transformers (PTs)CTs are processed by a Discrete Fourier Transform (DFT) to generate the corresponding voltage/current phasors. In order to validate effectiveness of the proposed algorithm, bias error data in three phase voltage and current was generated artificially and added to the simulation data measured without any bias error, so that voltage and current phasors were "contaminated" with bias. The advantage of using simulated data lies in having the control over bias errors in PMU measurements. This means that theoretical CFs can be calculated exactly. With theoretical CF values as references, the effectiveness of the proposed algorithm can be validated by comparing the calculated CFs with their corresponding theoretical references.

As a first test, the algorithm was used at IMBIH to calculate CT and VT errors without any errors in the synchrophasor measurements. The CT and VT errors were on the 10^{-3} % and 10^{-4} % level, respectively. In the more realistic case with bias error in the reference voltage (representing a VT error less than its accuracy class) and noise in PMUs, the results show that the error uncertainty of the voltage channels is equal to calibration uncertainty of the reference voltage setup (being ±0.05 % in amplitude and ±3 min in phase, being much better than the accuracy class), whereas in the case of current channels it is increased with factor between 2 and 3.

By applying the proposed method, the requirements for reference equipment are significantly reduced as well as the duration of the process in comparison to the classical on-site calibration. The advantages of this approach come from the fact that calibration/verification of instrumentation channels can be carried out remotely without knowing all equipment installed in the measurement chain in advance. Obtained results have shown superior performances of the method in the case of determination of voltage channel errors while in current channel errors it is not the case. In our method, the uncertainty propagates through the wide area network with factor 1 so that all voltage instrumentation channel errors will be determined with uncertainty close to reference voltage setup, making it a very suitable option for calibrating voltage instrumentation channels in wide area networks.

3.3.3 Harmonic impedance

Harmonic impedance (i.e., impedance at harmonic frequencies) of transmission lines can be estimated using the same method as used for 50 Hz impedance as described above. However, in real measurements, the signal-to-noise-ratio of the much smaller harmonic signals that are present on top of the huge 50 Hz fundamental component in combination with other noise sources makes this method less suitable. As an alternative method, a decomposition method was developed by NPL, making use of the rich harmonic content present when short interruptions occur in the grid.

A single-phase network of impedance was developed in the NPL laboratory using an air cored inductor (0.9 Ω and 15 mH). Figure 7 shows an amplifier driven by an arbitrary waveform generator was used to create suitable waveforms. A load constructed from both resistance and inductance was used to represent the load on the power supply.

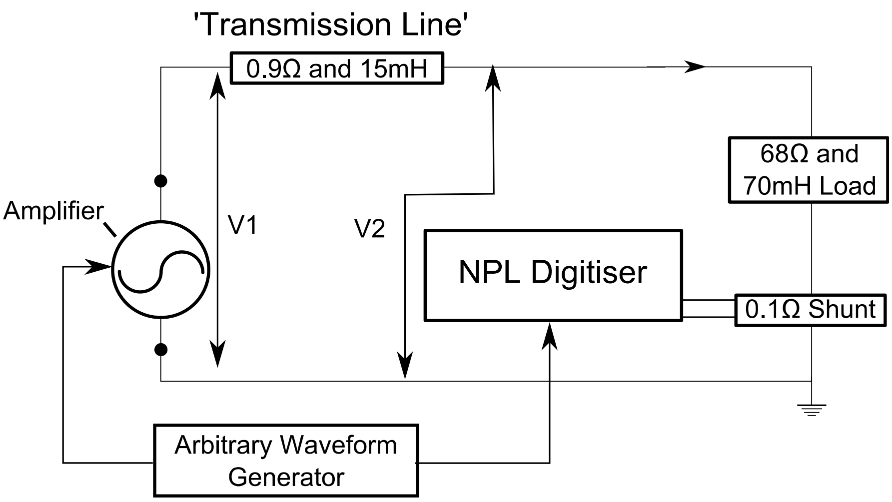


Figure 7: Lab based equipment setup for impedance test.

As the testing is primarily associated with harmonic content the input waveform is designed to be switched on at 90 degrees. The measured waveform before and after the inductor is shown in Figure 8.

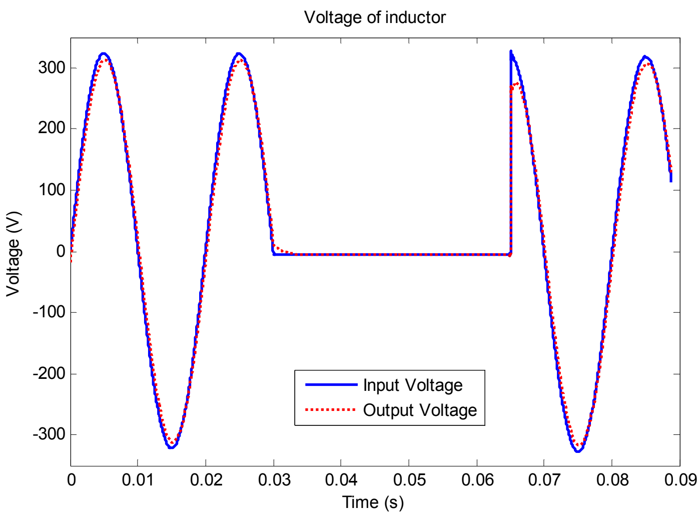


Figure 8. Voltage measured before and after inductor due to impulse

The input and output voltage of the transmission line have Fourier transforms of their voltage (512 samples) calculated. As the window that is being sampled moves across the waveform the ratio of the output voltage to the input voltage should give

$$H(j\omega) = \frac{V_2}{V_1} = \frac{Z_2}{Z_1 + Z_2}$$

This method enables a simplification where the impedances of the network and the impedance of the load form a voltage divider. This can be applied in the frequency domain.

A fitting technique can then be used to modify the Z_1 and Z_2 to fit to match the curves. This does require a reasonable knowledge of the system as a starting point and relies on the curve fitting and the window chosen.

Summary and Conclusions

The specific Scientific and Technical objectives that have been accomplished are:

- ***Network impedance and system resonances.*** Wide-area measurements and the analysis of system impedance and resonances in HV/MV/LV networks. Results will be evaluated against network design data and models.

And the key results are:

- Grid impedance measurements will always be a significant challenge, however the project has made some major steps forward with new algorithms and methods demonstrated both in the lab and on-site. This includes new methods for determining in-situ line impedance using two PMUs on either side of the line, with an uncertainty significantly lower (<5%) than for other methods. Extensions to harmonic frequencies were made using a new convolution method making use of the frequencies present during transient disturbances.
- The ratio and phase errors of installed VTs throughout electricity networks is largely unknown and their measurement is highly inconvenient requiring the use of large and heavy equipment installed during a power interruption. A new PMU method to remotely determine the errors of VTs connected in energised networks has been developed in the project and could be of significant benefit to the industry providing improved revenue settlement accuracy and PMU measurements.

[1] Vladimir Milojevic, Srdan Calija, Gert Rietveld, Milos Acanski, Daniele Colangelo, “A Robust Synchrophasor-Based Method for Determining Three-Phase Line Impedance”, submitted to AMPS Conference 2017

[2] Vladimir Milojevic, Srdjan Calija, Gert Rietveld, Milos Acanski, “Method for determining 50 Hz instrumentation channel errors in power transmission systems from synchrophasor measurements”, Conf. Proc. MedPower 2016, DOI: 10.1049/cp.2016.1097

3.4 To provide a metrology framework for the PMU/PQ transducers; these devices convert the high voltage and current levels on the grid to measureable low levels, but introduce errors in the process.

Current and voltage transducers are vital components of PQ/PMU measurement chains. They are required to scale the grid current and voltage to levels compatible with the input of the PMU or the PQ measuring instrument without introducing waveform modifications or time delay. However, any uncertainty introduced by these devices propagates through the quite complex PQ/PMU measurement chain, finally affecting the measured parameters. In most situations, already installed inductive voltage transformers (VTs) and current transformers (CTs), which are designed for metering or protection and are generally calibrated at power frequency only and are connected to the measuring instruments without any information on their behaviour at higher frequencies. Considering the complex distorted waveforms likely to be experienced in the medium voltage (MV) grids, knowledge of the transducer actual frequency response in a range up to the 50th harmonic and over is a key-issue. A new generation of openable sensors is available in particular for current measurements, which could replace the inductive CTs, because of their better linearity and non-invasiveness. On the other hand, these sensors are more sensible to harsh on-site conditions, showing little measurement repeatability and high measurement uncertainties up to several percent.

The project then faced four specific unresolved issues that are:

- the reduction of the on-site current measurement uncertainty to levels of the order of a hundred of ppm by developing/optimising non-invasive current sensors and defining suitable measurement protocols;
- the set-up of calibration facilities for the assessment under distorted realistic MV waveforms of the complex frequency response of inductive MV VTs of the same type as those normally installed in the grid and used for PQ/PMU measurement;
- the real-time compensation of the unsatisfactory frequency response of VTs by development of compensating procedures to obtain a reduction of the VT errors up to two orders of magnitude in a frequency range a up to 2.5 kHz;
- the evaluation of the propagation of the transducer and circuit component uncertainty through the complex measurement chain by Monte-Carlo Methods and by simplified analytical models.

3.4.1 Optimised non-invasive CTs and utilization methods for minimizing on-site measurement errors.

Starting from an extensive analysis of the available current sensors and sensing methodologies, a set of non-invasive devices was selected for characterisation and/or optimisation, based on technology maturity and availability.

VTT/MIKES characterised several models of Rogowski coils (RCs), including flexible openable coils and rigid split-core ones, as well as an openable Hall current sensor. The effects on sensor response of measurement conditions likely to be experienced on-site were quantified in terms of ratio and phase errors, considering primary current linearity up to 5 kA phase; effect of centre conductor position under worst case situations, i.e. with the coil hanging on the primary conductor, adjacent conductors proximity effect, coil tilt and frequency response.

Ratio and phase errors obtained for each kind of test greatly varied, from a few tens of ppm (microradians) up to some parts per thousand (milliradians), as a function of the measurement conditions (e.g. gap position, distance from return conductor, test frequency) and sensor type and model. Quite good performances were obtained for a flexible, small radius openable coil, whose error contributions due to linearity, return conductor proximity and frequency are each, with the exception of a few measurement conditions, within 0.01 %.

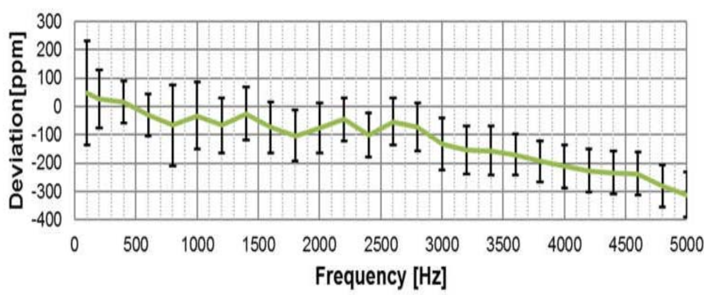
A critical further uncertainty contribution can be due to the temperature dependence of the coil mutual inductance, which was found from (-8 to 45) μH/H/K for the investigated sensors. A new method for optimising the Rogowski coil temperature coefficient together with high frequency response was developed by VTT MIKES, based on finding a value for the termination resistance and for its temperature coefficient, which results in negligible change of coil output voltage vs. temperature while still allowing for any damping ratio.

Characterisation was further performed on two models of combined VTs, but none of them showed a performance suitable for PQ measurements up to 2.5 kHz, due to their frequency response being quite poor.

On the basis of the experience gained in the characterisation of the different sensors, a good practice guide was prepared by VTT MIKES, which gives indication on the best procedures and techniques to minimise errors when using RC sensors in an actual measurement situations.

A non-invasive split-core CT with nanochrystalline core material was instead developed by CMI. Cores wound by a strip from a nanocrystalline material with thickness of 20 μm were used for CT core construction, which also involved core splitting and grinding the contact surfaces. The dependence of apparent permeability and loss angle of split cores was measured in the design phase. Based on these results three split-core CTs with primary currents 100 A, 500 A and 1000 A were made. An extensive characterisation was performed both in amplitude and frequency.

Results obtained by CMI show that the core air gap linearizes both the apparent permeability and loss angle dependences vs. magnetic flux density, and the dependence of errors vs. measured current magnitude. For two of the realised CTs, introduction of a suitable correction for the transformation ratio thus enables to reduce the ratio error to values that differ minimally from target 0.01 %, for applied primary currents from 20 % to 120 % of the rated current. Measurement of the error frequency dependence, demonstrated that use of nanocrystalline materials for CT core construction, enables their usage in the range up to 50th harmonic with ratio error variations of the order of a few hundreds of ppm.



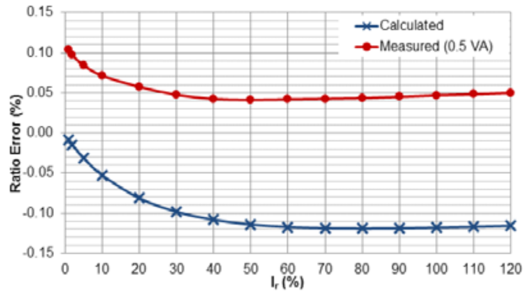


Figure 9 Measured frequency response (ratio error) of a flexible RC

Figure 10: Ratio error frequency dependence of the 100 A/0.1 A CT

3.4.2 Calibration facilities for the assessment of the complex frequency response of inductive MV voltage transformers under distorted realistic medium voltages

As a starting point specifications and constraints of the facility for the frequency calibration of MV inductive VTs were identified by INRIM, considering a range of generated voltages from 1 kV up to 30 kV (phase to ground) with superimposed harmonics up to 50th (minimum range). Ratio and phase errors of conventional inductive voltage transformers with standardised output (100 V, 100 V/√3) were the quantities to be measured. Target uncertainties were fixed from 30 to 10 times lower than the limit values indicated for the harmonic range by relevant standards for transducers used in the measurement of PQ disturbances (5 % and 90 mrad for ratio and phase errors respectively from the 3rd up to 50th harmonic).

Two circuit layouts were identified and developed at INRIM. In particular, a new set-up was proposed, which is a modified extension of the two steps procedure based on the use of a high voltage (HV) capacitance bridge, and is currently used in NMI laboratories for the power frequency calibration of inductive VTs. The key elements of this set-up are a power amplifier (±30 kVp, 20 mA, DC to 20 kHz, with full generation capabilities up to 7 kHz), supplied by an arbitrary waveform generator, and a suitably built digital comparator with associated control and measurement software developed with the support of UniNA2. The currents flowing into the capacitors are measured when they are both directly connected to the MV supply as-and-when the VT under calibration is inserted between one of the capacitor and the MV voltage. VT ratio and phase errors are evaluated as a function of the current ratios and phase displacements measured in the two steps. Using this approach, the increasing weight of the harmonic currents is exploited, which amplifies the smaller amplitudes at the higher frequencies. Uncertainty contributions due to the imperfections of the method, which in principle is are absolute errors, have been identified, leading to a standard uncertainty within 200 μV/V and 300 μrad for ratio and phase errors respectively at frequencies up to 10 kHz.

A second layout, more focused on the calibration of non-conventional VTs with low voltage output was also implemented in INRIM, where the VT is calibrated by comparison with a reference sensor, making use of the previously described supply systems. The reference sensor, designed and built at INRIM, is a resistive capacitive divider with suitable shields introduced to improve its frequency response and reduce proximity effects. With respect to the first set-up, it allows calibration at higher voltages (30 kV rms), in a narrower frequency range (DC to 8 kHz) with similar uncertainties. Comparison of the performances of the two calibration systems showed good equivalence between them within the associated uncertainties.

Figure 11: VT calibration by the HV capacitance bridge

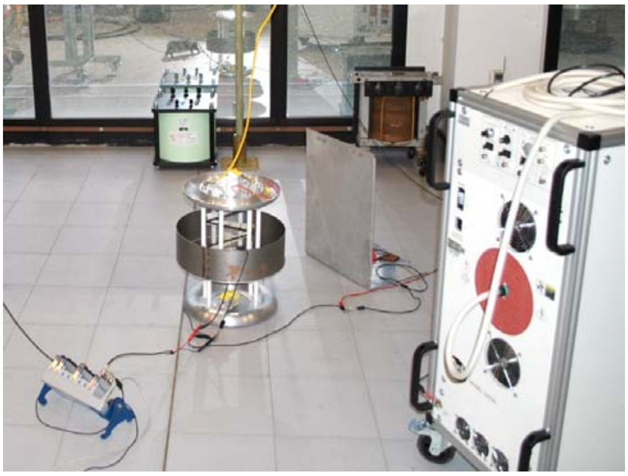


Figure 12: Characterisation of the calibration set-up with reference sensor

The development of these new measurement capabilities makes possible the determination of the complex frequency response of VTs of the same type as those currently employed for on-site PQ measurements. VT ratio and phase errors up to the first resonances were measured by INRIM on commercial VTs with primary voltages from 1 kV up to 50 kV. Measurements were performed carrying out a frequency sweep with the fundamental at the rated MV voltage (up to 30 kV) with a superimposed harmonic of amplitude from 20 % to 0.2 % of the fundamental component. In particular, characterisation of a 0.2 class 10 kV/√3 VT, which was provided by NPL among those used in WP1 on-site measurements, showed a quite flat frequency response with its first resonance at ~ 16 kHz. First resonances at lower frequencies were measured on a 20 kV/√3 VT (~ 6 kHz) and on a 55 kV/√3 oil insulated VT (~ 5 kHz), provided by VSL, and a 50 kV VT (~ 2 kHz). For these last two VTs, the range of operating frequencies with errors compliant with the standards was limited to 1.8 kHz and 1 kHz respectively. Measurements performed at low voltage demonstrated, for the investigated VTs, an increase of 2 % and 3 % of the ratio errors with respect to the values obtained when the frequency sweep was carried out with the fundamental at MV voltage at conditions closer to those used in practice.

3.4.3 Real-time compensation of the VT frequency response.

Based on their experience in the development and application of numerical filters, a technique for compensating ratio and phase errors of MV VT up to some tens of kHz was developed by UniNA2.

Starting from the metrological characterisation of the VT over a certain frequency range, cascading a device with a frequency response equal to the transducer inverse transfer function allows compensation of its systematic deviations. For this purpose, an impulse infinite response digital filter was adopted, whose complex transfer function is factorised in N second-order sections and whose best coefficient set had to be identified to best fit the given transducer.

To this end, a suitable objective function, describing the difference among desired frequency response and obtained values was defined, which weighs the ratio between the model frequency response and the frequency response data at each frequency and uses a logarithmically spaced frequency interval. To minimise the errors in the fit, a hybrid scheme based on the combination of a stochastic and a deterministic approach was adopted to take advantage of their complementary characteristics that are respectively the fastest way to work out a solution and best capability of identification of the optimal solution.

The reconstruction capabilities of the considered technique have been numerically quantified by considering the circuit model of a LV resistive divider and of a resistive-capacitive (RC) divider made and characterised by INRIM. The compensation algorithm performance was first investigated by UniNA2 simulating the compensated "filter + resistive divider" frequency response, both in ratio and phase and then by comparing the maximum absolute differences between the RC divider measured frequency behaviour and the inverse of the reconstructed filter function. Both the characterisation results showed that the developed technique allows the compensation of the voltage transducer behaviour from 10 Hz to 10 kHz, reducing its frequency response errors of a factor enclosed between 1 and 3 orders of magnitude, depending on the frequency value.

The technique has been applied to the compensation of the 50 kV VT whose frequency response, provided by INRIM, showed a series of resonances in the range up to 5 kHz, with the first one at ~1 kHz, with maximum errors of about 1.4 V/V for the ratio and 1.3 rad for the phase. Matlab implementation of the filter, as identified by UniNA2, shows a significant improvement of the frequency response which is well within the prescribed limits up to 5 kHz. Ratio error in correspondence of the first resonance peak reduces of more than one order of magnitude, from -50 % to less than 3 %. Compliance with standards limits is reached also for the phase, whose error at the first resonance reduces from 1.3 rad to less than 50 mrad, against a limit of 90 mrad, obtaining a reduction of about 70 times.

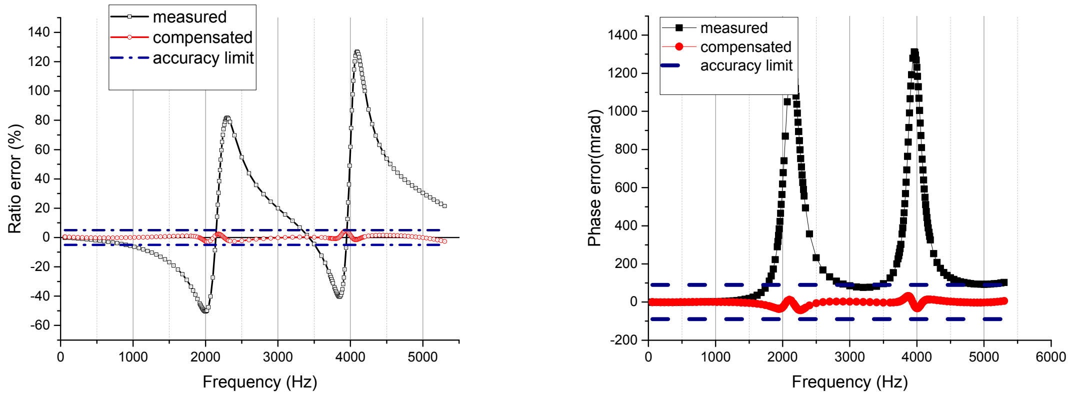


Figure 13: 50 kV VT ratio and phase error compensation

The infinite impulse filter correction was Labview implemented by a PXI platform by UniNA2, within the INRIM frequency response measurement circuit. Labview implementation of the filter was then tested in an attempt to compensate the frequency response of the 55/√3 VT. The first resonance peak is at about 5 kHz with a quite significant ratio error of 800 % and an error of -3 rad for the phase. In this case, after the compensation, compliance with the standard limits is obtained up to 4 kHz and the resonance peak is 35 times lower after compensation.

As a final step, the frequency response compensating filter of a 1 kV VT was successfully implemented. The VT frequency analysis was carried out by INRIM and the first resonance was found at about 54 kHz. The correction filter was identified by UniNA2 and real time implemented by a FPGA embedded in a CompactRIO platform. The comparison between the Matlab implemented filter function and the actual filter function response from FPGA implementation showed full overlapping with an error compensation of two orders of magnitude around the resonance. The same good compensation results were obtained for the phase, after introduction of a systematic correction for the time delay.

3.4.4 Evaluation of the propagation of the transducer uncertainty through the complex measurement chain

A Phasor Measurement Unit (PMU) simulator was developed by CMI to calculate the uncertainty of PMU output quantities by means of Monte Carlo method (MCM). The PMU simulator (*pmusim*) consists of three blocks: the generator of simulated data, the PMU measuring system and the synchrophasor estimation algorithm for total Vector Error (TVE), rate of change of frequency (ROCOF) and Total Harmonic Distortion (THD). The simulator was written in GNU Octave and optimized for run on CMI supercomputer *čokl* with GNU Linux operating system.

The PMU simulated measurement system included a 20 kV/√3:100 V voltage transformer, whose frequency calibration data were provided by INRIM for several frequencies up to 10 kHz, the connecting cable, a digital compensating filter algorithm developed by UniNA2, digitising boards of different models simulated as an analogue-to-digital converter with measured gain and phase errors. The synchrophasor estimator algorithm is based on a four parameters fitting method.

Uncertainty propagation on each measured PMU/PQ parameter was estimated by CMI by application of Monte Carlo technique. Considering selected transducers and acquisition modules, achievable uncertainties under sinusoidal waveform for TVE parameter ranged from $3 \cdot 10^{-3}$ to 0.7, depending on the characteristics of the selected acquisition module. No influence was found for the introduction of the compensating stage. As to the ROCOF, output uncertainties resulted from some to 16 part in 10^6, being the higher value due to the increased digitiser noise, which was the main source of uncertainty together with the resolution uncertainty. The THD uncertainty resulted to be essentially determined by the digitiser THD only, being the applied signal a sinusoidal one and introducing the transducer a very low distortion.

Sensitivity to input quantities was evaluated for each output parameter by varying the most significant input uncertainty sources as determined in the uncertainty evaluation phase and keeping fixed all the others.

To reduce the computational effort, a simplified uncertainty model was further developed by CMI for TVE and ROCOF by fitting results of the sensitivity and uncertainty calculations. The uncertainty was calculated for a number of input quantities selected between the most influencing ones and the results were fitted by an n-polynomial fit. For the TVE parameter uncertainty, input uncertainty associated with the digitizer and transducer ratio error were considered, leading to a 2-dimensional polynomial fit for *u*(TVE), whose maximum value is 0.7 %. As a whole, the standard uncertainties by this approach differ less than 10 % from the values given by the MCM simulations.

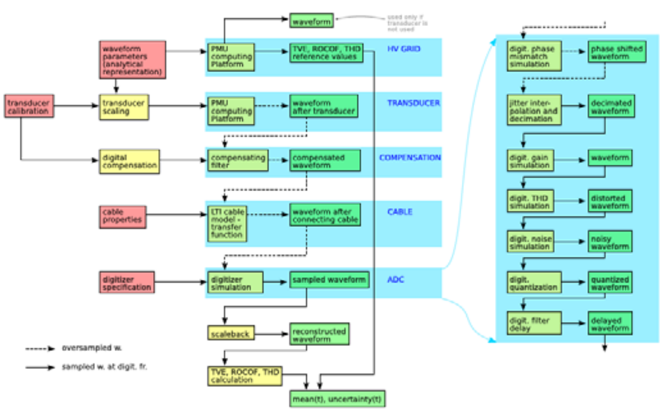


Figure 14: Scheme of Phasor Measurement Unit (PMU) simulator pmusim

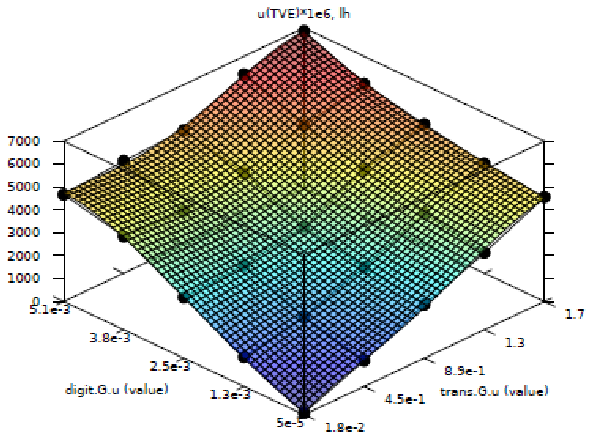


Figure 15: u(TVE) two-dimensional polynomial fit

Summary and Conclusions

The specific Scientific and Technical objectives that have been accomplished are:

- ***PMU/PQ Transducer Characterisation***. Develop/apply wideband evaluation facilities for transducers and optimise non-invasive transducers specifically applied to the PMU/PQ measurement chain.
- ***Digitised Waveform Corrections***. Develop and evaluate signal processing methods to apply transducer frequency response corrections to sampled complex wave shapes typically present in PMU/PQ measurements. Reconcile the propagation of transducer uncertainties through complex PQ and PMU algorithms.

And the key results are:

- Non-invasive current measurements are essential in grids to avoid interrupting supply and dismantling the circuit to fit shunts. Techniques based on Rogowski Coils generally only provide measurements at “quick check” level of accuracy and are not suitable for revenue or compliance measurements. The JRP has developed optimisations and new split-core CTs to reduce measurement uncertainties by some two order of magnitudes down to a few 0.01 %.
- Traditionally high voltage transformer frequency response measurements have been performed at low voltages and a “leap of faith” has been made that there are no differences. The reason for this is that high voltage measurements are too difficult, however following this project the world’s first facility for the calibration of VTs at realistic voltages levels is now available. This allows measurement of VT complex errors under the relatively high MV level voltages at which the VTs are used in practice. VT are exposed to waveforms with frequency content up to 20 kHz achieving a calibration uncertainty one hundred times less than standard limits for VT errors in PQ measurements. This has indeed questioned the “leap of faith” and has shown that some VTs have resonance related errors when the primary voltage greater than 15 kV.
- Once VT complex frequency response errors are found, corrections must be applied. As the frequency response changes the shape of a measured waveform, corrections must be applied in the manner of an inverse filter, i.e. by convolution in real time. A digital compensation procedure for the real-time correction of the VT frequency response, as measured by the calibration facility, has been developed and implemented on an industry platform. This has proved capable of reducing the ratio and phase errors of VTs from ten to one hundred times, even in the presence of resonances.
- The complex algorithms used by PMUs are sensitive to multiple input errors developed in the PMU measurement chain. To properly analyse and determine these errors, a PMU simulator has been developed which allows estimation of output uncertainties of measured parameters (TVE, ROCOF and THD) by Monte-Carlo analysis. By a sensitivity analysis, the most significant input uncertainty components of each considered parameter can be identified and through a simplified analytical model a rather accurate estimate of the output parameter uncertainty is obtained as well. This will allow industry to understand the confidence limits on the actionable information obtained from PMUs.

3.5 Summary of the Projects Key Results and Conclusions

In conclusion all of the top levels aim and the Specific Scientific and Technical objectives have been met. The key results and conclusions are:

- A prototype harmonic location method was developed using a simulation of the Bornholm grid. Following the successful development of the location method in the simulation, significant challenges were overcome to implement the method using the six instruments on Bornholm. Location determinations of predictable cyclic harmonic disturbance has proved plausible and the feasibility of the technique looks highly promising, but will require further development and generalisation for routine use by utilities.
- On-site measurement using PMUs has resulted in a new method for the aggregation of harmonic currents which proposes an update of summation coefficients designed for use in the assessment of emission limits of installations. The results of the summation method could revolutionise the way that utilities assess the impact of new renewable connections and will be presented to the Normative working group CIGRE/CIRED C4.40 in the autumn meeting of 2017.
- A fully operational advanced PMU calibrator has been designed and implemented to permit the calibration of PMUs designed around the standard C37.118.1 as well for PMUs used in distribution networks for which no standard exist. These advanced PMUs are characterised by a TVE (Total Vector Error) between 0.02 and 0.05 % which is up to 50 times better than traditional PMUs used in transmission networks. This significant accuracy improvement in PMUs performances forced an even more important enhancement of the TVE of the PMU calibrator to 0.002 to 0.005 %.
- PMU algorithms are at the core of the process transforming waveform samples into phasors under the exacting PQ conditions and frequency deviations that exist in real networks. Six different PMU algorithms where investigated using simulations and a comparison guide was published. This will help manufacturers choose the best algorithms for future PMUs and will become a benchmark for new algorithms. These were implemented in reference PMU hardware for further lab and field testing.
- Grid impedance measurements will always be a significant challenge, however the project has made some major steps forward with new algorithms and methods demonstrated both in the lab and on-site. This includes new methods for determining in-situ line impedance using two PMUs on either side of the line, with an uncertainty significantly lower than for other methods. Extensions to harmonic frequencies were made using a new convolution method making use of the frequencies present during transient disturbances.
- The ratio and phase errors of installed VTs throughout electricity networks is largely unknown and their measurement is highly inconvenient requiring the use of large and heavy equipment installed during a power interruption. A new PMU method to remotely determine the errors of VTs connected in energised networks has been developed in the project and could be of significant benefit to the industry providing improved revenue settlement accuracy and PMU measurements.
- Non-invasive current measurements are essential in grids to avoid interrupting supply and dismantling the circuit to fit shunts. Techniques based on Rogowski Coils generally only provide measurements at “quick check” level of accuracy and are not suitable for revenue or compliance measurements. The JRP has developed optimisations and new split-core CTs to reduce measurement uncertainties by some two order of magnitudes down to a few 0.01 %.
- Traditionally high voltage transformer frequency response measurements have been performed at low voltages and a “leap of faith” has been made that there are no differences. The reason for this is that high voltage measurements are too difficult, however following this JRP the world’s first facility for the calibration of VTs at realistic voltages levels is now available. This allows measurement of VT complex errors under the relatively high MV level voltages at which the VTs are used in practice. VT are exposed to waveforms with frequency content up to 20 kHz achieving a calibration uncertainty one hundred times less than standard limits for VT errors in PQ measurements. This has indeed

questioned the “leap of faith” and has shown that some VTs have resonance related errors when the primary voltage greater than 15 kV.

- Once VT complex frequency response errors are found, corrections must be applied. As the frequency response changes the shape of a measured waveform, corrections must be applied in the manner of an inverse filter, i.e. by convolution in real time. A digital compensation procedure for the real-time correction of the VT frequency response, as measured by the calibration facility, has been developed and implemented on an industry platform. This has proved capable of reducing the ratio and phase errors of VTs from ten to one hundred time, even in presence of resonances.
- The complex algorithms used by PMUs are sensitive to multiple input errors developed in the PMU measurement chain. To properly analyse and determine these errors, a PMU simulator has been developed which allows estimation of output uncertainties of measured parameters (TVE, ROCOF and THD) by Monte-Carlo analysis. By a sensitivity analysis, the most significant input uncertainty components of each considered parameter can be identified and through a simplified analytical model a rather accurate estimate of the output parameter uncertainty is obtained as well. This will allow industry to understand the confidence limits on the actionable information obtained from PMUs.

4 Actual and potential impact

4.1 Metrology Achievements

The project has led to significant Metrological advancements in relation to Smart Grids operations. Some of the most significant metrological achievements are summarised below:

- A prototype harmonic location method was developed and demonstrated on Bornholm Island Smart Grid. Location determinations of predictable cyclic harmonic disturbance has proved plausible and the feasibility of the technique looks highly promising, but will require further development and generalisation for routine use by utilities.
- A new method for the aggregation of harmonic currents which proposes an update of summation coefficients designed for use in the assessment of emission limits of installations. The results of the summation method could revolutionise the way that utilities assess the impact of new renewable connections.
- Three (METAS, EPFL, VSL) fully operational advanced PMU calibrators have been designed and implemented to permit the calibration of PMU designed around the standard C37.118.1 as well for PMUs used in distribution networks for which no standard exists. These calibrators will meet the specific requirements of commercially available PMUs ensuring uncertainties of at least 10 times better than the commercial specifications.
- A simulation platform has been developed for testing PMU algorithms. The platform includes tests for the static and dynamic signals that are required by the IEEE Standard C37.118.1-2014 and tests that were considered important by the consortiums stakeholders such as immunity to interference and the ability to measure rapidly changing signals. The platform also allowed the numerical performance of the algorithms to be evaluated.
- PMU algorithms where investigated using simulations and field testing and a comparison guide was published. This will help manufacturers choose the best algorithms for future PMUs and will become a benchmark for new algorithms which are at the core of the process transforming waveform samples into phasors under the exacting PQ conditions and frequency deviations that exist in real networks.
- A new PMU method to remotely determine the errors of VTs connected in energised networks has been developed in the project and could be of significant benefit to the industry providing improved revenue settlement accuracy and PMU measurements.
- A digital compensation procedure for the real-time correction of the Voltage Transformer frequency response has been developed and implemented. It proved capable of reducing the uncertainties by up to 2 orders of magnitude, even in presence of resonances. This will allow the real time correction of PMUs leading to more accurate results and smaller tolerances on critical grid control decisions.
- A world leading new facility for the calibration of inductive Voltage Transformers has been developed. Its calibration uncertainty is two orders of magnitude better than standard limits for Voltage Transformer uncertainties in PQ measurements.
- A new method for optimizing Rogowski Coil temperature coefficient with high frequency response was developed which has resulted in negligible change of coil output voltage vs temperature. A new technique has been proposed for on-site measurement of Voltage Transformers using this technique that would reduce uncertainties by two orders of magnitude improving the measurement to levels accurate enough for some revenue settlement without going to the expense and incontinence of breaking the grid circuit to fit shunts.
- A PMU simulator of actual measurement chains has been developed, which allows estimation of output uncertainties of measured parameters (TVE, ROCOF & THD) by Monte Carlo Methods. This has led to the ability to do a sensitivity analysis of the measurement chain and concentrate on reducing the most important source of uncertainty.

Moreover, all the methods are described in scientific papers (see list in section 6), and some of them have been described in Good Practice Guides (See section 4.2) which allow the user community to have access to them.

4.2 *Dissemination Activities*

Scientific publications

The project has generated 34 high impact publications in key journals and 15 are in preparation. These incorporate the significant scientific outputs of the project. In addition the project has led to 3 Masters thesis being accepted. A list is provided in section 6.

Conferences and relevant fora

In total, 29 oral presentations as well as 9 poster presentations have been given by the partners during the life time of the project. Positive reactions were received to all these contributions, attracting discussions and comments. The results were presented at a range of different types of conferences, reflecting the diverse range of expertise on the project and academic and industry stakeholders. Major measurement conferences include Conference on Precision Electromagnetic Measurements (CPEM), World Congress of the International Measurement Confederation (IMEKO). Major electricity industry conferences include International Conference & Exhibition on Electricity Distribution (CIRED) and IEEE International Workshop on Applied Measurements for Power Systems (AMPS).

Good Practice Guides

Two new, and one updated, Good Practice Guides have been produced and are available on the project website, they are:

- Best Practice Guide for using Rogowski coils in field measurement campaigns:
- Best Practice for On-Site Power Quality Measurement Campaigns
- PMU Best Practice Guide for on-site PMU Calibration Standards

Trade Journals

The work was publicised at the end of the project in Smart Grid Today, www.smartgridtoday.com, an online trade journal dedicated to Smart Grid related topics. The project was also publicised in the Elektor magazine, in September 2016. Elektor magazine, www.elektormagazine.com , has an international audience and is published monthly in English and has a mixed readership of professionals and non-professional interested in electronics.

Engagement with Standards Bodies

The consortium has been an active member of the relevant working groups (11) of the relevant standards committees. See section 4.1 for metrology achievements.

Stakeholder Engagement

In planning and carrying out the measurements campaigns required for the completion of this project the consortium have been engaged with seven network operators throughout Europe (Göteborg Energi AB, Energinet, Östkraft, Lilander, DNWG, Západoslovenská distribution, Hellenic Transmission System Operator S.A.). The operational engineers have had to work closely with members of the consortium to select measurement sites, understand the placement and connection of transducers and plan the logistics of the measurement. This means the three measurement Good Practice Guides have been written in light of actual experience gained and not from a the theoretical point of view.

The regular attendance of meetings and workshops by Fluke (Fluke Corpoartion is a manufacturer of industrial testing equipment including electronic test equipment) has greatly brought the “voice of the industry” into this research. Some of the discussion about on the design of PMU calibrators have been instrumental to the successful development of advance PMU calibrator.

Workshops

Three workshops were held by the consortium. A mid project workshop held in the University of Strathclyde UK was attended by 40 attendees from NMIs, industry and academia. This workshop was a joint workshop with ENG63 GridSens. A workshop at the end of the project in Haarlem NL and was attended by more than 70 attendees from NMIs, industry and academia. The workshop was a combined workshop of all the Euramet projects on Electricity Grids finishing in 2017 (ENG61 FutureGrid & ENG63 GridSens) and was attended by the majority of the stakeholder community. Most of the presentations are available from the various project websites. PowerPoint recordings are available for the SmartGridsII session on the ENG52 website. A further stakeholder workshop on PMU algorithms was hosted by EPFL where academics and PMU manufacturers presented and discussed the various figures of merit and potential performance of various algorithms.

In addition to the workshops the consortium also participated in the provision of training to external audiences at four events. The training focused on algorithms and the metrological characterisation of PMUs.

4.3 Effective cooperation between JP-Partners

The European Metrology Research Programme (EMRP) is a metrology-focused European programme of coordinated R&D aimed at facilitating closer integration of national research programmes and ensuring collaboration between National Measurement Institutes, reducing duplication and increasing impact.

This project has been a good example of the implementation of this programme, gathering 15 NMIs/DIs and four academic partners (three Research Excellent Grant researchers and one non-funded partner) from 15 European Countries and from the EC. Several NMIs from countries which are smaller contributors to the EMRP are also involved in the project.

Much of the work in the project was collaborative and effective cooperation between the project partners was essential to its success. Many exchanges between the partners have taken place. This is shown in the frame of the “Research Mobility Grants” (one researcher from DPM has spent seven months at METAS) and the three secondments that took place. (LNE > METAS, STRATH > NPL, UNINA2, CMI > INRIM). . A summary of some of best examples of joint working that took place on the project is given below.

- NPL and Trescal cooperate in running the measurement campaign in the Bornholm Distribution grid, this involved maintenance of instruments, communication links and data management. This was essential to project success.
- REG(STRAT) collaborated with NPL and LNE to integrate a state-of-the-art PMU algorithm with their respective “field PMU” and “reference PMU” platforms. This work has enabled comparisons between different PMU implementations under realistic, real-time conditions.
- INRIM and UniNA2 collaborated to the development of the VT compensation procedure: the compensating digital filter was elaborated by UniNa2 starting from the experimental data provided by INRIM, which successively carried out its circuital implementation and characterisation.
- INRIM, LNE, METAS, SIQ and VSL worked closely to produce the PMU calibration infrastructure. The collaboration consisted of the simultaneous use of the PMU calibrator and the reference PMU and the various algorithms that were developed by various institutes (METAS – LNE – SIQ). The use of phase correction filters designed has been integrated in the PMU calibrators and reduced its phase error (INRIM – METAS). The development of a concept for the calibration of PMU calibrator (METAS – VSL) was also effective.

4.4 Examples of early Impact

Standards and regulation:

The new method for the aggregation of harmonic currents which proposes an update of summation coefficients designed for use in the assessment of emission limits of installations will be presented at the Normative working group CIGRE/CIRED C4.40 in their autumn meeting of 2017. This new method should revolutionise the way that utilities assess the impact of new Renewable Energy Source connections. The comparison of the six published and proposed algorithms have been reported in a document for the Cigré WG C4.34. This Working Group plans to publish a dedicated brochure on the comparisons by the end of 2017. VSL co-authored the new IEEE SCASC Test Suite Specification (TSS) for labs testing PMUs according to the IEEE C37.118.1 standard.

User uptake:

In planning and carrying out the measurements campaigns required for the completion of this project the consortium have been engaged with seven network operators throughout Europe (Göteborg Energi AB, Energinet, Östkraft, Lilander, DNWG, Západoslovenská distribution, Hellenic Transmission System Operator S.A.). The operational engineers have had to work closely with members of the consortium to select measurement sites, understand the placement and connection of transducers and plan the logistics of the measurement. This means the three measurement Good Practice Guides have been written in light of actual experience gained and not from a the theoretical point of view.

- The relationship has exposed them to the objectives of this project as they have had access to all of the results generated on their respective sites. They worked with the consortium to interpret and analyse the results in the context of PQ propagation, impedance and the operational state of their networks. They have already gained useful insights to the way the sites operate and they now understand the changing state of their network as loads and Renewable Energy Sites switch on and off throughout the daily, weekly and seasonal cycles.

NPL and Trescal have demonstrated data concentration software to the Bornholm Network operator. This shows a map display of Bornholm with the live data from the six bespoke PMUs and weather data to correlate renewable generation. The operator is able to see the voltage and power response at various locations on Bornholm such that events and operating conditions can be monitored. A copy of the software has been given to the operator. The measurements at Bornholm are continuing beyond the life of the project as the PQ methods are further refined.

The operator DNWG worked closely with VSL who specified and helped install the six PMUs on this ring distribution grid. The project has helped develop measurement strategies and to interpret the complex PMU data. This collaboration will continue beyond the life of the project and new network management techniques will result.

The new method for measuring PMU reporting latency, developed by STRAT, has been modified to measure the latency of data outputs from a novel merging unit which uses distributed photonic sensors. This has ensured that the device meets standardised performance requirements.

The consortium are in discussions with electricity distributors with regard to installing digitisers on power quality analysers on their grids.

Commercialisation:

Applicability of the Rogowski Coils for use with C37.118.1 compliant PMU has been discussed with a representative of a PMU manufacturer and relevant characterisation data resulting from this project has been passed on to them. Discussions are ongoing.

Frequency characterisation of commercial MV Voltage Transformers provided by a commercial instrument manufacturer is in progress. This will allow the manufacturer to extend his knowledge on the errors introduced by the sensor under different conditions and study possible improvement/corrections.

4.5 Potential Impact

Targeted Investment

Presently, harmonics are summed algebraically, rather than as vectors and in some cases a new applicant connection could actually mitigate harmonics, yet it will be refused under the present grid codes, delaying economic benefits or new renewable power part connections or giving rise to unnecessary capital investment on network reinforcement. This project has demonstrated a new method to assess this and if eventually accepted could revolutionise grid connections.

Grid impedance measurement techniques developed in this project can be used to verify the engineering estimates used by DNO to model and control their networks. Good measurements will improve design; for example a knowledge of the grid impedance at harmonic frequencies will allow optimal designs of harmonic mitigation filters, which for major plants such as HVDC stations are significant civil and electrical engineering projects. Impedance measurements also include resistance measurements which can be used to infer temperature change of an overhead line. Temperature can be used to dynamically rate the line, allowing engineers to pass larger current on cold, rainy or windy days deferring investments for new lines (which cost millions per mile) to reinforce overloaded areas of the grid. This projects has been a major step forward in accurate resistance measurements under extremely challenging conditions.

Instrumentation

In the field of PMUs, the project has effectively provided all the metrological infrastructure for PMU manufacturers to supply reliable and accurate instruments under a full range of complex modulated signals. This will allow TSOs and DNOs to purchase PMUs from multiple vendors and use them interchangeably to ensure the stability and reliability of the electricity supply. Manufacturers of PMU calibrator will also now have a traceability infrastructure to assure the accuracy of their products.

This will also act as an enabler for future R&D into PMU applications in the more exacting environment of distribution networks, opening up further markets for PMU.

Environmental

Smart Grids have a large indirect environmental impact; without them it would not be practical to integrate large scale renewable generation into the electricity system. Measurements are essential to the management of Smart Grid power quality and stability through the balance of variable distributed generation (DG) and variable demand; the effect of getting this balance wrong is instability, poor PQ and ultimately blackouts. This project has provided the measurement tools and infrastructure to help manage future SmartGrids thus enabling the timely integration of distributed renewable generation into electricity networks.

The method developed for the location of source of PQ disturbance developed as prototype in this project if it was applicable to a wide range of grids, will enable DNOs to investigate, mitigate and in some cases enforce improvement on disturbing sources. This will reduce energy losses, improve access to new customer's connections, improve supply quality and reliability and reduce or defer capital investment in network reinforcement.

Social

The social impact of poor PQ most obviously affects consumers, where spikes and dips on the mains can trip electrical equipment; voltage fluctuations can create the light to flicker and cause visual discomfort. The financial effects of poor PQ is more subtle, yet extremely serious, causing energy loss, plant overheating and the premature degradation of trillions of euros of installed network assets. In this project wide-area PQ measurements have determined the capacity of specific networks to absorb PQ disturbances avoiding unnecessary curtailment of connection or mitigation measures, whilst protecting the network assets and maintaining an event-free supply for consumers and businesses.

5 Website address and contact details

- A public website has been open, where the main public deliverables have been made available for the end-users and keep them informed about project meetings and events: www.smartgrids2.eu
- The contact person for general questions about the project is Dr Paul Wright, NPL, Pauls.Wright@npl.co.uk

6 List of publications

1) Measurement Infrastructure to Support the Reliable Operation of Smart Electrical Grids G Rietveld, J-P Braun, R Martin, P S. Wright, W Heins, N Ell, P Clarkson, N Zisky *IEEE transactions on instrumentation and measurement*, Vol 64, No.6, pp1355 - 1363, (2015)
2) Phasor Measurement Unit Testing in Accordance with the IEEE C37.118-2011 Synchrophasor Standard N T A Nguyen, M Popov, G Rietveld *Proceedings of the 2014 Conference on Precision Electromagnetic Measurements (CPEM 2014), Rio de Janeiro, Brasil,* Vol 11, No 2, pp. 70 – 71 (2014)
3) Smart Grid Power Quality and Stability Measurements in Europe P S Wright, J P Braun, G Rietveld, H E van den Brom, G Crotti *Proceedings of the 2014 Conference on Precision Electromagnetic Measurements (CPEM 2014), Rio de Janeiro, Brasil*, pp. 70 – 71 (2014)
4) Traceability for accurate resistive dividers U Pogliano, B Trinchera, D Serazio Benevento, Italy, 20th IMEKO TC4 International Symposium and 18th International Workshop on ADC Modelling and Testing Research on Electric and Electronic Measurement for the Economic Upturn, pp. 950-954 (2014)
5) A Characterized Method for the Real-Time Compensation of Power System Measurement Transducers G Crotti, D Gallo, D Giordano, C Landi, M Luiso *IEEE Trans. On IM*, Vol. 64, No. 15, pp. 1289-1404 (2015)
6) Bandwidth Extension of Measurement sensors for MV Grids by real-time filtering technique D Picco *Master thesis, Dipartimento Energia, Politecnico di Torino, Italy,* (2014)
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