Metrology Excellence Academic Network for Smart Grids

WP3 Final research report

Deliverable D3.2

WP3. Smart Grids: Power Quality Analysis

Metrology Excellence Academic Network for Smart Grids

Grant agreement: 676042

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APPROVALS

	Company
Author/s	LNE, CIRCE, TU/e
Task Leader	T3.1 (CIRCE); T3.2 (TU/e); T3.3 (LNE)
WP Leader	LNE

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ABBREVIATIONS

ANOVA: Analysis of Variance

CA: Consortium Agreement

DoA: Description of Action

EC: European Commission

ESR: Early Stage Researcher

GA: Grant Agreement

IPR: Intellectual Property Right

LV: Low Voltage

MEAN4SG: Metrology Excellence Academic Network for Smart Grids

MV: Medium Voltage

PCDP: Personal Career Development Plan

PLC: Power Line Communication

PST: Personal Supervisory Team

REnS: Renewable Energy Sources

RVCs: Rapid Voltage Changes

SB: Supervisory Board

TC: Training Committee

WD: Wavelet Decomposition

WP: Work Package

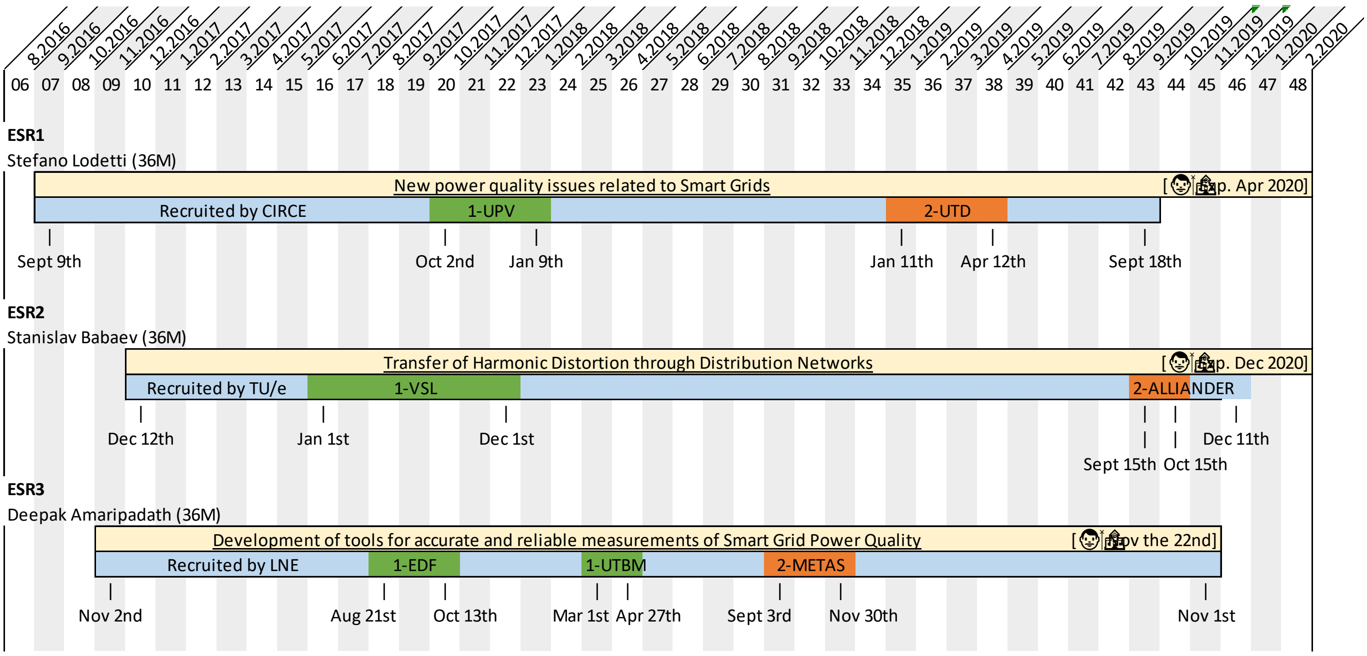
EXECUTIVE SUMMARY

This document presents the progress of the research activity in

WP3 Smart Grids: Power Quality Analysis.

There are three tasks defined in the MEAN4SG's DoA within the Grant Agreement in this Work Package based on Power Quality Analysis: a) Flicker measurements for newer lighting techniques, b) PQ measurements and propagation in distribution grids, and c) Development of tools for accurate and reliable measurements of Smart Grids.

The development of these tasks corresponds to the topics treated through 3 doctoral theses performed by Early Stage Researchers (ESR) 1, 2 and 3



<u>Task 3.1 Flicker measurements for newer lighting techniques</u>

PhD title (ESR 1): *New power quality issues related to Smart Grids*

MEAN4SG beneficiary: Fundación CIRCE, Spain

The research focused on the improvement of algorithms devoted to the measurement of supra-harmonics as well as on the quantification of effect of RVCs (Rapid Voltage Changes) on flicker severity.

The main contribution to the scope of MEAN4SG is the extension of available tools (flicker and supra-harmonics) applicable to Power Quality measurements on Smart Grids.

Task 3.2 PQ measurements and propagation in distribution grids

PhD title (ESR 2): *Transfer of Harmonic Distortion through Distribution Networks*

MEAN4SG beneficiary: Technical University of Eindhoven, Netherland

The main focus of this research was the propagation of harmonic distortion through distribution networks. This involves the modelling of the harmonic emission of non-linear devices, the frequency response of the network components - and in particular the uncertainty of their modelling, and the simulation of the impact of multiple harmonic sources on the voltage distortion on every busbar within a distribution network. A particularly important step for achieving these goals is the measurement of these phenomena on multiple network locations at the same time. The time synchronisation of Power Quality meters is analysed both from the standpoint of waveform recording and spectrum recording. Propositions for improved harmonic modelling are based on the results of laboratory measurements and the definition of modelling uncertainty.

As the main scope of the project is metrology within Power Systems, the main contribution of this research is the application of synchronised Power Quality measurements, and in particular, the requirements for time-synchronisation between multiple meters to achieve impedance estimation for a wide frequency range. This work resulted also in a laboratory setup for synchronised waveform recording which enables efficient harmonic observability.

Task 3.3 Development of tools for accurate and reliable measurements of Smart Grids

PhD title (ESR 3): *Development of Tools for Accurate Study of Supraharmonic Emissions in Smart Grids*

MEAN4SG beneficiary: Laboratoire National de Métrologie et d'Essais, France

The main objective is to quantify and reproduce the supraharmonic emissions in the frequency range of 2 to 150 kHz. The research focused on a design of experience approach and a statistically based analysis method to identify the sources of the supraharmonic emission from field measurements on real smart grids. The development of an advanced calibrator to synthesize and generate arbitrary waveforms representative to real grid conditions was another important part of the performed activity.

The main contribution of this thesis is the implementation of a metrology-grade platform for the characterization of PQ instruments under severe conditions with a complete uncertainty budget for the 2 generation channels and the 4 acquisition ones.

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1 Task 3.1 Flicker measurements for newer lighting techniques (ESR01)

1.1 Summary

The research carried out by the ESR01 included two novel aspects that nowadays are becoming more and more important and they affect directly to the existent Power Quality of the electrical network: a) the proliferation of **high frequency contents** in the grid (supra-harmonics) and b) the correlation of **rapid voltage changes** (RVC) to flicker severity.

The point is that currently, there is not any standardized method for the measurement of grid disturbance levels in the supra-harmonic nor any study evaluating the sensitivity of modern lighting technologies to different types of RVSs.

During the work, the researcher not only used simulated signals, but also real ones captured on industries. This reinforced the validation process of the developed algorithms, especially those oriented to be included in future power quality analyzers.

In the first secondment at University of the Basque Country, ESR01 accomplished a complete review that led to propose the definition of a new immunity test to be added to the lamp immunity protocol IEC TR-61547-1, to ensure that newly produced lamps cause limited irritation to grid users.

During his second secondment at TU Dresden, the researcher validated his wavelet-based decomposition algorithm by real measurements where frequency variations were applied to electric vehicle chargers and photovoltaic inverters.

1.2 Background and organisation of the project

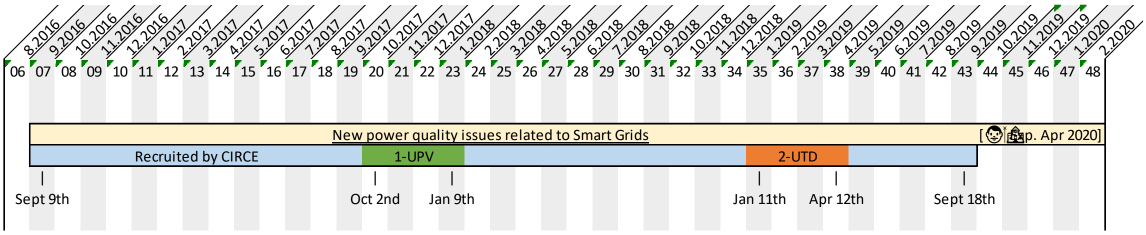
1.2.1 ESR01 Factsheet

Thesis title: *New power quality issues related to Smart Grids*

Research fellow: Stefano Lodetti
Current position: Higher Research Scientist at the heart of The National Physical Laboratory (NPL), The UK
Contact beyond the project: linkedin.com/in/stefano-lodetti

Recruitment organisation within MEAN4SG: Fundación CIRCE
Secondment organizations:

(1) University of the Basque Country (UPV), Spain
(2) TU Dresden (UTD), Germany



Main Contribution to MEAN4SG:
Stefano Lodetti's research focused on the improvement of algorithms devoted to the measurement of supra-harmonics as well as on the quantification of effect of RVCs (Rapid Voltage Changes) on flicker severity.

In this sense, his main contribution on the scope of MEAN4SG is the extension of available tools (flicker and supra-harmonics) applicable to Power Quality measurements on Smart Grids

Link to the presentation: https://youtu.be/hZyUsDkzHwc

1.2.2 Background

One of the power quality disturbances most easily perceived by grid customers is flicker. Flicker is defined as the impression of unsteadiness of visual sensation induced by a light stimulus whose luminance fluctuates with time.

In the last few decades, many countries have been implementing regulations to ban incandescent lamps, encouraging the use of more efficient lighting technologies such as CFL and, mainly, Light Emitting Diodes (LEDs). This change has a direct effect on the power quality. On the one hand, new lighting technologies lead to an increase of the current and voltage distortion in the grid. On the other hand, the replacement of incandescent lamps with more efficient lighting technologies gave rise to poor correlation between measured flicker levels and customers complaints. The interest of scientific community is reflected in recent papers that studied the characteristics of RVCs and their correlation with flicker indices, claiming the necessity of more research and standardization. These efforts led to the publication, in 2015, of the last edition of IEC 61000-4-30, which provides a definition and a precise measurement method for the detection and characterization of RVCs.

On the other side, the unstoppable proliferation of distributed generation and modern loads in smart grids, operating concurrently in the power system, is an important factor that determines the level of existent distortion for the grid. This modifies the well-known and characterized harmonic spectrum based on linear loads and traditional and centralized power sources as well as introducing other critical effects on the overall quality of supply. In principle, the high-frequency harmonic assessment could take advantage of the traditional characterization tools, but the reality is different as the distortion in the 2 kHz to 150 kHz range (supra-harmonics) is intrinsically different from the harmonic distortion. The periodicity assumption of the Fourier analysis is therefore not valid, resulting in energy leakage across the frequency spectrum, especially from the fundamental component, which has the highest magnitude.

1.2.3 Objectives

The planning and objectives for this combined research (RVCs+supra-harmonics) is the following.

- With regards to RVC research:
    1. Research on how flicker severity is affected by existent RVCs
    2. Modeling and simulation of one IEC 61000-4-15 flickermeter to test synthetic input signals
    3. Understanding of RVCs phenomena and their relationship with flicker severity
    4. On-site measurement campaigns recording on real installations
    5. Evaluation of the sensitivity of modern lighting technologies to different types of RVCs
    6. Writing of, at least, one journal paper

- With regards to supra-harmonic:
  1. Improvement of a Wavelet Packet-based algorithm developed for the evaluation of harmonics (up to 63rd order) (work done by the thesis supervisors 4 years ago)
  2. Adaptation of the previous algorithm to be compatible with the measurement of supra-harmonics
  3. Benchmarking of existing tools for the evaluation of supra-harmonics, including the one developed in the thesis
  4. Writing of, at least, one journal paper

1.3 Research line of the fellow

1.3.1 Research tasks, activities to attain the project goals

In this first part of the work, the connection between the increasing importance of Rapid Voltage Changes (RVCs) and the evolution of illumination technologies has been studied. The main objective is to measure the response of modern lighting technology when subjected to RVCs.

From one side, the increasing attention given to RVCs, from the point of view of international standards. Several researches pointed out the lack of standardized measurement methods, proposed methods to characterize RVCs and studied the possible requirements. These studies, among others, led to the definition of a measurement method for RVCs in the 2015 version of standard IEC 61000-4-30.

As to planning levels: Compatibility levels are defined (albeit somewhat vaguely) in IEC 61000-2-2 and 61000-2-12 as follows: In normal circumstances, the value of rapid voltage changes is limited to 3% of nominal supply voltage. In IEC 61000-3-7, planning levels are recommended for Medium Voltage (MV), High Voltage (HV) and Extremely High Voltage (EHV) applications, while planning levels do not presently exist for Low Voltage (LV) applications. RVCs can cause or contribute to flicker, but they are a type of voltage fluctuation not considered in IEC 61000-4-15.

On the other side, there is the relationship between RVCs and flicker. It is not clear how RVCs can cause discomfort to customer and what kind of relationship exists between RVCs and flicker. Alongside, flicker perception is challenged by the integration of modern lighting technology, whose response is different from the traditional incandescent lamp, and IEC 61000-4-15 only consider incandescent lamps response.

A large set of lamps has been subjected to simulated RVCs and their illuminance has been measured. The experimental setup consists of two parts:

- generation of the input voltage signals, containing the RVCs to be supplied to the lamps,
- acquisition of the illuminance produced by the lamps.

A light flickermeter has been used to measure the light output response.

The analysed lamps correspond to Light Emitting Diode (LED) and Compact Fluorescent Lamp (CFL) technology, as well as a 60 W incandescent lamp, used as reference. The lamps have been chosen between the commercially available technologies, from different manufacturers, and giving more emphasis to LED lamps over CFLs, with the aim of reproducing the current trend of the market. The lamps present different values of power, from 3 W to 23 W, luminous flux, from 250 lm to 2452 lm, and energy efficiency rating. All of them are made for 230 V/50 Hz systems.

According to the classification, four types of RVCs have been defined for the present study:

- Instantaneous Ramp RVC
- Instantaneous Motor-Start RVC
- Gradual Ramp RVC
- Gradual Motor-Start RVC

The sensitivity of modern lighting technologies to RVCs has been studied by an extensive experimental campaign, where RVCs of different kinds have been supplied to a large number of CFLs and LED lamps. Their response, in terms of illuminance, has been measured using a high precision light flickermeter, which allowed to accurately evaluate the instantaneous flicker sensation P_{inst}. A correlation between P_{inst} and RVC amplitude, already expected for the incandescent lamp, has been found also for modern lighting technologies. Moreover, the dependence on the type of RVC and the rate of change have been measured. Most of the tested lamps showed the same behaviour as the incandescent lamp, but with lower values of perceptibility i.e., less visible flicker. However, several lamps exhibited P_{inst} values above the perceptibility threshold, even for RVC amplitudes less than 3 %. This result questions the limits given in IEC 61000-3-7, where only RVCs with amplitude greater than 3 % are considered. However, work remains to be done in order to evaluate the relationship with the annoyance that such RVCs can cause to customers.

With regards to supra-harmonic emissions, current electrical network management strategies, as well as power-controlled systems, have led to changes in the harmonic spectrum. In this context, researchers must ensure that existent harmonic tools work properly under this new situation (time-varying operation of the grid) at the same time the range of measurement is stretched (up to several hundreds of kHz) to be able to characterize current and future smart grids. This demands more advanced algorithms and therefore more complex Power Quality (PQ) analyzers with higher sampling rates. In this regard, the performance of the algorithms implemented in the analyzers must be carefully checked under realistic situations to be later compared to the applicable IEC standards limits.

In principle, the high-frequency harmonic assessment could take advantage of the traditional characterization tools, but the reality is different as the distortion in the 2 kHz to 150 kHz range (supra-harmonics) is intrinsically different from the harmonic distortion. The harmonic emission is mainly made of waves whose frequency is an integer multiple of the fundamental frequency which, in power systems, is the power frequency (nominally 50 Hz or 60 Hz, although in this paper only 50 Hz systems are considered). The term supra-harmonics, instead, refers to the emission beyond (supra) the harmonic range, but not necessarily multiple of the power frequency.

Thanks to their nature, the use of Fourier analysis is a very effective way to analyze harmonics in power systems. The frequency resolution of the Fourier spectrum is given by 1/t, where t is the duration of the measurement interval. Therefore, the Fourier analysis performed on an integer number of cycles of the fundamental wave provides a spectrum where the harmonic components are perfectly represented by the resulting frequency resolution (if the signal is stationary and periodic). This is the case of the IEC 61000-4-7 harmonics measurement method, that requires the measurement of 10 cycles of the power frequency fN, resulting in a fN/10 frequency resolution, that matches the harmonic emission at fN, 2fN, 3fN, etc. Even in the case of a slight deviation of the power frequency from its nominal value, the frequency resolution would still be a submultiple of the power frequency, regardless of its value, allowing a correct evaluation of all the harmonic components.

The supra-harmonic distortion, however, is independent of the power frequency as it is typically originated from devices whose operation is not correlated with the power frequency, like power electronic converters. In this case, the Fourier analysis must be performed carefully, as important drawbacks could arise. In case of a deviation of the power frequency, as said, all its multiple frequencies will shift accordingly and the frequency resolution will change as well, modifying all the frequency bands.

The supra-harmonic components, however, are not affected by the deviation of the power frequency, maintaining their values. The resulting effect would be an apparent shift of the supra-harmonic emission with respect to whole spectrum. This effect is well known and, in order to avoid it, the IEC 61000-4-7 standard suggests performing the Fourier analysis of supra-harmonics using a fixed 200 ms window, instead of the traditional 10 cycles window [2]. In this way the frequency resolution is fixed, and no apparent shift is observed. This solves the problem of the apparent shift but creates another issue. Fourier analysis assumes that the analysed signal is infinitely periodic or, at least, strictly periodic inside the measurement window. However, in case of a deviation of the power frequency from the nominal value of 50 Hz, a fixed 200 ms window will not contain exactly 10 fundamental cycles anymore. The periodicity assumption of the Fourier analysis is therefore not valid, resulting in energy leakage across the frequency spectrum, especially from the fundamental component, which has the highest magnitude. Moreover, the use of a different measurement interval for harmonics and supra-harmonics analysis (10 cycles and 200 ms) requires flexible power quality analyzers, with two different processing threads, which increases their complexity and, therefore, price. Moreover, the Discrete Fourier Transform (DFT), shows important limitations when applied to fluctuating signals, which is the normal situation in modern power systems. When non-stationary harmonics are analyzed with a DFT, severe energy leakage can be observed, producing large errors.

Extending the work developed by the thesis supervisors, this work proposes a hybrid measurement method for harmonic and supra-harmonics analysis based on the Wavelet Packet Decomposition (WPD). The method is compliant with the IEC 61000-4-7 standard for harmonics under stationary conditions and shows a better performance under non-stationary conditions. The proposed method is also comparable with the supra-harmonic methods described in IEC 61000-4-7 and CISPR 16-1, but with the advantage of working with a 10 cycles window (synchronized measurement) without being affected by power frequency deviations. Therefore, the method is more robust against typical deviations from ideal conditions that occur in real smart grids. The robustness of the method is proved by showing that the drawbacks of a fixed 200 ms window approach are avoided without compromising the accuracy. Moreover, the proposed method does not require any pre-processing stage, while the IEC analysis should be preceded by a High Pass Filter (HPF) in order to achieve good accuracy under power frequency deviations.

1.3.2 Recruitment and Training Overview

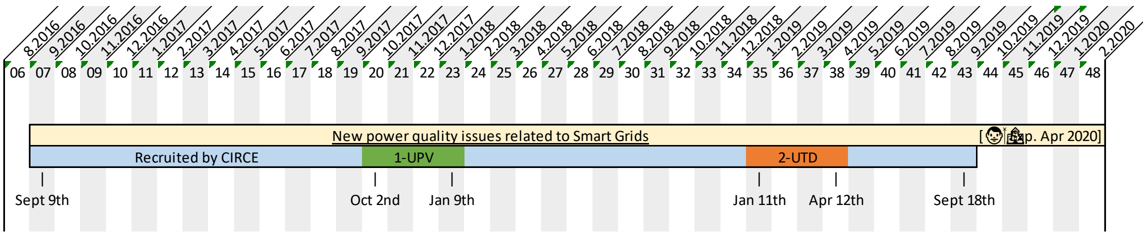


Figure 1 ESR01 recruitment timeline

<u>Recruitment Organisation</u>

Stefano Lodetti has been recruited by Fundación CIRCE in a total duration of 36 months, from 19.09.2016 until 18.09.2019. During his training he has acquired skills in Flicker measurements, corresponding to the dedicated task 3.1 within the project framework.

Stefano has been a PhD. student in Fundación CIRCE, very well integrated in the Network Studies and Smart Grids working group within the organization. It has been highlighted a great collaboration with the PST (Personal Supervision Team) and CIRCE colleagues during the project.

In this sense, the main facilities used to validate scientific results have been:

A) Accredited Laboratory of Electrical Metrology (LME-CIRCE).
B) High-end harmonic calibrators /digitizers

Secondment organisations

In total, Stefano has collaborated at the heart of two secondment organisations within his research during MEAN4SG project.

Table 1 Secondments performed by ESR01

Information about secondments for ESR01				
Fellow	**Secondment Organization**	**Start Date**	**End Date**	**Duration (months)**
Stefano Lodetti (ESR01)	U. of the Basque Country (UPV)	2.10.2017	19.01.2018	3.6
Stefano Lodetti (ESR01)	TU Dresden (TUD)	11.01.2019	12.04.2019	3

During Stefano's **first secondment at University of the Basque Country**, there has been a great integration with the UPV working group as well as a strong collaboration with the PST for writing and submitting conference/journal papers. One of the main facilities used to validate scientific results has been the Experimental flickermeter of the UPV. Stefano accomplished a complete review that led to propose the definition of a new immunity test to be added to the lamp immunity protocol IEC TR-61547-1, to ensure that newly produced lamps cause limited irritation to grid users.

During his **second secondment at TU Dresden**, the researcher validated his wavelet-based decomposition algorithm by real measurements where frequency variations were applied to electric vehicle chargers and photovoltaic inverters. It should be highlighted a great integration with TU Dresden working group during the laboratory measurements as well as a strong collaboration with the PST for writing and submitting conference/journal papers. In what regards the main facilities used to validate scientific results, these were EV chargers, PV generators and Large controlled power supplies

Courses and summer schools organized in the framework of MEAN4SG

ESR01 has participated in the 3 Specific Courses and 3 Summer Schools organized in the framework of the project

- 1st MEAN4SG Specific Course: Hold in CIRCE, Zaragoza, Spain on 31/01/2017-02/02/2017, as a training activity within the ITN-ETN MEAN4SG project
- 1st MEAN4SG Summer School: Hold in the Van der Valk Hotel, Haarlem, The Netherlands, on 19-20/04/2017
- 2nd MEAN4SG Specific Course: Hold in the University of Strathclyde, Glasgow, UK, on 6-8/06/2017, as a training activity within the ITN-ETN MEAN4SG project

- 3rd MEAN4SG Specific Course: Hold in CIRCE, Zaragoza, Spain on 28-30/11/2017, as a training activity within the ITN-ETN MEAN4SG project
- 2nd MEAN4SG Summer School: Hold in the University of Strathclyde, Glasgow, UK, on 23-25/01/2018, as a training activity within the ITN-ETN MEAN4SG project,
- 3rd MEAN4SG Summer School: Hold in ORMAZABAL, Boroa, Spain on 19-21/06/2018, as a training activity within the ITN-ETN MEAN4SG project

<u>Other training events performed/promoted within MEAN4SG</u>

Among the training events taken place within the project's framework, ESR01 did participate to the following:

- Demo workshop about insulation diagnosis on MV grids for maintenance departments of utilities. Hold in LCOE, Madrid, Spain on 03/06/2019, as a training activity within the ITN-ETN MEAN4SG project
- Researchers meet Innovators. Hold in Berlin, Germany on 11-12/07/2019, an organized by the Marie Curie Alumni Association aiming researchers and innovators to synergistically and successfully work together.

Figure 2 Networking session during "Researches meet Innovators" event

- Courses at University of Zaragoza:
  - Energy Efficiency
  - Hydraulic and Wind Power Solar
  - Power and Biomass
  - Fundamentals of Power Engineering

<u>Seminar Presentations</u>

ERS01 did participate in the 2 seminar events proposed in the framework of the project:

- CIRED'19. The Leading Forum where the Electricity Distribution Community meets, holds the major International Electricity Conference & Exhibition every two years in different venues in Europe with a worldwide perspective and participation. 3-6 June 2019. Paper Title: “Method of the evaluation of new power quality parameters: a review of RVC and supraharmonics”
- PhD Webinar. Group PQ – Power Quality: September, Wednesday the 11th: Stefano Lodetti [10:30] - New power quality issues related to smart grid. [Link to the presentation: https://youtu.be/hZyUsDkzHwc]

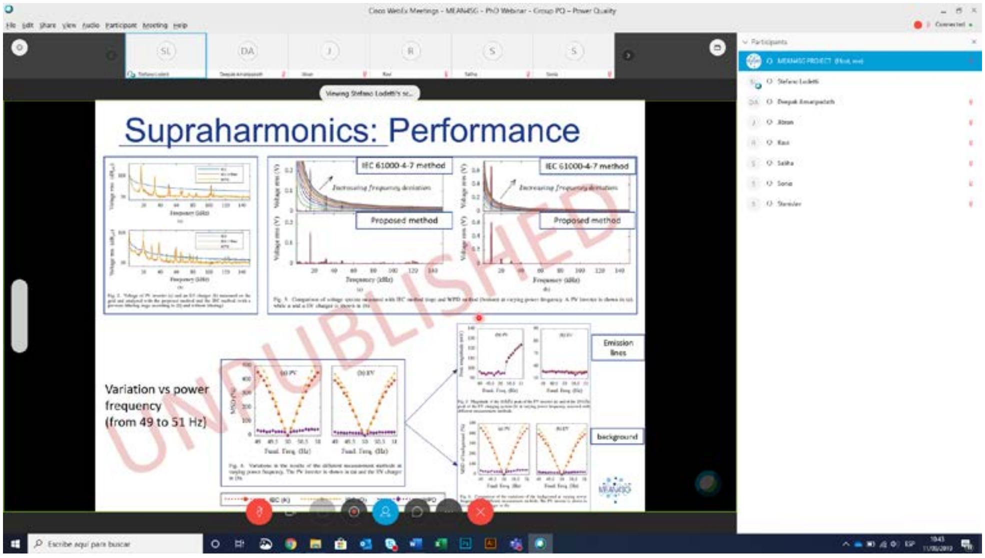


Figure 3 Screenshot from ESR01 presentation during the last PhD Webinar

1.3.3 Skills learnt under MEAN4SG framework

Research Skills:	Technical Skills:
Dissemination, writing journal, patents, and review of publications	MATLAB scripts NI DAQ cards
Management Skills:	**Communication Skills:**
Team management, Time management and Stress Management	Confidence Meetings Posters Elevator Pitches

1.4 Achievements

1.4.1 Research results

The main contributions of the ESR01 research activity regarding RCV-flicker subject, have been the following:

- ✓ Establishment of the cause-effect relationship between RVCs and flicker severity
- ✓ Adaptation of one flickermeter (lamp-based) supplied with a controlled power supply. This allowed to input recorded voltage signals containing RVCs
- ✓ RVC-flicker assessment of several lamps with different technologies to test several RVCs patterns
- ✓ 3 papers delivered (1 journal, 2 conferences)

And regarding supra-harmonic work:

- ✓ Upgrading of the existing algorithm developed by the thesis supervisors 4 years ago to be able to measure supra-harmonics. The method met IEC 61000-4-7 standard requirements.
- ✓ Comparison with Fourier-based methods
- ✓ 3 papers delivered (1 journal, 2 conferences) + 1 paper submitted to IEEE Transactions on Instrumentation and Measurement (revision)

1.4.2 Thesis

- **Title**: New power quality issues related to Smart Grids
- **Defense date** (Upcoming): April 2020
- **Defense place**: University of Zaragoza, Spain
- **Doctoral school**: University of Zaragoza, Spain
- **Thesis supervisor**: Dr. Julio J. Melero

1.4.3 Publications

During the drafting of the current document, six (6) have been the publications performed by ESR01 Stefano Lodetti

- Lodetti, S., Azcarate, I., Gutierrez, J.J., Redondo, K., Saiz, P., Melero, J.J., Bruna, J., 'Sensitivity of Modern Lighting Technologies to Rapid Voltage Changes', 18th International Conference on Harmonics and Quality of Power (ICHQP) 2018, DOI: 10.1109/ichqp.2018.8378925
- Lodetti, S., Azcarate, I., Gutierrez, J.J., Leturiondo, L., Redondo, K., Saiz, P., Melero, J.J., and Bruna, J. , "Flicker of Modern Lighting Technologies Due to Rapid Voltage Changes", *Energies* **2019**, *12*(5), 865; **https://doi.org/10.3390/en12050865**
- Lodetti, S., Bruna J., and Melero J. J., "Methods for the Evaluation of New Power Quality Parameters: a Review of Rapid Voltage Changes and Supraharmonics", CIRED 2019
- Lodetti, S., Bruna J., Sanz J. F., and Melero J. J., "Characterization of the Emission of an Electric Bus Inductive Charging in the 2 kHz to 150 kHz Range", AEIT International Conference of Electrical and Electronic Technologies for Automotive (AEIT AUTOMOTIVE), 2019, DOI: 10.23919/EETA.2019.8804604
- Lodetti, S., Bruna J., Sanz J. F., and Melero J. J., "Wavelet Packet Decomposition for IEC Compliant Assessment of Harmonics under Stationary and Fluctuating Conditions", *Energies* **2019**, *12*(22), 4389; **https://doi.org/10.3390/en12224389**
- Lodetti S., Khokhlov V., Meyer J., Bruna J., Melero J.J., "A Robust Measurement Method for Supraharmonics Under Power Frequency Deviations", IEEE 10th International Workshop on Applied Measurements for Power Systems (AMPS), DOI: 10.1109/amps.2019.8897762

Besides, another (1) publication not yet published has been noticed to be accepted beginning of march 2020

- Lodetti S., Bruna J., Melero J.J., Khokhlov V., Meyer J., "A Robust Wavelet-based Hybrid Method for the Simultaneous Measurement of Harmonic and Supraharmonic Distortion", IEEE 2020

1.5 Networking and Exploitation Plan

1.5.1 Synergies with third parties

It shall be noticed that during the conferences attended by the researcher, several interactions with important players on the development of PQ algorithms have taken place.

Besides, as part of the same Working Package ESR01 Stefano Lodetti has identified potential ways of collaboration with other ESRs, notably:

- ESR-03 Deepak Amaripadath (LNE) | Development of tools for accurate and reliable measurements of Smart Grid Power Quality. With Deepak, active conversations regarding the inclusion of ESR01 supra-harmonic algorithm in ESR03 platform have taken place
- ESR-02 Stanislav Babaev (TUE) | Transfer of Power Quality Disturbances through Distribution Networks. ESR01 Stefano has attended common conferences with Stanislav and participated in discussions about the importance of supra-harmonic assessment on Smart Grid measurements.

1.5.2 Exploitable foreground that can potentially derive from the ESR project

The algorithms developed in the framework of the ESR01 research were tested and validated through simulations as well as on the laboratory with real PQ disturbances. In this sense, several patents have been identified.

Table 2 Exploitation Plan for ESR01

Exploitation Plan for ESR01					
Fellow	**Title**	**Direct Applications / Commercial use**		**Patent**	**Future Research Required**
Stefano Lodetti (ESR01)	Flicker measurements for newer lighting techniques	Yes	Yes	Possible	YES
Stefano Lodetti (ESR01)	Novel method for the Supraharmonic estimation based on WPD	Yes	Yes	Possible	YES

Details on how the detected patents could be developed are explained in its dedicated deliverable: "D8.2 Exploitation roadmap in consonance with the end user feedback"

2 Task 3.2 PQ measurements and propagation in distribution grids (ESR02)

2.1 Summary

The researcher has studied the propagation phenomenon of harmonics in distribution systems. The work is the combination of **theoretical studies, experimental tests in laboratory and field, simulations and mathematical modelling**.

The core of the research study is utilization of data acquisition systems installed at the different points of power network and synchronized to the same time source.

During his research, ESR02 Stanislav Babaev got involved in the modelling of the harmonic emission of non-linear devices, the frequency response of the network components - and in particular the uncertainty of their modelling, and the simulation of the impact of multiple harmonic sources on the voltage distortion on every busbar within a distribution network. A particularly important step for achieving these goals is the measurement of these phenomena on multiple network locations at the same time. The time synchronisation of Power Quality meters is analysed both from the standpoint of waveform recording and spectrum recording. Propositions for improved harmonic modelling are based on the results of laboratory measurements and the definition of modelling uncertainty.

This project contributes to:

- Efficient detection, characterization and evaluation of the impact of PQ disturbances
- Localization of the source of disturbances
- Prediction and analysis of harmonics
- Planning adequate mitigation measures
- Establishing highly accurate measurement infrastructure

2.2 Background and organisation of the project

2.2.1 ESR02 Factsheet

Thesis title: *Transfer of Harmonic Distortion through Distribution Networks (provisional title)*

Research fellow: Stanislav Babaev

Current position: Associate Project Manager at the heart of ABB, Delft, The Netherlands

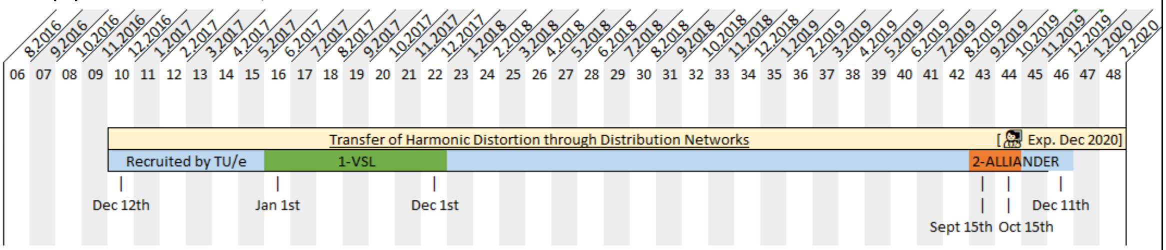
Contact beyond the project: linkedin.com/in/stanislav-babaev-b1353262

Recruitment organisation within MEAN4SG: Eindhoven University of Technology (TU/e)

Secondment organizations:

(1) VSL, Delft, the Netherlands

(2) Alliander N.V., the Netherlands



Main Contribution to MEAN4SG:

Stanislav Babaev's research focused on the propagation of harmonic distortion through distribution networks, involving the modelling of the harmonic emission of non-linear devices, the frequency response of the network components - and in particular the uncertainty of their modelling, and the simulation of the impact of multiple harmonic sources on the voltage distortion on every busbar within a distribution network.

In this sense, his main contribution on the scope of MEAN4SG is the application of synchronised Power Quality measurements, and in particular the requirements for time-synchronisation between multiple meters to achieve impedance estimation for a wide frequency range. This work resulted also in a laboratory setup for synchronised waveform recording which enables efficient harmonic observability.

Link to the presentation: https://youtu.be/hZyUsDkzHwc

2.2.2 Background

Harmonic emission evaluation has been known as complex problem for many decades. Fluctuating nature of harmonics, high level of diversity and additional implications which arouse with interconnection of Renewable Generation require improvement of the existing assessment and measurement methods. The closely linked problem is determination of the origin of harmonic distortion in case when multiple sources of harmonics are connected to the network.

The system-wide studies of harmonic propagation phenomena and emission assessment present challenges for researchers and engineers. In essence, the broad term 'propagation' includes several specific harmonic-related mechanisms among which are:

- Harmonic interaction
- Phase angle diversity and cancellation
- Harmonic attenuation
- Impact of system and load impedance

Giving a dynamic nature of mentioned processes an appropriate solution for investigation of harmonic propagation in specific parts of the power grid would be the application of multi-point distributed measurement system synchronized to the precision clock with high accuracy. Such measurement system configuration will allow to study the harmonic response of a system to the current injection from diverse loads at different points of the electrical network.

2.2.3 Objectives

The results of the Phd project are expected to be used by grid operators and other interested parties for efficient detection, characterization and further evaluation of the impact of Power Quality disturbances. Taking into account the rapidly increasing level of Distributed Generation and dynamic nature of the state of distribution grid, the obtained knowledge and understanding propagation phenomenon will also contribute to the prediction and probability analysis for the certain types of Power Quality disturbances, thus allowing to undertake specific mitigation measures.

The objectives of the project were:

- Identifying and validating methods for assessing the level of propagation of harmonic distortions
- Performing measurements in various locations at the power system
- Establishing and utilizing synchronized measurements
- Identifying associated uncertainty of the measurement chain
- Developing applicable models of components and setting up simulations

2.3 Research line of the fellow

2.3.1 Research tasks, activities to attain the project goals

In order to meet the objectives of the research project the following studies were performed:

1. Metrology:

A performance of multi-point synchronized harmonic measurement systems was studied and a method for assessing the performance of such measurement systems was developed. An influence of time synchronization accuracy on the phase angles and magnitudes of spectral components is studied. It has been shown that a time delay at microsecond level can lead to the significant angle difference between two identical signals at higher harmonic orders. Based on the results the limit for the phase angle difference is proposed.

As a next step, a customized system capable of recording synchronized waveforms of voltages and currents has been built in the lab. Hardware specifications of the systems are carefully chosen (including those of current clamps and Rogowski coils) in order to provide a superior accuracy for capturing spectral components. Labview-based acquisition software was developed. The system features time synchronization between devices of not worse than 500 ns.

Further, with provision of field measurements by enabling Phasor Measurement Units (PMUs) infrastructure an uncertainty of instrumentation chain and its impact on measurement of harmonic components was investigated. One of the aspects affecting accuracy of measurements in the medium and high voltage grids is the utilization of the voltage and current transformers. The impact of these instrument transformers on the measurements performed at power frequency is well described in the literature. However, at frequencies other than fundamental the performance of these measurement transformers becomes a source of a larger uncertainty. Having one VT and one CT fixed as reference (with higher accuracy class), the uncertainty of another pair of instrument transformers with lower accuracy class can be reduced by introducing correction factors. The performed study proposed methodology for calculating these correction factors.

2. Signal processing:

A methodology based on application of wavelet transforms to synchronized voltage and current waveforms was developed. This method allows to take into account the characteristics of time varying waveform distortions. The methodology includes analysis of the harmonic behaviour of non-linear appliances and their combined impact on the harmonic voltage distortion at PCC. Additionally, a graphical visualization of wavelet coefficients was proposed method demonstrates the correlation between time-varying harmonic injections of a particular load and its influence on harmonic voltage at different point of the network.

Further, a performance of FFT-based advanced algorithm was evaluated. Among several options a choice was made to utilize Welch averaged periodogram for particular purpose of calculating harmonic impedances. The parameters of the algorithm and their impact on the final result were carefully studied and concrete values together with the selection guidelines were proposed.

3. <u>Power system components and their impact on quantifying harmonic distortion:</u>

To characterize the propagation of PQ phenomena, disturbance levels at non-monitored locations/feeders often need to be estimated as well, which requires modelling based on limited measurements and network parameters. The modelling of predominantly linear network elements such as transformers, cables, lines and generators is mature knowledge, covered and summarized in many references. The validity of these models is sometimes possible to check in the laboratory, and some studies have shown the deviations from the usually assumed frequency dependent parameters. Generalizing these deviations is

however difficult, and differences between the laboratory and field conditions – e.g. frequency dependence of parameters, uncertainty of cable length, conductivity of surrounding soil etc., make this task even more difficult. This opens up the question of the accuracy of modelling results if such effects cannot be included. To partially answer these questions a field measurement campaign was performed in order to test an algorithm which quantifies an uncertainty associated with the lumped impedance model of a HV 50 kV underground cable. The algorithm makes use of synchronized harmonic phasors supplied by PMUs installed at both end of the cable. Using a comparison between the measured harmonic current at one end of the cable and the same current calculated based on the cable parameters and the measurements of other variables in the model the uncertainty of the pi model was calculated. The results show that starting from 7th harmonic order the uncertainties of this model become significant.

For LV distribution systems a novel non-invasive method for estimating harmonic impedances of underground cables was developed. The methodology employs natural variations of harmonic currents and voltages, however, the impedance angle is preserved due to the utilization of synchronized measurement samples. A harmonic impedance is estimated as a transfer function describing frequency response of Linear Time Invariant System. Welch averaged periodogram is utilized as underlying signal processing algorithm. Additionally, an attention was given to the metrological characterization of the measurement system and evaluation of uncertainty of impedance values.

4. <u>Modelling of harmonic sources:</u>

Accurate models of harmonic producing sources are essential for studying their impact on voltage distortion levels. The challenge in developing a model suitable for harmonic propagation studies in the distribution networks is to accurately represent the impact of background voltage distortion on harmonic current emission of certain device. This challenge is governed by a trade-off between the complexity of a model and its level of details. Moreover, not only the modelling approach itself is important but also the convenience of applicability of developed model in the commercially available simulation packages. In order to address these mentioned issues, it has been proposed a novel method for modelling individual harmonic producing sources based on the foundations of circular statistics. A measurement procedure attributed to the harmonic fingerprinting was used for obtaining the initial sets of data for three modern PE devices: photovoltaic inverter, battery charger and a group of CFLs. The novelty of the proposed method lies in the procedure of deriving the relationships between applied harmonic background voltage angle and the phase angle response of the harmonic current emission of the device. In essence, coefficients of the models are estimated with the application of circular regression algorithm.

5. <u>Distribution system modelling and simulations:</u>

In order to include full consideration of the interaction between background harmonic voltages and produced harmonic currents of non-linear devices as well as diversity between phase-corrected current injections a new methodology for performing harmonic studies by means of computer simulation has to be adopted. Taking this into consideration we have modelled a practical low-voltage feeder in PowerFactory with specifically developed measurement-based regression models of harmonic loads. Thereafter a sequence of continuous harmonic simulations driven by unique Python script has been executed. Results proved that harmonic interaction, phase-angle diversity and uncertainty of system

Harmonic impedances are among the most important factors influencing the accuracy of harmonic load flow and therefore need to be considered in harmonic studies of low-voltage distribution systems.

2.3.2 Recruitment and Training Overview

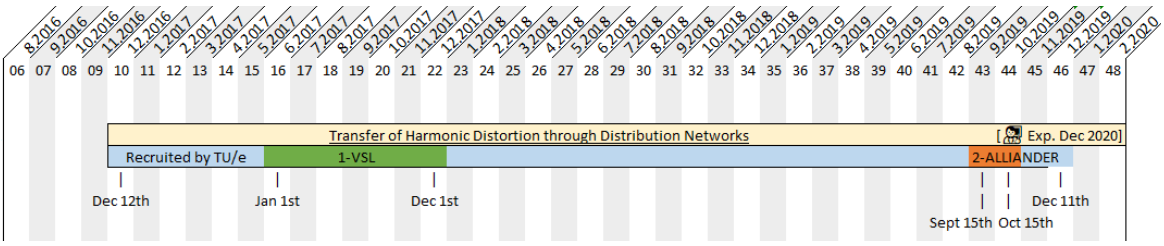


Figure 4 ESR02 recruitment timeline

Recruitment Organisation

Stanislav Babaev has been recruited by Eindhoven University of Technology (TU/e) in a total duration of 36 months, from 12.12.2016 until 11.12.2019. During his training he has acquired skills in PQ measurements and propagation in distribution grids, corresponding to the dedicated task 3.2 within the project framework.

During the whole duration of the project, Stanislav is employed as a PhD student in the EES research group of the Electrical Engineering faculty. The PhD trajectory at TUe lasts 4 years, so Stanislav stays employed in the group to finalize his thesis and defend it.

In this sense, the main facilities used to validate scientific results has been the SmartGrid laboratory

Secondment organisations

In total, Stanislav has collaborated at the heart of two secondment organisations within his research during MEAN4SG project.

Table 3 Secondments performed by ESR02

Information about secondments for ESR02				
Fellow	**Secondment Organization**	**Start Date**	**End Date**	**Duration (months)**
Stanislav Babaev (ESR02)	VSL	1.06.2017	1.12.2017	6
Stanislav Babaev (ESR02)	Alliander	15.09.2019	15.10.2019	1

During his **first secondment at VSL**, Stanislav was working together with VSL on the synchronisation of meters in a wide-area measurement system.

One of the main facilities used to validate scientific results has been the internal laboratories at the VSL.

During his **second secondment at Alliander**, Stanislav was given a task and support to execute the following lab measurements relevant for network operators:1.Modeliling of harmonic sources in the frequnecy domain, 2. Modelling of the propagation of harmonic distortion in low and medium voltage networks. For this purpose, Stanislav visited the PNDC laboratory in UK to perform the relevant measurements. In this sense, two of the main facilities used to validate his scientific results have been the Lab Lemco Kortrijk (Belgium) as well as the PNDC in Glasgow UK.

Courses and summer schools organized in the framework of MEAN4SG

ESR02 has participated in most of the Courses and Summer Schools organized in the framework of the project

- 1st MEAN4SG Specific Course: Hold in CIRCE, Zaragoza, Spain on 31/01/2017-02/02/2017, as a training activity within the ITN-ETN MEAN4SG project
- 1st MEAN4SG Summer School: Hold in the Van der Valk Hotel, Haarlem, The Netherlands, on 19-20/04/2017
- 3rd MEAN4SG Specific Course: Hold in CIRCE, Zaragoza, Spain on 28-30/11/2017, as a training activity within the ITN-ETN MEAN4SG project
- 2nd MEAN4SG Summer School: Hold in the University of Strathclyde, Glasgow, UK, on 23-25/01/2018, as a training activity within the ITN-ETN MEAN4SG project,
- 3rd MEAN4SG Summer School: Hold in ORMAZABAL, Boroa, Spain on 19-21/06/2018, as a training activity within the ITN-ETN MEAN4SG project

Other training events performed/promoted within MEAN4SG

Among the training events taken place within the project's framework, ESR02 did participate to the following:

- Demonstration Workshop on Electric System Modelling, Development of an integrated model of electric systems and Development and validation of distributed generation management at customer sites for service provision through virtual power plant concept. Hold online by ENEL with special guests from the Universities of Cagliari and Genova on 10.10.2019, as a training activity within the ITN-ETN MEAN4SG project
- Digsilent Power Factory training. March 2017 in Gomaringen, Germany
- ICHQP 2018 conference. May 2018 in Ljubljana, Slovenia
- AMPS 2018 conference. April 2018 in Bologna, Italy

Seminar Presentations

ERS02 did participate in the following seminar event proposed in the framework of the project:

- PhD Webinar. Group PQ – Power Quality: September, Wednesday the 11th: Stanislav Babaev [11:00] - Transfer of Power Quality Disturbances through Distribution Networks. [Link to the presentation: https://youtu.be/hZyUsDkzHwc]

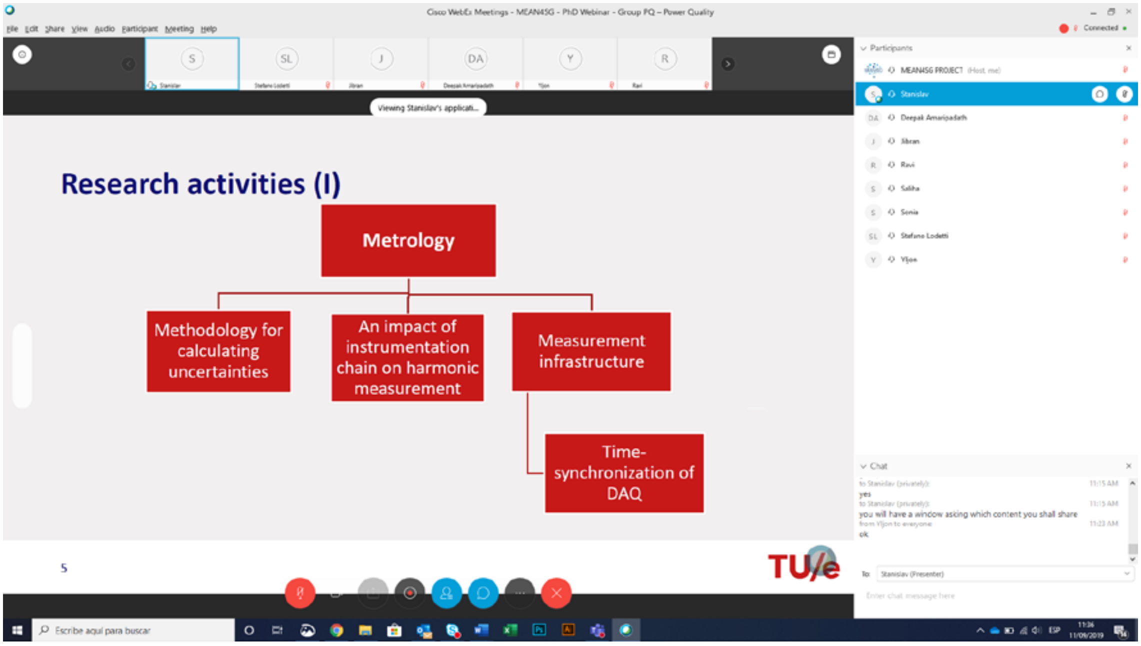


Figure 5 Screenshot from ESR02 presentation during the last PhD Webinar

2.3.3 Skills learnt under MEAN4SG framework

Research Skills:	Technical Skills:
Metrology, Frequency domain modelling, synchronised measurements	Power System simulation software, Laboratory experimentation

Management Skills:	Communication Skills:
Organizing own research, setting up a research plan	Scientific writing, Presenting skills

2.4 Achievements

2.4.1 Research results

The main contributions of the ESR02 research activity have been the followings:

- ✓ Answer to the Uncertainty of harmonic models of network components by processing Laboratory measurements using synchronised waveform recorders. **Results: Synchronisation requirements for waveform recording, uncertainty definition of a cable model in a wider frequency range**
- ✓ Answer to the Synchronised waveform recording issues by Data acquisition programming, synchronisation protocols. **Results: Laboratory setup for multi-point recording**
- ✓ Answer to the Harmonic emission modelling issues by Frequency domain modelling of harmonic sources. **Results: Proposition for a novel frequency-domain harmonic model**
- ✓ 6 papers delivered (2 journals, 4 conferences)

2.4.2 Thesis

- **Title**: Transfer of Harmonic Distortion through Distribution Networks (provisional title)
- **Defense date** (Upcoming): December 2020
- **Defense place**: Eindhoven University of Technology
- **Doctoral school**: Eindhoven University of Technology
- **Thesis supervisor**: dr V. Cuk, prof. dr J.F.G. Cobben

2.4.3 Publications

During the drafting of the current document, six (6) have been the publications performed by ESR02 Stanislav Babaev

- S. Babaev, V. Ćuk, J.F.G. Cobben and H.E. van den Brom, 'Harmonic Source Location in the Distribution Grid Using TimeSynchronized Measurements', International Conference on Renewable Energies and Power Quality (ICREPQ'18)
- S. Babaev, V. Cuk, J.F.G. Cobben, H. van den Brom, G. Rietveld, A. Jongepier, 'On the limitations of harmonic modelling with measured inputs - a case study', 2018 18th International Conference on Harmonics and Quality of Power (ICHQP)
- S. Babaev, V. Cuk, J.F.G. Cobben, H.E. van den Brom, 'Harmonic Source Location in the Distribution Grid Using Time-Synchronized Measurements', Renewable Energy and Power Quality Journal 2018, DOI 10.24084/repqj16.284
- Stanislav Babaev, Ravi Shankar Singh, Joseph Cobben, Vladimir Cuk, Helko Van Den Brom, 'Considerations on the Performance of Multi-point Synchronized Harmonic Measurement System', 2018 IEEE 9th International Workshop on Applied Measurements for Power Systems (AMPS)
- Ravi Shankar Singh, Stanislav Babaev, Vladimir Cuk, Sjef Cobben, Helko van den Brom, 'Line Parameters Estimation in Presence of Uncalibrated Instrument Transformers', 2019 2nd International Colloquium on Smart Grid Metrology (SMAGRIMET)
- Stanislav Babaev, Sjef Cobben, Vladimir Cuk, Helko van den Brom, 'Online Estimation of Cable Harmonic Impedance in Low-Voltage Distribution Systems', IEEE Transactions on Instrumentation and Measurement, DOI 10.1109/tim.2019.2926690

Besides, another (1) publication not yet published has been noticed to be accepted

- S. Babaev, V. Cuk, S. Cobben, H. vd Brom., "Application of Wavelets for Study of Harmonic Propagation in Distribution Networks", IEEE 2020

2.5 Networking and Exploitation Plan

2.5.1 Synergies with third parties

For performing measurements, Stanislav got in touch with two eminent laboratories in the field: the Lemco Lab in Kortrijk, University of Ghent and the PNDC laboratory in Glasgow UK. He performed measurements in those labs during the scope of the project.

At scientific conferences, Stanislav reached out also to the external network of specialist in the area of Power Quality for discussions.

Besides, Stanislav Babaev has identified potential ways of collaboration with other ESRs, notably:

- ESR-08 Ravi Shankar (TUE) | PMU Applications in Distribution Grids. Working on several research questions together, including laboratory measurements and producing common papers.
- ESR-03 Deepak Amaripadath (LNE) | Development of Tools for Accurate Study of Supraharmonic Emissions in Smart Grids. Networking and exchange of ideas: both ESRs participated in different seminars organized as a part of MEAN4SG and scientific conferences.
- ESR-01 Stefano Lodetti (CIRCE) | New power quality issues related to Smart Grids. Discussion on the topic of Power Quality which is common for both researchers. Attending several conferences together

2.5.2 Exploitable foreground that can potentially derive from the ESR project

The main target audience of the research has been the network operators themselves.

It shall be highlighted that during the project, the second secondment was performed at Alliander N.V., which is one of the largest distribution network operators in the Netherlands. In this sense, network operators were the target users of the technology for the project.

In terms of relevant innovation activities carried out (prototypes, testing activities, standards) and new potential applications, products, services, reference materials, For the purpose of assessing propagation of harmonic distortion, a wide-area laboratory measurement experiment was designed at the PNDC lab, utilizing both low-voltage and medium-voltage measurements. This is not seen a potential product, but a paper is in preparation about the experiments which will give guidance to network operators how to perform similar measurements in the field as well.

Table 4 Exploitation Plan for ESR02

Exploitation Plan for ESR02					
Fellow	**Title**	**Direct Applications / Commercial use**		**Patent**	**Future Research Required**
Stanislav Babaev (ESR02)	PQ Measurements and propagation in distribution grids	Yes	No	Not Possible	No

Details on how the detected patents could be developed are explained in its dedicated deliverable: "D8.2 Exploitation roadmap in consonance with the end user feedback"

3 Task 3.3 Development of tools for accurate and reliable measurements of Smart Grids PQ (ESR03)

3.1 Summary

Smart electrical grids are confronted to challenges raised by the increasing uptake of Renewable Energy Sources (REnS) as well as new loads of electricity such as electric vehicles and mobile electronic devices. Both lead to a complex dynamic operating environment for distribution networks. Distortions coming from these REnS are generally larger and less regular then those due to traditional generation sources and loads, making power quality (PQ) measurements difficult to perform.

In this context, the research contributed to develop a metrology grade calibration platform for the generation of distorted waveforms with supraharmonic components (2 - 150 kHz). These developments are based on field measurements on real smart grids. Thus, the power quality instruments can be characterized under real-grid dynamic conditions.

3.2 Background and organisation of the project

3.2.1 ESR03 Factsheet

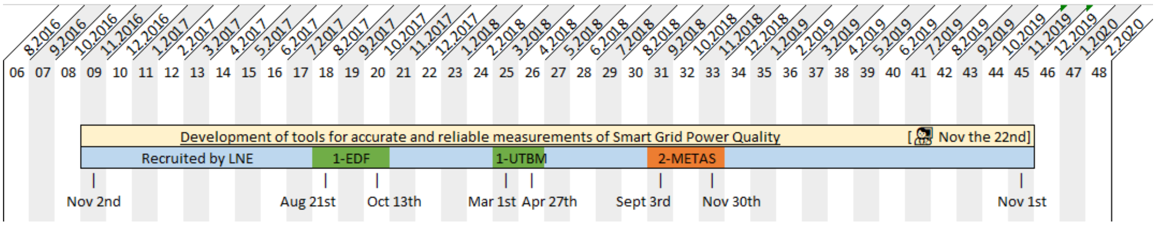
Thesis title: *Development of tools for accurate and reliable measurements of Smart Grid Power Quality*

Research fellow: Deepak Amaripadath
Current position: Open to job opportunities
Contact beyond the project: linkedin.com/in/deepakamaripadath

Recruitment organisation within MEAN4SG: Laboratoire Nationale de Métrologie et d'essais (LNE)

Secondment organisations:

(1) EDF
(2) UTBM
(3) METAS



Main Contribution to MEAN4SG:

The activity and the results obtained during the PhD thesis contribute to the determination of those PQ parameters that affect active customers, to the study of the cause-effect relationship between the different parameters, such as the PVIs, residential equipment, etc. in the network; to the development of generation tools for characterizing PQ parameters that propagates through Smart Grids.

Link to the presentation: https://youtu.be/hZyUsDkzHwc

3.2.2 Background

The smart electrical networks must tackle the challenges raised by the increasing uptake of the renewable energy sources and the equipment, such as photovoltaic inverters (PVI), electric vehicle chargers (EVC), etc. This introduces a complex dynamic operating environment for the distribution system. The distortions are generally larger and less regular than those due to the traditional generation and load equipment, making the power and energy measurements difficult to perform. In this context, the thesis aims to quantify and reproduce the supraharmonic emissions in the frequency range of 2 to 150 kHz. The thesis dealt with (1) identification of parameters of distorted waveforms (from field measurements on real smart grids) due to RenS; (2)development of mathematical tools and signal processing algorithms for the determination of distorted waveforms parameters;(3)development of a platform for the generation of complex waveforms (strongly dependent on both the electronic design and the algorithms capable of reproducing real-grid like waveforms);(4)implementation of a metrology-grade platform for the characterization of measuring instruments for PQ parameters under severe conditions.

Despite all the benefits of implementing smart grid technology, there are still few areas of concern. The need to anticipate and address these possible downsides with smart grids, such as PQ issues, is of high significance. The residential equipment, like the heat pumps, EV chargers (EVC), light emitting diode (LED) lamps, etc. are important sources of the supraharmonic emissions. The main effects of the supraharmonic emissions include the capacitor overheating, electromagnetic incompatibility, and interference with PLC.

Identifying the sources of the supraharmonic emissions in the electrical networks with multiple equipment is challenging due to interactions between the equipment. In these scenarios, this thesis proposes the Design of Experiment (DoE) approach and the Analysis of Variances statistical method for the analysis of network.

The existing standards for supraharmonic emissions provide guidelines for the measurement and equipment testing, but do not detail the network measurements involving multiple equipment. As more and more power quality instruments are designed, it is proposed to develop a dedicated platform for their characterization in the frequency range of 2 to 150 kHz.

3.2.3 Objectives

The **objectives** to be accomplished through this PhD thesis are:

- Field measurement data base for power quality disturbances;
- Development of mathematical algorithms for waveform processing and validation;
- Electronic design and realization of complex waveform generator;
- Calibration platform to characterize the power quality instruments under real-grid dynamic conditions.

3.3 Research line of the fellow

3.3.1 Research tasks, activities to attain the project goals

The initial task involved **literature review** concerning the power quality parameters. The state-of-the art analysis indicates the supraharmonic emissions (emissions from the grid equipment in the frequency range of 2 to 150 kHz) as one of the significant PQ issues in the smart grids appearing with the renewable energy sources. The performed research and documentary work dealt with several aspects related to supraharmonics: sources of emission, type of emissions, measurement techniques and set-up, analysis methods.

Two relevant challenging aspects emerged from this analysis:

1. Design the appropriate measurement system
2. Create the measurement plan

The main challenges in the measurement of supraharmonic emissions in the frequency range of 2 to 150 kHz are:

- lower amplitudes at higher frequencies, which requires measurement sensors with high sensitivity and wide bandwidth to detect these emissions accurately;
- non-invasive connections (sensors) for the public electrical networks, which are not always reconfigurable;
- recording with high resolution and dynamic range to acquire even the smallest emissions.

Aiming at the design of a flexible **measurement system** considering safety aspects for actual grid measurements, a 4-channel measurement and acquisition system was designed and implemented. The first two channels are dedicated to voltage measurement and the remaining two channels are used for the current measurement. These channels measure fundamental and supraharmonic components separately in order to maximize the dynamic range of the recording device.

The parameters of the network that guided the dimensioning of the measurement system are:

- fundamental frequency, 50 Hz;
- supraharmonics frequency bandwidth, from 2 to 150 kHz;
- phase to phase voltage, 400 V;
- phase to neutral voltage, 230 V;
- peak current, less than 100 A (rms value less than 60 A).

The acquisition part of the system is a National Instrument PXIe-6124 recorder with the following technical specifications:

- maximum bandwidth of 3 MHz;
- maximum sampling rate of 4 MS/s per channel;
- 4 analogue input channels;
- maximum voltage level up to ± 11 V;
- resolution of 16 bits.

The fundamental **voltage** component is measured using channel 1, which consists of the voltage transformer that steps down the voltage from 230 to 10 V at a frequency of 50/60 Hz under no load condition and ensures the electrical isolation between the network and the measurement system. A voltage divider with ratio 2:1 is added at the secondary side of the transformer to reduce the voltage to 5 V, such that it is compatible with the NI card input. The supraharmonic voltage components are measured using channel 2, which consists of a 2nd order passive high-pass filter. This filter is followed by an optoisolator, which has a transmitter and receiver connected by an optical fibre. The optoisolator has an input voltage level of 3.5 V and provides isolation between the network and recorder. This ensures the safety of both user and equipment.

The Rogowski coil type current sensors are used to measure the fundamental and supraharmonic **current** components with Channels 3 and 4. The Rogowski coils are flexible current sensors, which measure current and convert it into voltage. These openable sensors can be used for the measurements in the public electrical networks that are not reconfigurable. The fundamental current component is measured using the one model of the Rogowski coil and the channel 3. The supraharmonics components of the current signal are acquired on channel 4 of the NI card. A different Rogowski coil is used in combination with a first order passive high-pass filter in order to attenuate the lower order frequencies. The better sensitivity helps in measuring low amplitude emissions at higher frequencies.

Analyzing the emission patterns and propagation of supraharmonics is a challenge, especially in the presence of multiple sources. The influencing factors and their respective impact are currently not well known and deserve further research. Supraharmonic emissions may be classified into primary and secondary emissions. The equipment under test generates primary emissions, whereas secondary emissions are generated by different equipment and then propagate towards the equipment under test due to low impedance of the equipment terminal. The network measurement campaign with multiple factors and high sampling rate is challenging and time consuming due to the large amount of the measured data, and the required subsequent data analysis.

Therefore, the Design of Experience (DoE) approach was used to **create the measurement plan** and to identify the different relevant configurations and limit the number of experiments. This approach creates a multi-factor design and analysis with minimum external interference by considering the different factors that contribute to supraharmonic emissions in the frequency range of 2 to 150 kHz in the test network. It provides a cause and effect relationship between the different factors considered in the test, thereby creating a better and statistically valid understanding of the test results.

Based on the existing literature and an analysis of the Concept Grid architecture (the platform designed for smart grid testing), 4 factors that influence the generation of supraharmonic emissions are considered for the DoE: the generation equipment: i) low and ii) high power photovoltaic inverters, iii) the load equipment and iv) the measurement point location. The applied DoE is a full factorial plan at two levels of operation. Therefore, 2 positions (High and Low) are defined for each of the identified factor. "High" represents the operation in full capacity for the invertors and residential load, while "Low" represents the off state for the invertors and sole operation of the light bulbs for the residential load. The two positions of the measurement points are either closer to the residential load or to the invertors.

Once the factors and their position identified, it is necessary to choose a statistical model in order to build the measurement plan and the electrical network configurations. An additive model with interaction effect is chosen for the study of grid supraharmonic emissions. All possible combinations of the two levels of each factor are considered and the measurements are done on the Concept Grid platform according to the results of the chosen model. For each configuration, multiple acquisitions of fundamental and supraharmonic components of both voltage and current waveforms were performed simultaneously.

The waveforms acquired from the Concept Grid are **processed mathematically and statistically**. The waveforms in the time domain are converted to the frequency domain using the FFT algorithm. The frequency domain information is then used for the statistical analysis using the ANOVA – ANalysis Of VAriances method. The statistical analysis using ANOVA helps to identify the fluctuations and why it happens in the electrical network with multiple equipment.

The results of the measured data processing are available both in terms of harmonic amplitudes for the frequency components identified both in voltage and current signals and in terms of statistical table whose cells show the importance of the individual effects or of the interactions between factors with influence on the supraharmonic emissions. A colour code indicates if a factor or the relationship between 2 factors is highly significant or not.

The measurement campaign in the Concept Grid confirms the presence of the supraharmonic emissions in the grid. The equipment, such as the photovoltaic inverters, electric vehicle chargers are the main sources of the supraharmonic emissions in the grid. From the measurements performed in the concept grid, it is deduced that the supraharmonic emissions tends to attenuate with the increase in the cable length. The emission levels measured closer to the equipment under test (EuT) is higher than the emission levels measured at a distance from the EuT.

The outcomes from the measurement campaigns and the literature review lead to the design of a **complex waveform platform** (as illustrated in the following Figure) for the generation and the acquisition of the supraharmonic emissions in the frequency range from 2 to 150 kHz.

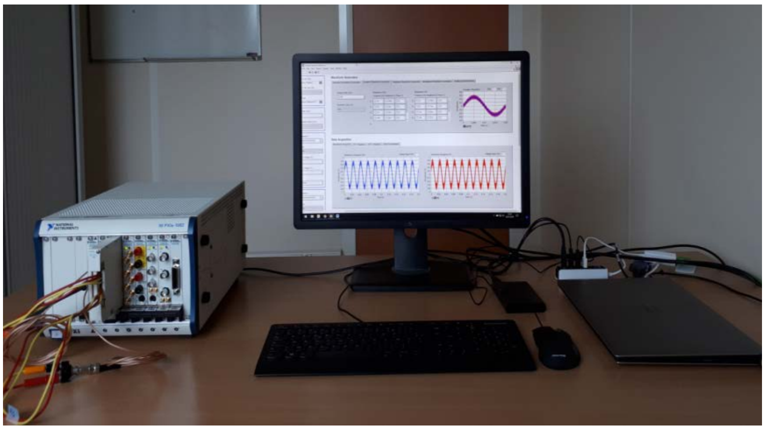


Figure 6 LNE waveform platform for supraharmonics generation and acquisitions

The waveform platform was metrological characterized both for the generation and for the acquisition part. The characterization tests were done in the Low Frequency Electrical Metrology Laboratory in a controlled environment, such as regulated temperature and humidity, and by means of the calibrated references. This guarantees the traceability of the measurement system and a low level of uncertainties. The uncertainty of the waveform platform is obtained as **± 1%.**

This platform is to be used for both laboratory and real grid applications. For the laboratory applications like calibration of PQ analyzers, the platform is used as a waveform generator. For the real grid applications like the measurement of supraharmonic emissions, the platform is used exclusively as a waveform acquisition unit.

The last task of the research work was dedicated to the characterization of a commercial Power Quality device in the frequency range of 2 to 150 kHz for the various voltage levels. The obtained error values are within the acceptable levels of variation specified by the manufacturer.

3.3.2 Recruitment and Training Overview

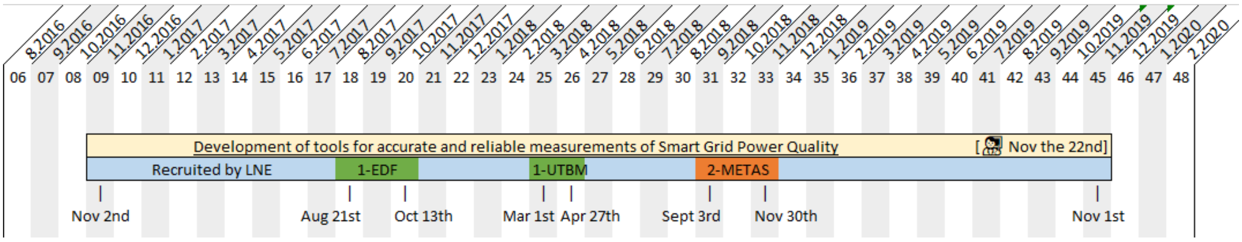


Figure 7 ESR03 recruitment timeline

Recruitment Organisation

Deepak Amaripadath has been recruited by Laboratoire Nationale de Métrologie et d'essais (LNE) in a total duration of 36 months, from 2.11.2016 until 1.11.2019. During his training he has acquired skills in **Development of tools for Accurate and Reliable Measurements of Smart Grids Power Quality**, corresponding to the dedicated task 3.3 within the project framework.

Deepak successfully ended his 3 years of activity with a platform characterized from a metrological point of view. All along this research period Mr. Amaripadath collaborate in very good conditions with the PST (Personal Supervision Team) and established nice relations with colleagues.

In this sense, the main facilities used to validate scientific results have been the Primary standard for voltage traceability: Calibrators, reference current sensors and measurement digital multimeters which was used to validate the generation and the acquisition parts of the built platform; statistical methods to analyse and validate the measurement results.

Secondment organisations

In total, Deepak has collaborated at the heart of three secondment organisations within his research during MEAN4SG project.

Table 5 Secondments performed by ESR03

Information about secondments for ESR03				
Fellow	**Secondment Organization**	**Start Date**	**End Date**	**Duration (months)**
Deepak Amaripadath (ESR03)	EDF	21.08.2017	13.10.2017	1.7
Deepak Amaripadath (ESR03)	UTBM	1.03.2018	27.04.2018	1.9
Deepak Amaripadath (ESR03)	METAS	3.09.2018	30.11.2018	2.9

During his **first secondment at EDF**, Deepak was very well welcomed by the EDF Personal Supervision Team. They defined together the measurement plan and test configurations. Friendly discussions in French language were initiated and improved. One of the main facilities used to validate scientific results has been the EDF Concept Grid platform, the main facilities were houses with Renewable Energy Sources and household appliances. The results were compared with EDF's PQ measurment equipment and technical characteristics of the measured devices.

During his **second secondment at UTBM**, Deepak and the UTBM Supervision team processed the on-field measurement data with FFT (Fast Fourier Transform) and STFT (Short Time Fourier Transform) methods. The paper presented at the CPEM 2018 conference was equally written and reviewed by the UTBM PST during this secondment. Deepak has used Matlab and Labview softwares to validate his scientific results

During his **third secondment at METAS**, Deepak and the METAS Personal Supervision Team worked toghether to design the functionalities and the architecture of the complex waveform platform that runs very well. The 3 months secondement at METAS represents a rich professional experience with a lot of fruitful discussions and advices provided to Deepak. In this sense, Deepak did use LabView software and transconductance amplifiers.

Courses and summer schools organized in the framework of MEAN4SG

ESR03 has participated in the 3 Specific Courses and 3 Summer Schools organized in the framework of the project

- 1st MEAN4SG Specific Course: Hold in CIRCE, Zaragoza, Spain on 31/01/2017-02/02/2017, as a training activity within the ITN-ETN MEAN4SG project
- 1st MEAN4SG Summer School: Hold in the Van der Valk Hotel, Haarlem, The Netherlands, on 19-20/04/2017
- 2nd MEAN4SG Specific Course: Hold in the University of Strathclyde, Glasgow, UK, on 6-8/06/2017, as a training activity within the ITN-ETN MEAN4SG project
- 3rd MEAN4SG Specific Course: Hold in CIRCE, Zaragoza, Spain on 28-30/11/2017, as a training activity within the ITN-ETN MEAN4SG project
- 2nd MEAN4SG Summer School: Hold in the University of Strathclyde, Glasgow, UK, on 23-25/01/2018, as a training activity within the ITN-ETN MEAN4SG project,
- 3rd MEAN4SG Summer School: Hold in ORMAZABAL, Boroa, Spain on 19-21/06/2018, as a training activity within the ITN-ETN MEAN4SG project

Other training events performed/promoted within MEAN4SG

Among the training events taken place within the project's framework, ESR03 did participate to the following:

- Demo workshop about insulation diagnosis on MV grids for maintenance departments of utilities. Hold in LCOE, Madrid, Spain on 03/06/2019, as a training activity within the ITN-ETN MEAN4SG project

Figure 8 Visit to the HV labs during the Demo workshop about insulation diagnosis

- Demonstration Workshop on Electric System Modelling, Development of an integrated model of electric systems and Development and validation of distributed generation management at customer sites for service provision through virtual power plant concept. Hold online by ENEL with special guests from the Universities of Cagliari and Genova on 10.10.2019, as a training activity within the ITN-ETN MEAN4SG project
- UPEC 2017 - 52nd International Universities Power
- Engineering Conference from 28th - 31st August 2017 at Heraklion, Greece.

Seminar Presentations

ERS03 did participate in the following seminar events proposed in the framework of the project:

- CIRED'19. The Leading Forum where the Electricity Distribution Community meets. 3-6 June 2019. Paper Title: "Design of a versatile waveform platform for supraharmonic testing and calibration"
- PhD Webinar. Group PQ – Power Quality: September, Wednesday the 11th: Deepak Amaripadath [11:30] - Development of Tools for Accurate Study of Supraharmonic Emissions in Smart Grids. [Link to the presentation: https://youtu.be/hZyUsDkzHwc]

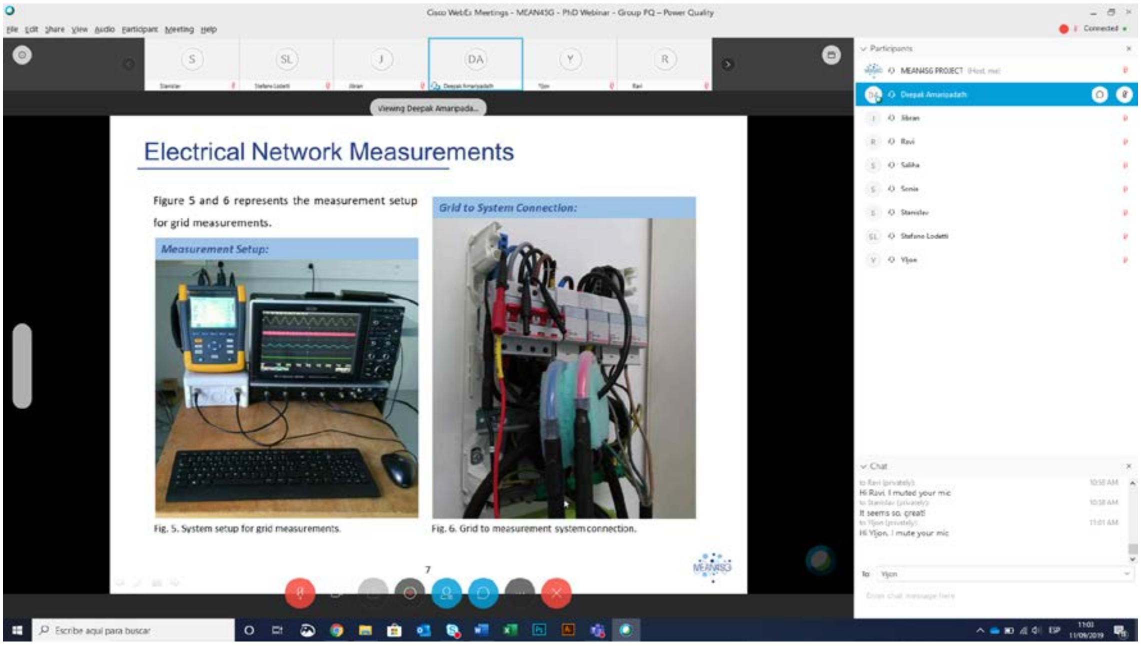


Figure 9 Screenshot from ESR03 presentation during the last PhD Webinar

3.3.3 Skills learnt under MEAN4SG framework

Research Skills:	Technical Skills:
Data collection. Analysis of information from different sources. Finding information.	Electrical engineering design. Software algorithm implementation. On-site measurements.

Management Skills:	Communication Skills:
Effective communication skills. Excellent time management skills	Clarity and Concision. Confidence

3.4 Achievements

3.4.1 Research results

The main contributions of the ESR03 research activity have been the followings:

- ✓ Answer to the Understanding the underlying faults and causes of the supraharmonic emissions in smart grids by On-field measurements performed according to the design of experience method. **Results: Database with supraharmonic emission for both individual equipment and residential network.**
- ✓ Answer to the Development of a platform for the generation of complex waveforms by Choising the electronic design and components, development of the algorithms capable of reproducing real-grid like waveforms. **Results: LabView and NI cards based complex waveform platform**
- ✓ Answer to the Implementation of a metrology-grade platform for the characterization of measuring instruments for PQ parameters under severe conditions by Characterizing the designed platform by means of calibrators and references devices both for generation and acquisition parts. **Results: Complete uncertainty budget for the 2 generation channels and the 4 acquisition ones.**
- ✓ 4 papers delivered (4 conferences)

In this sense, ESR03 has provided an added value to not only the MEAN4SG project but the field itself via:

- the establishment of the cause-effect relationship between the different parameters with impact on supraharmonic emissions, such as the high-power photovoltaic inverter, residential equipment, etc. in the network;
- the 4-channel system for the accurate and reproducible measurement of the voltage and current emissions in the supraharmonic frequency range of 2 to 150 kHz;
- the design and implementation of the waveform platform for the characterization of the commercial PQ instruments in the supraharmonic frequency range of 2 to 150 kHz;
- the metrological traceable characterization of the waveform platform with a complete uncertainty budget within the range of ± 1% for all the generation and measurement channels.

Overall, these contributions can be used for the new developments concerning the reliable measurement and characterization of supraharmonic emissions.

3.4.2 Thesis

- **Title**: Development of Tools for Accurate Study of Supraharmonic Emissions in Smart Grids
- **Defense date**: November 22nd , 2019
- **Defense place**: LNE, Trappes, France
- **Doctoral school**: SPIM (Sciences Pour l'Ingénieur et Microtechniques), Besançon, France
- **Thesis supervisor**: Assoc. Prof. Fei GAO, Lecturer Robin ROCHE, Dr. ing. Daniela ISTRATE

3.4.3 Publications

During the drafting of the current document, four (4) have been the publications performed by ESR03 Deepak Amaripadath

- D. Amaripadath et al., "Measurement and Analysis of Supraharmonic Emissions in Smart Grids," in *54th International Universities Power Engineering Conference (UPEC)*, Bucharest, Romania, 2019, pp 1-6.
- D. Amaripadath et al., "Design of Versatile Waveform Platform for Supraharmonic Testing and Calibration," in *25th International Conference and Exhibition on Electricity Distribution (CIRED)*, Madrid, Spain, 2019, pp 1-4.
- D. Amaripadath et al., "Measurement of Supraharmonic Emissions (2 - 150 kHz) in Real Grid Scenarios," in *Conference on Precision Electromagnetic Measurements (CPEM)*, Paris, France, 2018, pp. 1-2.

- D. Amaripadath et al., “Power Quality Disturbances on Smart Grids: Overview and Grid Measurement Configurations,” in *52nd International Universities Power Engineering Conference (UPEC)*, Heraklion, Greece, 2017, pp. 1-6.

3.5 Networking and Exploitation Plan

3.5.1 Synergies with third parties

Deepak had several opportunities to meet actors from the Smart Grids field.

During the Summers Schools organized in the framework of H2020 MEAN4SG project he met industrial and academic partners involved in H2020 - EriGrid project, researchers and engineers acting in Electrical Metrology European field (Euramet combined workshop).

Deepak attended 4 conferences: UPEC 2017, CPEM 2018, CIRED 2019, UPEC 2019. These were excellent opportunities for Deepak to meet manufacturers, operators, industrial and academic actors in Electrical Energy domain.

Besides, Deepak has identified potential ways of collaboration with other ESRs, notably:

- ESR-06 Jibran Ali (ENEL) | Distributed Generation Management through Virtual Power Plant (VPP) Concept. ESR06 spent 2 months secondment at LNE premises. The exchanges with ESR 03 were focused on Renewable Energy Sources.
- ESR-02 Stanislav Babaev (TUE) | Transfer of Power Quality Disturbances through Distribution Networks. PQ parameters: it is the common research issue. Different analysis methods were implemented to study the supraharmonics propagation in the network: ESR 02 used a network impedance-based approach, while ESR 03 used a design of experience based approach. Networking: both ESRs participated in different seminars organized as a part of MEAN4SG.
- ESR-01 Stefano Lodetti (CIRCE) | New power quality issues related to Smart Grids. Supraharmonics: it is a common topic. However, different mathematical tools were implemented by ESR 01 and ESR 03. Exchanged on the obtained results occurred. Networking: both ESRs participated in different seminars organized as a part of MEAN4SG research group

3.5.2 Exploitable foreground that can potentially derive from the ESR project

The main target audience of the research are the Metrological and test laboratories, Manufacturers of PQ devices, Electrical Network Operators.

In terms of relevant innovation activities carried out (prototypes, testing activities, standards) and new potential applications, products, services, reference materials, the complex waveform platform is modular and portable device that allows generating several type of signals as well as 4 channel acquisition data with real time signal processing. This equipment can be used for new calibration services concerning PQ measuerment devices and supraharmonics (2-150 kHz) emissions.

Table 6 Exploitation Plan for ESR03

Exploitation Plan for ESR03					
Fellow	**Title**	**Direct Applications / Commercial use**		**Patent**	**Future Research Required**
Deepak Amaripadath (ESR03)	Development of tools for accurate and reliable measurements of Power Quality (PQ) in Smart Grid	Yes	No	Not Possible	No

Details on how the detected patents could be developed are explained in its dedicated deliverable: “D8.2 Exploitation roadmap in consonance with the end user feedback”

4 Conclusions

The research activity in WP3 progressed well and the obtained results are in good agreement with the initially defined work plan.

Task 3.1.

The obtained results:

- Determination of the correlation of RVCs and flicker severity (modulation, duration and amplitude).
- Proposal of new test for the lamp immunity protocol to be considered in the future revision of the IEC TR 61547-1 standard
- Development of an IEC compliant algorithm for supra-harmonic measurements based on Wavelet Decomposition

offers a broad range of potential improvement through the development of generation tools for characterizing PQ parameters that propagates through Smart Grids.

Task 3.2.

The research project advances the knowledge in the field of power quality and introduces new approaches and measurement techniques for assessment of harmonic distortion and their impact on wide networks. Additionally, the results of the research are expected to further facilitate integration of devices with global synchronization of the samples and their utilization for power quality assessment.

The results and considerations of this study can be used for network design, analysis of the connection requirements for installations and assessments of the emission limits as well as planning of mitigation activities.

Task 3.3.

The objectives of this task are achieved since a database with supraharmonic emissions based on field measurements was created. The statistically based analysis of the cause-effect relationship of different parameters on supraharmonic emission for both individual equipment and residential network allowed the estimation of the grid state and the deduction of the main influencing factors in supraharmonic emissions. The implementation of the metrology-grade platform used already to characterize PQ instruments under severe conditions fulfil the targeted objectives.