European Research Infrastructure supporting Smart Grid Systems Technology Development, Validation and Roll Out

Technical Report TA User Project

WAHPS

Grant Agreement No:	**654113**
Funding Instrument:	**Research and Innovation Actions (RIA) – Integrating Activity (IA)**
Funded under:	**INFRAIA-1-2014/2015: Integrating and opening existing national and regional research infrastructures of European interest**
Starting date of project:	**01.11.2015**
Project Duration:	**54 month**

Contractual delivery date:	**29/11/2019**
Actual delivery date:	**29/11/2019**
Name of lead beneficiary for this deliverable:	**Stanislav Babaev, Eindhoven University of Technology, Netherlands**
Deliverable Type:	**Report (R)**
Security Class:	**Public (PU)**
Revision / Status:	**Final**

Project co-funded by the European Commission within the H2020 Programme (2014-2020)

Document Information

Document Version:	1
Revision / Status:	draft
All Authors/Partners	Stanislav Babaev
Distribution List	Public

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Executive Summary

Harmonic emission evaluation has been known as complex problem for many decades. Fluctuating nature of harmonics and high level of diversity as well as additional implications which arise with interconnection of Renewable Generation some of the guidelines for distortion measurements and compliance assessment provided by leading Power Quality standards need further improvement. Further, another closely linked problem is determination of the origin of harmonic distortion under the case when multiple sources of distortion are connected to the network. This can therefore be referred to as the “harmonic propagation” phenomena.

Our research project focuses on the study the phenomenon of harmonic distortion propagation through distribution networks. The core of the research is employment of multi-point distributed measurement system synchronized to the precision clock with high accuracy. This measurement configuration allows to evaluate power network response at different nodes to time-varying harmonic current injections.

The proposed set-up includes voltage and current measurements at both medium and low-voltage levels. Several MV/LV substations are involved in the experiment. The harmonic impact of solar power inverter and electrical vehicle charger is assessed in this work. Additionally, a synthetic harmonic current was generated as reference injection.

The objectives of the research comprise investigation of the phenomena of harmonic interaction between background voltage harmonic distortion and harmonic current injections of the non-linear sources under the study. Furthermore, with provision of experimental measurements the diversity of harmonic phase angles and the degree of harmonic cancellation between non-linear loads are evaluated. Thus, special attention is given to the signal processing of recorded waveforms and retaining phase angles for every harmonic order.

To quantify harmonic impact of certain loads their spectrum is evaluated as a function of applied background voltage magnitudes and angles.

Furthermore, additional conclusions are derived based on the influence of network impedance and short-circuit powers on voltage distortion levels. The former involves network topology changes and varying powers of resistive loads at low-voltage levels.

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 its 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.

1. General Information of the User Project

User Project acronym	WAHPS
User Project title	Wide Area Harmonic Propagation Study
Name of the ACCESS PROVIDER	University of Strathclyde
INSTALLATION name	Power Networks Demonstration Centre (PNDC)
Name of the ACCESS PROVIDER representative	Ibrahim Abdulhadi
Name of the User Group Leader	Stanislav Babaev
User Group	1) Stanislav Babaev
Home Institution of the User Group Leader	Eindhoven University of Technology
Access period	30/09/2019 - 08/10/2019
Nº of Access days	6

2. Research Motivation

The system-wide studies of harmonic propagation phenomena and emission assessment, as well as validation of existing methods present challenges for researchers and engineers. This requires specific setup characterized by both flexibility and full control over experiments. Furthermore, these studies must allow to pursue the research beyond the typical assumptions and take into consideration uncertainties of the instrumentation chain, harmonic background voltage variations and frequency dependence of the system impedances. Another important aspect is the behavior and influence of different types of loads.

This work proposes a large-scale experiment which aims to study the harmonic response of the system to the harmonic current injection from diverse loads at different points of the MV and LV power grid. This includes evaluation of the emission levels and separation of the harmonic contributions with studies on system and load impedances. The employment of synchronized measurements is suggested for this task as key solution to resolving described challenges.

The proposed research is highly relevant in addressing questions of harmonic emission assessment in the modern power grid, which is characterized by large amount of connected non-linear sources and bi-directional power flows introduced by Renewable Generation.

2.1 Objectives

The main objectives of the project are:

- Assessment of harmonic profile of non-linear source by measuring its full harmonic fingerprint.

  In essence, a harmonic fingerprint of a power-electronic device is the selection of applied voltage background magnitudes and angles and recorded harmonic current emission of the device under test. Typical THD_i levels included in data sheets of harmonic producing equipment are reported under sinusoidal supply voltage conditions. Therefore, a testing procedure aiming to identify actual harmonic profile of the device under non-sinusoidal conditions is required in order to be able to draw conclusions about harmonic impact of that particular harmonic load on a system-wide level.

- Quantifying the summation of time-varying harmonics and correlating it with harmonic voltage distortion levels.

  The diversity of the phase angles of different harmonic-producing sources is what leads to cancellation effects between harmonic currents. According to IEC-61000 family of standards these effects are accounted by applying summation exponents to magnitudes of harmonic currents. To improve the evaluation of harmonic current components a grid measurement technique which relies on time synchronization is necessary. This allows to take into consideration time-variation of current components and preserve current phase angles. The latter factor results in vectorial summation of currents emitted by different harmonic sources. At this stage an accuracy of instrumentation chain and time synchronization are vital for accurate evaluation of harmonic emission. This type of analysis and configuration of measurement system provide advantage over conventional power quality assessment methods. The voltage harmonic distortion can be correlated in time with harmonic current injections at different locations.

- Evaluation of impact of system impedance on voltage harmonic distortion.

  The outcome of a harmonic analysis can differ given the situation when absolutely identical harmonic producing loads operating at identical power levels are connected to the system with dynamically changing impedance. To illustrate this case topology changes at the MV or LV levels can be invoked. This situation is studied with provision of measurements established for this research project. The spectral components extracted out of synchronized data are anticipated to provide a good insight into the consequences of varying system impedance. Furthermore, in order to complement this study, an impact of resistive loads connected to low-voltage busbars is investigated. These linear loads, depending on the operating power, act as a shunt impedance to the resistive part of the network and can therefore alter THD levels.

2.2 Scope

The scope of this research includes investigation of the harmonic distortion propagation through distribution networks. This involves utilization of highly-accurate distributed measurement system installed at MV and LV levels and synchronized to the precision clock. Several phenomena are studies and among these are harmonic interaction, diversity and cancellation effects and impact of topology and harmonic system impedance on the harmonic voltages.

3. Executed Tests and Experiments

During the access days the experiments were executed strictly according to the plan, which was thoroughly prepared and checked by both staff members of PNDC and TU/e. The experiments involved operation of large parts of the MV and LV networks and therefore were characterized by higher safety risks and complexity. All the associated risks were managed properly.

3.1 Test Plan

The overall experiment has been divided into two generic parts (Fig. 1):

A. Fingerprints
   The goal of this experiment is to comprise full look-up table of the harmonic behaviour of PV inverter and EV charger. This was done first by connecting each of the devices directly to the undistorted voltage supply. Further, individual harmonics with magnitudes between 0.5% and 3% depending on the harmonic order were added one by one. Next, within each level of harmonic voltage magnitude a phase shift was varied between 0 and 360 degrees with standard step of 30 degrees and the harmonic current response of equipment under test was recorded. This test did not involve wide-area power network, equipment under test was connected directly to the programmable power source via short cables.

B. Harmonic propagation
   All the tests of this experiment were performed within dedicated part of the PNDC distribution grid. The harmonic propagation study includes two distinct packages.
   In Package B.1 Motor-Generator (MG) set is used to energise the network with ideal sinusoidal voltage supply. Every harmonic load is connected separately at its designated position. The individual current waveforms and synchronized voltage waveforms are measured at various points of the network. This test concludes with putting all the loads into the operation simultaneously and recording all the electrical parameters synchronously.
   Package B.2 makes use of the public grid characterized by fair (~1.2%) THD levels. At the first stage the same configuration as in B.1 is tested with the difference of using two distinct power levels of PV inverters. Further, an equal share of the resistive load banks is connected to the two substations. Finally, the network is reconfigured by removing/adding some of the impedance sections at MV levels and by moving one of the low-voltage harmonic loads from one substation to the other. This test package involves the same configuration of the measurement system. During each test step voltage and current waveforms are captured synchronously at the various locations of the grid.

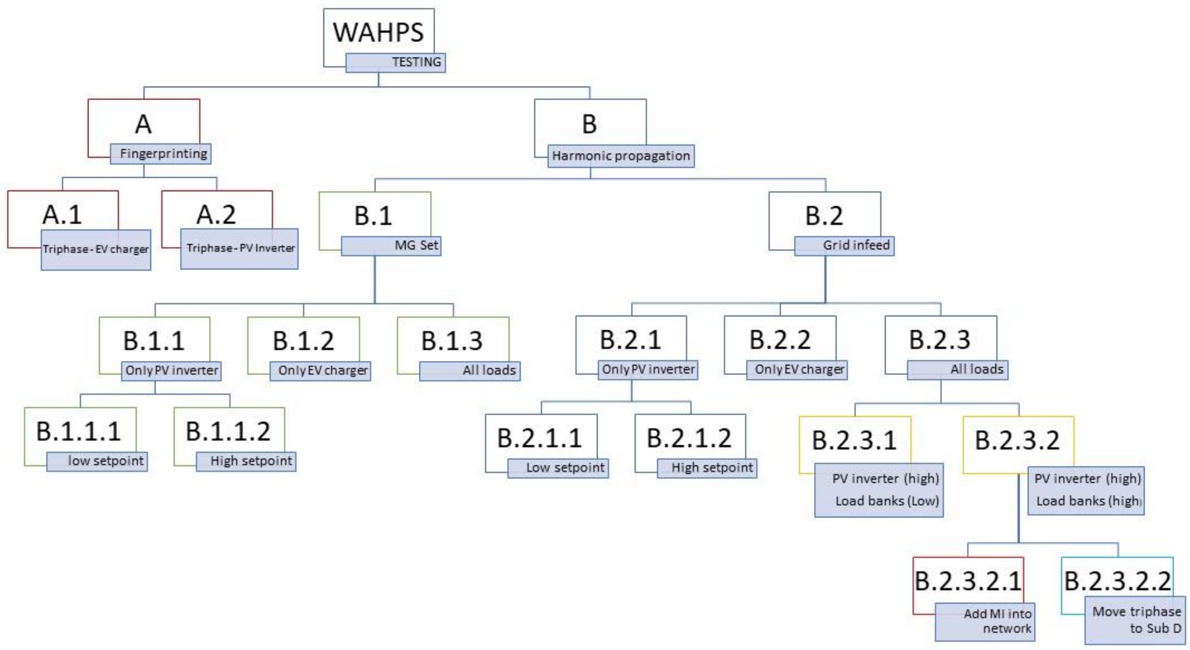

Figure 1. Test mapping.

3.2 Standards, Procedures, and Methodology

Not applicable.

3.3 Test Set-up(s)

Fig. 2 demonstrates accepted test network for the proposed research project. As for the non-linear loads, a 3-phase 10 kVA solar inverter SMA Sunny Tripower driven by Chroma DC power supply was used. Next, EV charger capable of operating at both AC 6 kW and DC 22 kW modes was connected to the network. Additionally, a reference industrial harmonic profile was programmed in Triphase operating as current source. It is worth noting that for fingerprint testing (see Fig. 1) this Triphase was used as programmable power source for the purpose of generating voltage harmonics.

The core of the test network is highly accurate distributed measurement system capable of recording voltage and current waveforms at the sampling frequency of 5 kHz. At the medium voltage levels the measurement points are designated with VTs and CTs in Fig. 2 whilst at the low-voltage level individual currents of all devices are measured and voltage at every LV test bay is recorded. The acquisition system is built on Beckhoff hardware which provided globally synchronized samples with distributed clock precision not worse than 1 µs. The monitoring and acquisition of the data is done through TwinCAT software.

The control of the most of the devices was performed through SCADA-software, however, in some cases manual switching actions and subsequent check procedures were required.

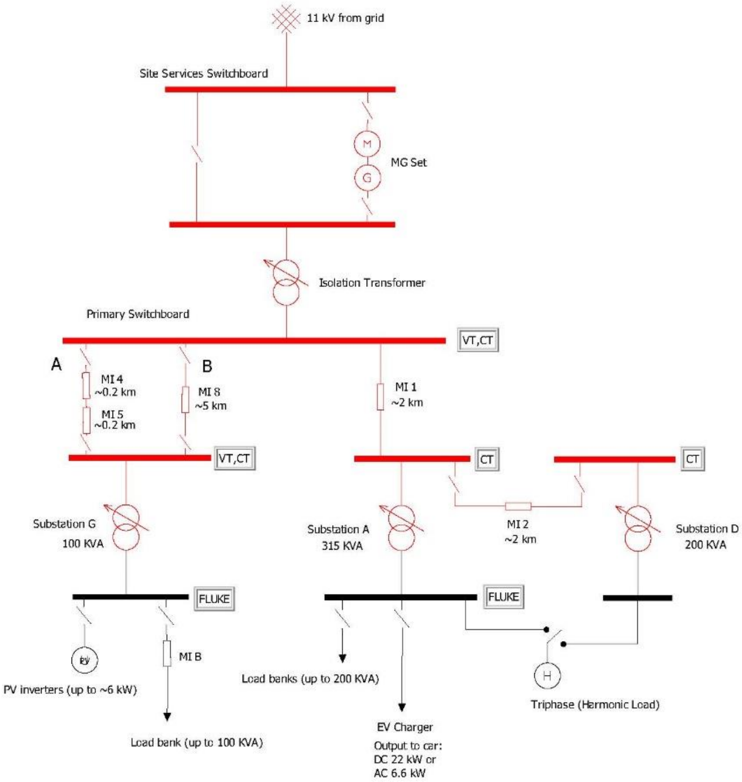

Figure 2. Single-line diagram of the experimental distribution network.

3.4 Data Management and Processing

Data is stored in the form of raw waveforms in tdms format on One Drive under PNDC and TU/e accounts and additionally on SurfDrive linked to TU/e subscription. The processing of the data involves filtering and performing Fast Fourier Transform (FFT) at every 10 cycles of fundamental frequency.

4. Results and Conclusions

The results of the harmonic fingerprint tests indicate that in most of the cases THD_i levels of power-electronic loads are larger than reported by manufacturers. Moreover, some loads are highly sensitive to the changes of applied harmonic voltage angles. This makes fingerprint characterization an important routine for evaluating harmonic voltage interactions at the system-wide level. Thus, harmonic voltage distortions can be estimated as the outcome of current emissions of particular device in presence of distorted voltage supply. As an additional application, this procedure forms the basis of measurement-based modelling. These models allow to perform harmonic loads flow calculations while taking into consideration dynamically changing background harmonics.

Moreover, based on the performed measurements, the global synchronization of current and voltage samples proved to be effective in evaluating diversity phenomena of harmonic currents emitted by various devices. Results show that, depending on the levels of background distortion, current emissions can exhibit cancellations. Further, taking into consideration summation of harmonics, synchronized voltage and current spectrums allowed to deduce conclusions about dominant sources of the distortion and make some judgement about the path of harmonic propagation. We observed that even raw synchronized waveforms monitored real-time can provide some insight into the evolution of power quality phenomena. Clearly, the background voltage affects the emission of devices, but so do harmonic loads, impacting in turn voltage distortion and making it complex bilateral process. An interesting case study involved banks of linear loads connected to separate cables yet affected at the same time by the voltage quality of dedicated busbar. In this situation synchronized measurements provided good solution as well as visual indication for distinguishing between sources and recipients of harmonics.

Finally, based on the executed experiments, system topology changes were considered to be determining in governing phenomena of harmonic distortion propagation. The effect facilitated also by the fact that power system components (cables and transformers) exhibit strong frequency-dependence at higher frequencies.

The results of signal processing analysis will be included in the dissemination materials at the later stage.

5. Dissemination Planning

- Journal publication planned for MDPI
- This study will be included in Doctoral dissertation of Stanislav Babaev