Publishable JRP Summary Report for ENG52 SmartGrid II
Measurement tools for Smart Grid stability and quality

Overview

The increased use of renewable energy is vital to meet emission reduction targets and ensure security of the electrical supply in Europe. However renewable energy tends to be small scale, distributed and intermittent, which means that the energy flow in the network is in two directions (i.e. both into and from the network), both of which need to be measured and controlled so there is no degradation to power quality (PQ), potentially leading to wide-spread blackouts. In addition, renewable electricity is direct current, and converting it to alternating current (AC) so that it can feed into the network grid, can be inexact or introduce harmonics which can affect the PQ.

A 'smart grid' is an electrical grid which includes smart meters, smart appliances, renewable energy resources and energy efficient resources, and allows two way flow of power. It therefore enables renewable energy to be used in the national electricity grid. In such a complex system the stability of the smart grid becomes delicate and the PQ can decrease due to voltage distortions. This project developed the technology and standards for monitoring stability and quality of supply, with the overarching aim to support the effective development of smart grids.

Need for the project

Environmental issues and the increase in renewable supplies are challenging the traditional model of electricity generation and distribution. Smart grids have the potential to balance variable renewable energy supplies with variable demand to achieve grid stability. Smart grids are seen as a crucial enabler for the future vision of clean, renewable, locally generated energy; which is required to meet society's energy challenges. However, smart grids are highly complex, difficult to optimise and vulnerable to instability. This means that a paradigm shift is required in the instrumentation and control requirements so that stable high quality electricity supply can be assured through smart grids.

New sensor and measurement tools are required for the stable operation of the electricity network and to cope with more complicated control and billing. The emergence of Global Positioning System (GPS) synchronised measurements has opened up many new measurement opportunities to determine grid parameters, such as the phase of AC, and behaviour over a wide geographical area. GPS synchronised measurements will be used in the measurement techniques being developed in this project in order to develop new grid management methods to help design, control and stabilise the smart grids of the future.

Network operators need tools to measure the voltage and the phase of the current so that they can assess the harmonics, this can be done using phasor measurement units (PMUs). These are increasingly seen as the 'life-support monitors' for smart grids and they present many new opportunities to understand the complex dynamics of the smart grids, such as points of failure or disturbance.

However, a complete metrology framework for PMUs must be implemented to support this rapidly developing technology. PMUs and associated transducers are used to monitor the stability of distribution networks where very small phase changes are critical, therefore they need accurate calibration. Measurements from geographically remote locations around an electricity grid also need to be time-synchronised to develop a wide-area measurement system using GPS. Such a wide-area system will allow dynamic network planning and management and prevent PQ degradation and cascading failures.

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

Report Status: PU Public

EMRP
European Metrology Research Programme
Programme of EURAMET
The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union

also highlighted the lack of traceability and standards. This project aimed to address these issues as well as test the technology on real networks.

Scientific and technical objectives

This project will build on the work of the previous EMRP project ENG04 Smart Grids which developed the measurements vital for maintaining the quality of electricity supply. This project will use these outputs to develop the reference standards and measurement instruments urgently needed for the monitoring and control of smart grids. The objectives of the project are:

To develop tools to determine power quality:

1. ***PQ propagation***. Determination of PQ propagation mechanisms associated with a selection of disturbance sources in a variety of distribution and transmission networks.
2. ***PQ disturbance and fault location***. Determination of the power flows associated with major PQ disturbance / faults.

To utilise PMUs in a tool to measure impedance:

3. ***Network impedance and system resonances.*** Wide-area measurements and the analysis of system impedance (which can be regarded as resistance for AC networks) and resonances in networks.

To develop the metrological framework for PMUs:

4. ***PMUs in distribution networks***. Selection, comparison and validation of new PMU algorithms suitable for use in distribution networks.
5. ***Dynamic calibration of PMUs***. Develop extensions to a laboratory PMU calibrator to provide new calibration support for the dynamic performance of PMUs.
6. ***On-site calibration of PMUs.*** On-site measurements using reference PMUs, suitably modified to calibrate/verify the operation under realistic conditions including PQ disturbances.

Monitoring actual network frequencies and harmonics:

7. ***PMU/PQ transducer characterisation***. Develop/apply wideband evaluation facilities for transducers and optimise non-invasive transducers applied to the PMU/PQ measurement chain.
8. ***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.
9. ***Standardisation input.*** Provide input to the standardisation bodies involved in PMUs for network controllability and PQ in a Smart Grid context

Results

PQ propagation:

The results are based on six independent on-site measurement campaigns in different parts of Europe, using calibrated PMUs in working electricity networks. Each of the electricity grids had a different generation mix of power (i.e. a mix of renewables and non-renewable energy) and served varying demographics, both urban and rural.

The results showed that traditional harmonic amplitude methods that are used to measure the state of distortion in a network can give a misleading impression of how many renewable sources or connections the network can take without reinforcement. The use of GPS synchronised PMUs allowed harmonic power flows to be determined, which in some cases could enable increased connections of renewable sources without expensive, time consuming network reinforcement. The results have led to a new method for the aggregation of harmonic currents which takes account of the phase, and is designed for use in the assessment of emission limits of installations. This objective was fully achieved, and this new method should revolutionise the way that utility companies assess the impact of connecting new renewable energy sources into the network.

PQ disturbance and fault location

Six bespoke GPS synchronised PMUs, designed by NPL, were installed at Bornholm Island, in Denmark. A real time display of measurements from the PMUs monitored changes in the system parameters including phase changes across the island. Changes in the load/generation balance were observed, as well as associated changes to PQ with different wind patterns. The network was modelled to predict the PQ propagation. The detailed analysis led to a prototype harmonic location method, in which sources of cyclic disturbance can be predicted. This is a world first and has the potential to allow network operators to locate disturbances that if left unchecked could cause serious damage to infrastructures or cause blackouts.

Network impedance and system resonances

Three new methods were developed to determine impedance: i) to determine in-situ line impedance using two PMUs, one on either side of the line, ii) to determine remotely the errors of voltage transformers in wide area networks and iii) to determine harmonic impedance. The first of these methods marks a significant improvement in the integrity of this measurements, whilst the other two methods are world firsts and have been fully tested in the laboratory and on real networks. Together, these three methods mean that the impedance of the grid can be assessed more reliably, in real time, and to greater accuracy. This will potentially lead to new methods for dynamic rating of overhead cables, i.e. the limit of the current at any particular moment. For example, the impedance in overhead cables currently causes heating and therefore expansion, so these methods will potentially allow more current to flow on colder days. This will have a significant impact by reducing the expensive and environmentally challenging installation of new pylons and cables, by improving the design of expensive grid-based harmonic filters and finally by improving the accuracy of smart grid models.

PMUs in distribution networks

A simulation platform was developed for testing PMU algorithms, which included tests for the static and dynamic signals that are required by the IEEE Standard C37.118.1-2014 for Synchrophasor Measurements for Power Systems. These tests include immunity to an interference and the ability to measure rapidly changing signals, which are key to network operators. Six project partners provided candidate PMU algorithms for testing. LNE coded them so that they would run on the reference PMU and could compared under the same test conditions. One algorithm met all the criteria, and was thus incorporated within the LNE reference PMUs, developed as part of ENG04 Smart Grids project

Dynamic calibration of PMUs

METAS, VSL and a Researcher Excellence Grant (REG) from EPFL each designed and implemented a fully operational advanced PMU calibrator for use in distribution networks, based on the IEEE Standard C37.118.1. These advanced PMU calibrators were designed to be fully automated, and therefore economical to use. The advanced PMU calibrators will also meet the specific requirements of commercially available PMUs, but with uncertainties which are 10 times lower than current commercial specifications. This means that Europe now has the ability to calibrate PMUs, and the infrastructure to support any future PMU use in distribution networks which require greater accuracy.

On-site calibration of PMUs

In order to investigate the performance of PMUs in real conditions, a comparison of a commercial PMU with a calibrated reference PMU, was performed by partners NQIS and RISE. The reference PMU successfully validated the performance of the commercial PMU and demonstrated that it was working within the manufacture's tolerance for voltage and current (0.1 %) and well within the IEEE PC37.118.1 standard's tolerance of (1 %). This work has proved that it is possible to assess the performance of installed PMUs using a calibrated reference PMU.

NPL and VSL performed successful tests of two independent designs of PMU with independent algorithms, in the presence of distorted and modulated waveforms recorded from real electricity grids. Further tests were also made of extreme disturbances, which were representative of fault conditions. In all test cases, the two independent designs of PMU achieved errors well within the tolerances, or accuracy requirements, of IEEE

PC37.118.1. These tests can therefore be used to ensure the reliable operation of these critical instruments (PMUs) in real-world situations.

PMU/PQ transducer characterisation

PQ measurement relies on wide frequency measurement of AC power (both voltage and current). Rogowski coils are transducers used on the network to provide such current information. The Rogowski coil signal needs to be integrated before a measurement can be made, these integrators can be incorporated in PMU's or be separate. The integrators are non-invasive, so can be used without breaking power circuits and are typically used for on-site evaluations.

By optimising the Rogowski coil, (an electrical device used for measuring AC), a new technique was developed by the project for on-site measurement of voltage transformers. The new technique reduces measurement uncertainty by two orders of magnitude. A PMU simulator of actual measurement chains was also developed, and allows the estimation of output uncertainties for measured parameters using statistical methods. In addition to this, a sensitivity analysis of the measurement chain was carried out so that important sources of uncertainty were identified.

A new facility for the calibration of inductive voltage transformers (VTs), a type of transducer, was developed. VTs are critical for PMUs, and to a lesser extent PQ, and the overall error specification is 'implied' in IEEE 37.118 in that it gives an overall system error and the system includes VTs. The calibration uncertainty was two orders of magnitude better than limits for VT uncertainty in PMU and PQ measurements. The new facility allows voltage transformers to be calibrated at the realistic working voltages, up to 30 kV, and means that Europe now has the infrastructure to be able to calibrate and assess the wideband performance of transducers and hence the characterise PMUs prior to installation the electricity grids.

Digitised waveform corrections

The frequency response of different parts of PQ voltage signals respond differently to voltage transformers i.e. some get damped, some get excited. Therefore the project developed and implemented a digital compensation procedure for the real-time correction of the voltage transformer frequency responses. The compensation procedure proved capable of reducing the uncertainties associated with voltage transformer ratio and phase frequency response by up to 2 orders of magnitude, even in presence of resonances. This is a significant step as it will eliminate the largest uncertainty contribution in PMUs. The compensation procedure also enables the voltage signal to be read and compensated in real time therefore improving the accuracy of calibration of voltage transformers which is particularly important in PMU and PQ applications.

Standardisation input

A new method for the aggregation of harmonic currents which proposes an update for the summation coefficients was produced by the project. The new method is designed for use in the assessment of emission limits of installations and has been presented to CIGRE(the Council on Large Electric Systems) Working Group (WG) C4.40. This new method should revolutionise the way that utility companies assess the impact of renewable energy source connections.

The comparison of the six published and proposed algorithms (in objective 4) was also reported to CIGREWG C4.34.

Further to this, VSL has co-authored the new IEEE Synchrophasor Conformity Assessment Steering Committee (SCASC) Test Suite Specification (TSS) for labs testing PMUs according to the IEEE C37.118.1 standard.

Actual and potential impact

Dissemination

A total of 34 peer reviewed papers, and 3 master's thesis were published. The consortium presented its work 29 times and gave 9 poster presentations to a variety of conferences including IEEE Applied Measurements for Power Systems (AMPS), Conference on Precision Electromagnetic Measurements (CPEM) 2014 & 2016 and IEEE International Conference on Power System Technology (POWERCON) 2016.

The project also provided 4 training events on algorithms and the metrological characterisation of PMUs for NMIs, distribution network operators and instrument manufacturers.

Four workshops including one on PMU algorithms were hosted by the project for academics and PMU manufacturers. The mid project workshop was held jointly with the EMRP project ENG63 GridSens. The workshop at the end of the project was attended by more than 70 representatives and combined the outputs from all the EMRP projects on electricity grids finishing in 2017 (i.e. this project, ENG61 FutureGrid and ENG63 GridSens), details are available on the project websites.

The project's results were publicised in Smart Grid Today, www.smartgridtoday.com, an online trade journal dedicated to smartgrid related topics, and the Elektor magazine www.elektormagazine.com , which has an international audience interested in electronics.

Two new, and one updated, Good Practice Guides have also been produced and are available on the project website http://www.smartgrids2.eu/:

1. Best practice guide for using Rogowski coils in field measurement campaigns
2. Best Practice for On-Site Power Quality Measurement Campaigns
3. PMU Best Practice Guide for on-site PMU Calibration

Standards

The consortium has been an active member of 11 relevant working groups of standards committees, including IEC TC95 WGH11 and CIGRE/CIRED working group C4.40. This has already led to one new standard, IEEE SCASC TSS for labs testing PMUs according to the IEEE C37.118.1 standard. This was co-authored by VSL and proposes new methods for dealing with the effect of renewable energy sources connect to the grid.

The assessment of emission limits of installations by aggregating harmonic currents was also presented to CIGRE WG C4.40 and the comparison of the six published and proposed algorithms was reported to CIGRE WG C4.34, which plans to publish a dedicated brochure on the comparisons by the end of 2017.

Early Impact

This project has met the requirement to balance variable renewable supply with variable demand in order to achieve smart grid stability by:

- Providing inputs to the development of new normative standards for improving decision making processes for the connection of new renewable energy sources.
- Demonstrating the value of PMUs in distribution grids by showing their ability to locate disturbances. Thus improving the management of grid supply quality and enabling the connection of increased renewables.
- Using new PMU based impedance measurements to help determine where grids need reinforcing which will help to target investment.
- Providing a European measurement infrastructure for the calibration of PMUs and associated transducers that meets the required current and future standards. This provides confidence in PMU measurements which will be used to ensure smart grid stability and avoid blackouts.
- Gaining useful insights into the way sites operate so that they can now understand the changing state of their network as loads and renewable energy sites switch on and off throughout the daily, weekly and seasonal or weather cycles.

The equipment and techniques developed during the project have already had commercial impact:

- The new method for measuring PMU reporting latency, or signal delay, developed by REG(STRAT) a Researcher Excellence Grant at Strathclyde University, has been modified to measure the latency of data outputs. This has ensured that the device meets the performance requirements of standards.

- VSL and REG(TU-E) are in discussions with Alliander, an electrical power distributor, with regard to installing digitisers on their grid
- Partners SMU and STU BA are negotiating with Západoslovenská distribution, a Slovakian network distributor, for the installation of power quality analysers.
- The applicability, and subsequent commercialisation, of the Rogowski Coils for use with C37.118.1 compliant PMUs has been discussed with a representative of a PMU manufacturer.
- Frequency characterisation of voltage transformers provided by a commercial instrument manufacturer has been carried out and will allow the manufacturer to understand how errors are introduced by the sensor under different conditions, so that they can make corrections for this.

Potential impact

Smart grids mean that large scale renewable generation, and many small scale generators, can be integrated into the existing electricity grid, therefore giving an environmental benefit. This project has provided the measurement tools and infrastructure to help manage future smart grids. It demonstrated a new method to assess and mitigate harmonics. Under present grid codes it cannot be used, however in the future, if accepted into new standards, it could revolutionise grid connections and bring economic benefits by minimising unnecessary capital investment on network reinforcement.

The grid impedance measurement techniques developed in this project can be used to verify the engineering estimates used by network operator to model and control their networks. Impedance measurements will be used to infer temperature change of an overhead line, which 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.

In the field of PMUs, the project has provided the metrological infrastructure for PMU manufacturers to supply reliable and accurate instruments under a full range of complex modulated signals. This will allow network operators to purchase PMUs from multiple vendors and 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.

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

The customer impact of poor PQ includes spikes and dips on the mains which can trip electrical equipment; and voltage fluctuations which can cause light flickering and visual discomfort. The financial effects of poor PQ is more subtle, yet extremely serious, causing energy loss, plant overheating and the premature degradation of 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.

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)

[7]. Filter design masks for C37.118.1a-compliant frequency-tracking and fixed-filter M-class Phasor Measurement Units (PMUs) A J Roscoe, B Dickerson, K E Martin *IEEE Trans. On Instrum. and Measur. Vol. 64,* pp: 2096 - 2107 (2015)

[8]. Analysis of the propagation of Power Quality phenomena using wide-area measurements V Ćuk, H van den Brom, S Cobben, G Rietveld *Proceedings of the 23rd International Conference and Exhibition on Electricity Distribution (CIRED), Lyon, France,* pp. 1 – 4 (2015)

[9]. Application of PMUs for monitoring a 50 kV distribution grid G Rietveld, A Jongepier, J van Seters, M Visser, P Liu, M Acanski, D Hoogenboom, H E van den Brom *Proceedings of the 23rd International Conference and Exhibition on Electricity Distribution (CIRED), Lyon, France,* pp. 1 – 5 (2015)

[10]. Analysis of Power Quality Disturbance Source Tracking Methods with Liander LiveLab A W Burstein *Master thesis, Department of Electrical Engineering, Eindhoven University of Technology* (2015)

[11]. Smart Grid Power Quality and Stability Measurements in Europe 18 Months of Progress P S Wright, J P Braun, G Rietveld, H E van den Brom, G Crotti *CPEM 2016 proceedings*, pp 1-2(2016)

[12]. Power Quality Propagation Measurements in Smart Grids P S Wright, A EChristensen, P N Davis, B Larson, T Lippert, P Patel *CPEM 2016 proceedings,* pp 1-2 (2016)

[13]. A technique for real-time bandwidth enhancement of instrument voltage transformers G Crotti, D Gallo, D Giordano, C Landi, M Luiso, D Picco *Proceedings of XXI IMEKO World Congress "Measurement in Research and Industry Prague, Czech Republic* (2015)

[14]. Frequency calibration of voltage transformers by digital capacitance bridge G Crotti, D Gallo, D Giordano, C Landi, M Luiso, M Modarres *Proceedings of 2015 IEEE International Workshop on Applied Measurement in Power System,* pp 1-6 (2015)

[15]. Accurate numerical modelling of MV and HV resistice dividers M Zucca, M Modarres, D Giordano, G Crotti *IEEE Trans. On Power Delivery,* Vol 32, No 3, pp 1645 - 1652 (2017)

[16]. Accurate Phase Calibration of PMUs and PMU Calibrators M Acanski, G Rietveld, D Hoogenboom *Proceedings of the 2016 Conference on Precision Electromagnetic Measurements (CPEM 2014)*(2016)

[17]. PMU Based Line Impedance Estimation P Liu *Masters thesis, VSL, Netherlands* (2015)

[18]. Methodology for testing and development of parameter-free fault locators for transmission lines M Popov, S Parmar, G Rietveld, G Preston, V Terzija *Electric Power Systems Research 138*, pp. 92 – 98 (2016)

[19]. The calibration of static and dynamic performances of PMUs J P Braun, S Siegenthaler *Proceedings of the 2015 International Congress of Metrology* (2015)

[20]. Requirements for an advanced PMU calibrator J P Braun, C Mester, M O André *CPEM 2016 proceedings* (2016)

[21]. Frequency Calibration of MV VoltageTransformer under Actual Waveforms G Crotti, D Gallo, D Giordano, C Landi, M Luiso, M Modarres *CPEM 2016 proceedings* (2016)

[22]. Improvement of Agilent 3458A Performances in Wideband Complex Transfer Function Measurement D Giordano, P Pescetto, G Crotti, M Luiso *IEEE Transactions on Instrumentation and Measurement*, Vol 66, No 6, pp 1108 - 1116 (June 2017)

[23]. Asynchronous Phase Comparator for Characterization of Devices and PMU Calibrator B Trinchera, D Serazio, U Pogliano *IEEE Transactions on Instrumentation and Measurement,* Vol 66, No 6, pp 1139 - 1145 (June 2017)

[24]. Method for Determining 50 Hz Instrumentation Channel Errors in Power Transmission Systems from Synchrophasor Measurements V Milojevic, S Calija, G Rietveld, M Acanski *Power Generation, Transmission, Distribution and Energy Conversion (MedPower 2016),* pp 1-8 (2016)

[25]. Power Quality Propagation Measurements in Smart Grids P S Wright, A E Christensen, P N Davis, B Larson, T Lippert, P Patel *Proceedings of the 2016 Conference on Precision Electromagnetic Measurements (CPEM 2016), Ottawa, Canada*, pp 1 - 2, (2016)

[26]. 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 2016 Conference on Precision Electromagnetic Measurements (CPEM 2016), Ottawa, Canada,* pp 1 - 2, (2016)

[27]. Multiple-Site Amplitude and Phase Measurements of Harmonics, for Analysis of Harmonic Propagation on Bornholm Island P S Wright, A E Christensen, P N Davis, T Lippert *IEEE Transactions on Instrumentation and Measurement,* Vol 66, No 6, pp 1176 - 1183 (June 2017)

[28]. Accurate Phase Calibration of PMUs and PMU Calibrators M Acanski, G Rietveld, D Hoogenboom *Precision Electromagnetic Measurements (CPEM 2016),* pp 1-2(2016)

[29]. Choice and Properties of Adaptive and Tunable Digital Boxcar (Moving Average) Filters for Power Systems and other Signal Processing Applications A J Roscoe, S M Blair *AMPS 2016 proceedings,* Vol 1, No 1, pp 1-6(2016)

[30]. Real-time compression of IEC 61869-9 sampled value data S M Blair, A J Roscoe, J Irvine *AMPS 2016 proceedings,* Vol 1, No 1, pp 1-6 (2016)

[31]. Dynamic algorithms for PMUs – methods for improving the signal processing effectiveness U Pogliano *Proceedings of the 2016 Conference on Precision Electromagnetic Measurements (CPEM 2016), Ottawa, Canada,* pp 1-2 (2016)

[32]. Frequency Calibration of MV VoltageTransformer under Actual Waveforms G Crotti, D Gallo, D Giordano, C Landi, M Luiso, M Modarres *IEEE Trans. On Instrum. and Measur*. pp 1-2 (2016)

[33]. Improvement of Agilent 3458A Performances in Wideband Complex Transfer Function Measurement D Giordano, P Pescetto, G Crotti, M Luiso *IEEE Trans. On Instrum. and Measur.* Vol 66, No 6 pp 1108 - 1116 (2017)

[34]. Asynchronous Phase Comparator for Characterization of Devices and PMU Calibrator B Trinchera, D Serazio, U Pogliano *IEEE Trans. On Instrum. and Measur*. Vol 66, No 6, pp 1139 - 1145 (2017)

[35]. Definition and Assessment of Reference Values for PMU Calibration in Static and Transient Conditions G Frigo, D Colangelo M Pignati, A Derviskadic, C Narduzzi, M Paolone *Applied Measurements for Power Systems (AMPS), 2016 IEEE International Workshop* pp 1-6 (2016)

[36]. Stochastic Residential Harmonic Source Modeling for Grid Impact Studies G Ye, M Nijhuis, V Cuk, J F G (Sjef) Cobben *Energies 2017,* Vol. 10, No. 3, pp 372 (2017)

[37]. Metrological characterization of a PMU calibrator in the 25 Hz to 3 kHz range D Colangelo, D Hoogenboom, E Dierikx, G Rietveld, G Frigo *PowerTech, 2017 IEEE Manchester*, pp 1-6 (2017)

JRP start date and duration:	June 2014, 3 years.
JRP-Coordinator: Dr. Paul Wright, NPL, UK, Tel: +44 (0)208 943 6367 E-mail: paul.wright@npl.co.uk JRP website address: http://www.smartgrids2.eu/	
JRP-Partners: JRP-Partner 1 NPL, UK JRP-Partner 2 BRML, Romania JRP-Partner 3 CMI, Czech Republic JRP-Partner 4 IMBiH, Bosnia and Herzegovina JRP-Partner 5 INRIM, Italy JRP-Partner 6 LNE, France JRP-Partner 7 METAS, Switzerland JRP-Partner 8 VTT, Finland	JRP-Partner 9 SIQ, Slovenia JRP-Partner 10 SMU, Slovakia JRP-Partner 11 RISE, Sweden JRP-Partner 12 Trescal, Denmark JRP-Partner 13 VSL, Netherlands JRP-Partner 14 NQIS, Greece JRP-Partner 15 STU BA, Slovakia JRP-Partner 16 SUN, Italy
REG1-Researcher (associated Home Organisation):	Mario Paolone EPFL, Switzerland
REG2-Researcher (associated Home Organisation):	Vladimir Cuk TU-E, Netherlands
REG3-Researcher (associated Home Organisation):	Andrew Roscoe STRAT, UK

The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union