Publishable Summary for 17NRM02 MeterEMI
Electromagnetic Interference on Static Electricity Meters

Overview

Smart electricity meters are currently widely being deployed by utilities across Europe. Recent studies have reported serious errors in some meters when exposed to interference of the type caused by some home appliances. This project has confirmed that some current waveforms measured at meter installation points indeed give rise to large errors in some makes of meter, indicating the need for action by standards bodies. The project has put in place a framework to enable changes to international standards and meter type approval. So that this EMI problem can be tested for, a set of recommended test waveforms has been devised and defined using an efficient and accurate representation that can be easily written into an international standard. New testbeds have been designed which can be used for future type-approval testing of meters. A new benchmark meter is available to help settle billing disputes between utilities and customers.

Need

With 200 million smart meters rolling out across Europe, the suggestion in 2016 studies of over-billing by some 500 % when meters are exposed to certain interference, threated to undermine consumer confidence in this €45 billion EU mandated roll-out. This was particularly worrying as all erroneous meters were already tested and approved under the EU's measuring instrument directive (MID).

In order to determine the extent of interference, field measurements were needed to capture the real-world interference that appears in typical houses and industrial sites, along with interference generated by the newest home appliances. This interference is highly complex and continuously changes severity, so new methods were needed to trigger its capture and to break the resulting waveforms into their constituent parts so that they can be efficiently written in a documentary standard. This required new mathematical algorithms based on the methods used to detect defects in cardiac waves or as used in computer recognition of images.

The distilled interference then needed to be regenerated in the lab in a reproducible way and used to test all types of European smart meter under identical conditions to see if any meters give significant errors. This required the development of new testbeds to generate the waveforms, which together with the most problematic interference, can form the basis of new normative testing methods for the MID. Interference immune "benchmark" meters were needed to resolve consumers billing disputes.

Objectives

The overall objective of the project is to conduct the metrology research necessary for standardisation in the calibration and testing of static electricity meters and smart meters used to ensure accuracy in consumer billing for supplied electricity in the presence of conducted interference.

The specific objectives of the project are:

1. To provide and characterise metrology grade sampling digitisers and transducers and use these to determine the nature of disturbing and interfering signals present in typical electricity networks, both in the lab and on-site. This will lead to the definition of accuracy boundary conditions for static electricity meters during use.

2. To develop new measurement algorithms to accurately measure ac power/energy in the presence of highly impulsive current signals. To furthermore develop and/or optimise non-stationary waveform transforms such as time-frequency distributions and wavelets to determine the parameters of typical disturbing currents such that they can be accurately classified and re-generated for type-testing of commercial smart meters. Implement the algorithms in a reference signal analysis tool suitable for diagnostic use by non-specialists to analyse disturbing current signals.

3. To develop a standard measurement testbed for testing static electricity meters with a target uncertainty of better than 0.1 %. The testbed will use the outputs from objectives 1 and 2, and together with a phantom power arbitrary signal source should provide reference power/energy measurements to match in-service conditions.

4. To develop new type-tests and validated methods for determining electricity meter performance and to modify and characterise a reference “benchmark meter” for use in consumer metering disputes. This includes the identification of the most appropriate test signals and the testing of a range of static electricity meters using the testbed developed in objective 3.

5. To contribute to the standards development work of the CEN and IEC technical committees, CLC/TC 13, CLC/TC 205A, and IEC/SC 77A and the legal metrology organisations WELMEC and OIML to ensure that the outputs of the project are aligned with their needs, communicated quickly to those developing the standards and to those who will use them, and in a form that can be incorporated into the standards at the earliest opportunity.

Progress beyond the state of the art

The underlying cause of the issues raised by the 2016 UTwente study is a disconnection between idealised MID type tests using simple single swept tones and the real-world signals present in the grid. These grid signals are induced by the power electronics used in increasing volumes of household appliances which give rise to highly impulsive current waveforms that are rich in harmonics and modulated in amplitude and phase. Under MID, meters are tested with single tones and whilst this tests the frequency response and issues related to aliasing, the dynamic range of meter electronics is not adequately tested.

Of the meters tested in the initial UTwente study, those that recorded the most startling errors employed Rogowski coils as current transducers (CT). These instruments respond to the differential of current (dI/dt) and their signal processing interface must therefore integrate the CT output to give a current response. As the dI/dt action is an amplifier of spikes, noise and signal edges, the CT output is likely to saturate the signal processing integrator when exposed to impulsive signals. This condition will never be picked up using simple swept sinewaves, as it is the edges typical in real appliance currents that will induce the saturation.

This work has advanced the state of the art by collecting and analysing real-word waveforms and developing the means to test meters using these waveforms as draft type-tests for the MID. This has comprised of several advances, namely: digitising real world waveforms at Metered Supply Points (MSP), developing advanced digital signal processing (DSP) algorithms to accurately and efficiently represent complex non-stationary waveforms, performing accurate synthesis of complex non-stationary current signals for use in meter type-testing, and finally establishing benchmark electricity meters and new type tests for the MID.

Results

Sample digitisers and transformers for capturing real world waveforms at metered supply points (MSP):

Currently, smart meters are tested under the MID using simple signals which contain a fixed amount of interference at the 5th harmonic and with a recently introduced frequency sweep up to 150 kHz. However, this is not representative of household appliances currents which are highly complex and subject to switching and variation. To realistically test meters, the waveforms at the MSPs were captured using accurate high bandwidth sampling instruments and wide-band transducers. These waveforms are the basis of recommended waveforms for use in standards to augment the present idealised MID tests.

A digitiser was selected with sufficient bandwidth, resolution and accuracy to capture the sort of current waveforms that cause EMI issues with static electricity meters. This commercial device was tested, characterised and multiple units were purchased by project partners so that they could be used for on-site measurements at MSPs. Current probes or transducers with enough bandwidth and range capable of measuring the high dI/dt currents were selected, assessed and characterised. Associated software to capture, analyse and visualise the digitised waveform data was written and tested.

A selection of mass-market electrical appliances were identified and purchased on the basis of their potential to cause fast changing current waveforms. Such waveforms are caused by power electronics such as those used in motor speed controls or power convertors. Examples of selected appliances include smart fridge, vacuum cleaner, food blender, solar invertor, speed-controlled pump, electric drill, direct drive washing machine, smart TV, a selection of energy saving lamps.

Measurements to digitise the current waveforms from these appliances in the laboratory were made on this collection of appliances and the digitised waveform data has been stored in data files.

Contacts with utilities, industrial companies and authorities were made to organise on-site measurements at MSPs to capture the current waveforms that meters are exposed to in domestic and industrial premises around Europe. Data from these on-site measurements of the type which is thought to cause meter errors was used to test meters and those waveforms that caused significant meter errors were then selected as candidate test waveforms.

Work to undertake a root cause analysis on the component parts of electricity meters was completed, this will be used to help manufacturers ensure future electricity meter designs can be made immune to EMI problems. Digital signal processing units used in electricity meters have been tested without transducers using small-signal versions of the captured waveforms, to see if they cause energy measurement errors. The processors are also be subjected to wideband sweep signal testing to check for signal processing related errors such as aliasing.

A collection of current transducers (CTs) typical of those used in meters were identified. These technologies include magnetic CT, Hall Effect, Rogowski coil and magneto-resistive. The CTs were subjected to fast edge current signal known to cause meter errors. The outputs of the CTs were examined for errors and malfunction and the results were used in the root cause analysis.

Algorithms to efficiently and accurately represent highly impulsive signals so that new test waveforms can be represented in international standards

Waveform recordings typically consist of 100's of thousands of data points which is inconvenient and impractical to write in aa documentary standard. Waveform transforms offer a means to reduce the amount of data yet maintain the accuracy of the waveform in so far that the waveforms continue to induce the same errors in some electricity meters.

Fourier transform methods are normally used to decompose waveforms into their different frequency components, however these transforms give errors when the waveforms are subject to the sporadic switching and variation as seen at real MSPs. Alternative transforms are required that can maintain the critical parts of the waveform so that the same meter errors are induced but with a significant reduction in the amount of waveform data.

The first method that was used is based on Wavelets which are a well-known method for analysing short-lived transient like signals. By using thresholding techniques commonly used in data compression, it was possible to represent and generate a test waveform to induce meter errors, but with much reduced waveform information using just a few percent of the original information. This is important because new test wave forms can be unambiguously specified in a highly efficient form, ideal for publication in future international standards.

A further technique based on the linear piecewise representation of waveforms also achieved a highly efficient specification of the error inducing waveforms. This technique breaks the waveform up into a series of linear sections, leading to a significant reduction in information, whilst still inducing meter errors. Again, this can be used to specify test waveforms in international standards.

These new waveforms representations were tested using test rigs (see below) with a series of meters and both methods were successful in inducing the same level of errors in the meters as the original waveform. Both methods are highly valuable for the efficient and accurate representation of long captured time series, suitable for accurate regeneration and inclusion in normative standards. The wavelet method offers more ability to trade-off accuracy against data size, but the piece-wise method is easier to understand so may be more universal for use in industry, and for this reason it was used to specify the final recommended waveforms.

New testbeds for MID meter type approval:

Currently testbeds sweep a single frequency tone to 150 kHz to test a meter response. Two designs of testbeds were developed, capable of accurately and repeatedly reproducing fast switching real world signals achieving an uncertainty of better than 0.1 %.

The first design essentially modifies the existing testbed design as specified in IEC61000-4-19, which mixes interference with the mains frequency waveform in a so-called "split-signal" method. The modification for this application generates and injects fast-edge current signals into the circuit such that they are superimposed on the sinewave current that is normally used in this test bed. The generated signals have a fixed and controllable alignment with the existing sinewave.

The second design uses an arbitrary waveform method where the digitised waveforms captured from appliances and real MSPs are loaded into the arbitrary waveform generator and are replayed to produce voltage signals that are then applied to current (transconductance) amplifiers. Current amplifiers with sufficient rise time to produce the required dI/dt levels were investigated and tested, resulting in the selection of a suitable amplifier. An optical isolation amplifier was developed which provides the necessary electrical separation of various parts of the test circuit, essential to protect personnel and equipment. The arbitrary waveform method also allows for the possibility to make small changes to waveforms known to cause meter errors, in order to investigate whether the meter errors are improved or worsened by certain changes to the waveform features. This waveform editing capabilities is closely linked with the waveform transform work described above.

In total, four independently designed and built testbeds were completed, two based on the split-signal method and two based on the arbitrary method. The four testbeds were found to induce similar meter errors when the testbeds were compared using a selection of “faulty” meters.

These testbed designs have been presented to standards committees and are available as the basis for future testbeds to be used in MID meter approvals.

One of the arbitrary testbeds was then be used to test a representative selection of 16 EU smart meters which were collected-together from manufacturers and electricity suppliers from around Europe. These meters were tested using regenerated versions of the captured waveforms and the magnitude of the errors assessed. This testing has essentially developed new prototype normative procedures for the future routine type-approval testing of meters in the presence of realistic interference. The results revealed metering errors in several models of meter when exposed to both appliance and on-site waveforms captured at real MSPs. The results have been presented to standard committees and are being considered in order to determine the scope and degree of the standardisation response.

Testing electricity meters and specifying “Benchmark” meters to settle customer billing disputes:
A so-called benchmark meter has been developed and its design published so that electricity supply utilities can use it to settle any customer disputes related to the billing accuracy of their installed electricity meter. The benchmark meter is portable and small so that it can be installed in confined spaces, connected in parallel with the customers meter and left in-situ for a prolonged period. The meter also records the waveforms, so that they can be used for further diagnostic investigations.

Impact
A kick-off workshop was held in the Netherlands attended by approximately 10 representatives of SDOs, manufacturers and utilities. The project team presented plans for the project and received suggestions and comments from the industry experts. A half-day midterm workshop was held at EMC Europe 2019 in Barcelona and was attended by over 30 people and the presentations are available here. The final workshop was held in April 2021 attended by some 70 people and the presentations are available here.

Throughout the project, presentations of the projects progress have been made to industry groups and national and international standards committees briefing members on the projects objectives and receiving feedback and suggestions from the industry experts. In the final month of the project, presentations of the final results were made to five different standards development organisations (SDO). This process will continue after the end of the project as discussion and debate for SDOs to decide how to act on the project’s final recommendations.

19 conference papers have been presented at several high profile international conferences including CPEM2018, + 2020, EMC Europe 2019,+ 2020 the International Conference on Renewable Energies and PQ 2019, and Applied Measurements for Power Systems (AMPS) 2019. 17 open access peer-reviewed publications have been published.

Impact on industrial and other user communities:
The 2017 worldwide media coverage suggesting that 200 million newly installed smart meters could be overbilling consumers has sent shockwaves through the electricity industry and consumer groups. This project

has developed new type-testing protocols that can be used to ensure all approved meters have sufficient immunity to interference present on the electricity grid. For consumers, this will restore confidence in metering. For utilities, interference immune benchmark meters are available to help them settle customer meter disputes and safeguard their reputation with their customers. Regulators and SDOs are charged with upholding the integrity of the MID and the results and recommendations of this project are now being used to inform the debate and clarify the details of the required standardisation response.

New testbeds for future MID testing using realistic waveforms are now available ready to implement future meter testing using the new protocols. Four NMIs now have the test beds and capability to undertake meter testing with the types of fast changing current waveform. This has advanced their capabilities in power and energy measurements and these NMIs are now able to offer contracted testing to meter manufacturers concerned about their meters and also to national regulators who might wish to conduct surveys of the meter types used in their countries. A new benchmark meter is also available, so that utilities can settle billing disputes with customers.

Meter manufacturers will also benefit from this evidence which will ensure that the MID mandates a proportionate response without unnecessary cost burden and develops appropriate protocols enforcing a level playing field for all manufacturers. The EU and national governments can be satisfied that new hardware, protocols and norms are now available to underpin the smart meter rollout.

The project has worked with utilities, regulatory authorities, meter and instrument manufactures and equipment manufacturers to ensure the project outputs are aligned with industries' needs and expectations. On-site measurements at MSPs have been carried out in participating counties and measurements have been carried out at industrial premises. Meter manufacturers and electricity supply authorities and regulators have worked with the project to provide a range of electricity meters used in several countries which have been tested using the new rigs and waveforms to gauge the levels of errors and develop new type testing procedures.

Impact on the metrology and scientific communities:

Just as sinewave power traceability required new norms and accuracy improvements over the past decades, accurate metering in the presence of complex waveform disturbances is the major issue for the metrological community with today's grid environment. The new type-approval testbeds and protocols developed in the project are available as a significant link in the revenue settlement chain which starts with traceability assured by NMIs and is implemented by notified body testing laboratories.

Advanced non-stationary waveform transforms have resulted from the project, which will have significant scientific impact both in terms of the application of mathematical techniques to electromagnetic interference (EMI) disturbance characterisation and the use of these advanced transforms in the metrological setting which includes the propagation of synthesis hardware imperfections, digitiser and transducer amplitude and phase responses through the transforms.

The legal metrology community WELMEC WG11 and OIML TC12 have been updated on progress at their annual meetings, in particular regarding the revision of R46: Electricity Meters. A final presentation of the project results and recommendations was given to both WELMEC and OIML in the final month of the project.

Impact on relevant standards:

New testbeds and protocols developed in the project are now available to underpin the MID mandated under EU directive 2014/32/EU which has been challenged by recent EMI issues with approved meters.

IEC TC13 WG11 oversees the norms related to meter testing such as IEC 50470-3. IEC SC77A is responsible for the norms that specify the testing methods which are called up by IEC TC13 norms. They oversee IEC 61000-4-19 which was recently modified to account for the 2 kHz to 150 kHz interference issue with meters. This norm will be targeted by this project for the inclusion of new protocols for meter testing to ensure future immunity to the problematic signals occurring on the grid. Members of the consortium have memberships and have maintained close links with these key committees and coordination groups such as the CEN-CENELEC-ETSI Coordination Group on Smart Meters which will ensure timely implementation of new normative protocols to quickly restore confidence in the MID. The final results and recommendations of the project were separately presented to IEC TC13 WG11 and CENELEC TC13 in the final month of the project and were communicated to IEC SC77A WG6 who take the lead from IEC TC13 on changes to standards related to metring.

At the conclusion of the project, a number of resources are ready to be included in amendments to standards. These include:

i) A set of recommended test waveforms based on real meter supply point waveforms.
ii) An efficient and accurate representation method to specify the recommended waveforms in standards.
iii) Two designs of testbed to generate the waveforms.
iv) Procedures to conduct meter testing.

In addition, evidence of testing 16 EU meters using the above resources is available to SDOs which shows problematic errors with some models of approved meters. This evidence will be used during further committee discussions scheduled with the project team after the end of the project when the standardisation response will continue to be debated and decided.

Longer-term economic, social and environmental impacts:
Different stakeholder groups have a strong economic interest in accurate metering assured by exacting but realistic norms. The impact on consumers is clear and obvious (overbilling). Meter manufacturers will get a level playing field enforcing realistic interference resilient design on all vendors. Energy suppliers will avoid reputational damage and costs; with each installation costing on average €220, the price of retrofitting 200 million meters will be tremendous. A proportionate and evidence-based response is now possible thanks to the meter tests carried out in this project and SDOs are debating the required action. By developing exacting but fair normative tests, the project has provided the tools to restore confidence without overburdening stakeholders with costs based on unnecessary restrictions.

Industry, Government regulators and the EU will be keen to address growing consumer concern over meter errors to prevent social consequences. For example, media stories about meter errors exacerbate mistrust in utilities and if consumers think they are being overcharged, some will shift to higher carbon fuel types such as gas. Other consumers will refuse to accept installations of new meters or will passively refuse meters by ignoring appointment letters. This will have cost implications for utilities who will still need to carry out meter readings on a piecemeal fashion.

The environmental impact of smart meters was a large part of the justification for the European mandate. Yet confidence and installation refusals will undermine the carbon-reduction benefits. If consumers lose trust in their meters, they will not trust time-of-use tariffs that encourage them to use energy when renewables are plentiful, they will not trust their in-home displays which are supposed to encourage the reduction of energy use. Refusers will not benefit from a smart meter's ability to meter excess home generated PV electricity for sale to the grid, and this will discourage the take up of distributed generation. If the tools developed in this project can restore confidence, issues with confidence and installation refusals can be mitigated.

List of publications

1 "Evaluation of EMI Effects on Static Electricity Meters", P.S. Wright; G. Rietveld; F. Leferink; H.E. van den Brom; F.R.I. Alonso; J.P. Braun; K. Ellingsberg; M. Pous; M. Svoboda, CPEM 2018, Paris, July 2018, DOI: 10.1109/CPEM.2018.8500945

2 "Faulty Readings of Static Energy Meters Caused by Conducted Electromagnetic Interference from a Water Pump", Bas ten Have, Tom Hartman, Niek Moonen, Cees Keyer and Frank Leferink, 17th International Conference on Renewable Energies and Power Quality (ICREPQ'19), Tenerife, Spain, 10th to 12th April, 2019, DOI: 10.24084/REPQI17.205.

3 "Detection Methods for Current Signals Causing Errors in Static Electricity Meters", Fani Barakou, Paul S. Wright, Helko E. van den Brom, Gertjan Kok, and Get Rietveld, 2019 International Symposium on Electromagnetic Compatibility - EMC EUROPE, DOI: 10.1109/EMCEurope.2019.8872120

4 "A Testbed for Static Electricity Meter Testing with Conducted EMI", H.E. van den Brom; Z. Marais; D. Hoogenboom; R. van Leeuwen; G. Rietveld, 2019 International Symposium on Electromagnetic Compatibility - EMC EUROPE, DOI: 10.1109/EMCEurope.2019.8872130

5 “Sensitivity of static energy meter reading errors to changes in non-sinusoidal load conditions”, Z. Marais; H.E. van den Brom; G. Rietveld; R. van Leeuwen; D. Hoogenboom; J. Rens, 2019 International Symposium on Electromagnetic Compatibility - EMC EUROPE, DOI: 10.1109/EMCEurope.2019.8872006

6 “Current waveforms of household appliances for advanced meter testing”, Ronald van Leeuwen; Helko van den Brom; Dennis Hoogenboom; Gertjan Kok; Gert Rietveld, Applied Measurements in Power Systems, DOI: 10.1109/AMPS.2019.8897771

7 “On-site Waveform Characterization at Static Meters Loaded with Electrical Vehicle Chargers”, Tom Hartman, Marc Pous, Marco A. Azpúrua, Ferran Silva and Frank Leferink, 2019 International Symposium on Electromagnetic Compatibility - EMC EUROPE, DOI: 10.1109/EMCEurope.2019.8871469

8 “Misreadings of Static Energy Meters due to Conducted EMI due to Fast Changing Current”, Bas ten Have, Tom Hartman, Niek Moonen and Frank Leferink, 2019 Joint International Symposium on Electromagnetic Compatibility, Sapporo and Asia-Pacific International Symposium on Electromagnetic Compatibility (EMC Sapporo/APEMC), DOI: 10.23919/EMCTokyo.2019.8893903

9 “Inclination of Fast Changing Currents Effect the Readings of Static Energy Meters”, Bas ten Have, Tom Hartman, Niek Moonen and Frank Leferink, 2019 International Symposium on Electromagnetic Compatibility – EMC EUROPE, DOI: 10.1109/EMCEurope.2019.8871982

10 “Why Frequency Domain Tests Like IEC 61000-4-19 Are Not Valid; a Call For Time Domain Testing”, Bas ten Have ; Tom Hartman ; Niek Moonen ; Frank Leferink, 2019 International Symposium on Electromagnetic Compatibility – EMC EUROPE, DOI: 10.1109/EMCEurope.2019.8872070

11 “Fast magnetic emission test for continuous measurements around an equipment under test”, Tom Hartman, Niek Moonen, Bas ten Have and Frank Leferink, 2019 ESA Workshop on Aerospace EMC (Aerospace EMC), DOI: 10.23919/AeroEMC.2019.8788950

12 B. t. Have, M. A. Azpúrua, M. Pous, F. Silva and F. Leferink, "On-Site Waveform Survey in LV Distribution Network using a Photovoltaic Installation," 2020 International Symposium on Electromagnetic Compatibility - EMC EUROPE, 2020, pp. 1-6, DOI:10.1109/EMCEUROPE48519.2020.9245831.

13 B. ten Have, T. Hartman, N. Moonen and F. Leferink, "Unfairly Faulty Energy Meter Reading due to Inappropriate Use of the Blondel Theorem," 2020 International Symposium on Electromagnetic Compatibility - EMC EUROPE, 2020, pp. 1-5, DOI: 10.1109/EMCEUROPE48519.2020.9245714.

14 B. t. Have, N. Moonen and F. Leferink, "Time Domain Analysis of Current Transducer Responses Using Impulsive Signals," in IEEE Letters on Electromagnetic Compatibility Practice and Applications, vol. 3, no. 1, pp. 19-23, March 2021, DOI: 10.1109/LEMCPA.2020.3031986.

15 B. t. Have et al., "Waveform Model to Characterize Time-Domain Pulses Resulting in EMI on Static Energy Meters," in IEEE Transactions on Electromagnetic Compatibility, DOI: 10.1109/TEMC.2021.3062948.

16 T. Hartman, R. Grootjans, N. Moonen and F. Leferink, "Time-Domain EMI Measurements using a Low Cost Digitizer to Optimize the Total Measurement Time for a Test Receiver," 2020 International Symposium on Electromagnetic Compatibility - EMC EUROPE, 2020, pp. 1-6, DOI: 10.1109/EMCEUROPE48519.2020.9245801.

17 J. Dijkstra, T. Hartman, N. Moonen and F. Leferink, "An AC Controlled-Current Load for Controllable Waveform Parameters to Quantify Static Energy Meter Errors," 2020 IEEE International Symposium on Electromagnetic Compatibility & Signal/Power Integrity (EMCSI), 2020, pp. 472-477, DOI: 10.1109/EMCSI38923.2020.9191617.

18 T. Hartman, N. Moonen and F. Leferink, "Direct Sampling in Multi-channel Synchronous TDEMI Measurements," 2018 IEEE 4th Global Electromagnetic Compatibility Conference (GEMCCON), 2018, pp. 1-5, DOI: 10.1109/GEMCCON.2018.8628576.

19 P. N. Davis and P. S. Wright, "Validating an Isolator to Eliminate Grounding Issues for High-Resolution Digitizer Measurements," in *IEEE Transactions on Instrumentation and Measurement*, vol. 70, pp. 1-8, 2021, Art no. 1502308, DOI: 10.1109/TIM.2020.3048517.

20 Helko van den Brom, Gert Rietveld, Dennis Hoogenboom, Ronald van Leeuwen, Zander Marais, Samriddh Sharma, Marijn van Veghel, “Towards improved standardization of electricity meter testing”, Proceedings of CPEM2020, DOI: 10.1109/CPEM49742.2020.9191719

21 T. Hartman, R. Grootjans, N. Moonen and F. Leferink, "Electromagnetic Compatible Energy Measurements Using the Orthogonality of Nonfundamental Power Components," in IEEE Transactions on Electromagnetic Compatibility, vol. 63, no. 2, pp. 598-605, April 2021, DOI: 10.1109/TEMC.2020.3019974.

22 Marais, Z., van den Brom, H.E., Kok, G. (VSL) and van Veghel, M.G.A. Reduction of Static Electricity Meter Errors by Broadband Compensation of Voltage and Current Channel Differences, DOI: 10.1109/TIM.2020.3039631

23 ten Have, B., Moonen, N. and Leferink, F. (University Twente, Enschede, the Netherlands), On-Site Efficiency Analysis of a Generator in the Millisecond Range, DOI: 10.1109/EMCSI38923.2020.9191607

24 B. t. Have et al., "Estimation of Static Energy Meter Interference in Waveforms Obtained in On-Site Scenarios," in IEEE Transactions on Electromagnetic Compatibility, doi: 10.1109/TEMC.2021.3089877

This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/

<table>
<tr><td colspan="2">Project start date and duration:</td><td>01 May 2018, 36 months</td></tr>
<tr><td colspan="3">Coordinator: Dr Paul Wright, NPL   Tel: +44 20 8943 6367   E-mail: paul.wright@npl.co.uk
Project website address: http://empir.npl.co.uk/meteremi/</td></tr>
<tr><td colspan="2">Chief Stakeholder Organisation: Netbeheer Nederland – Utilities Association for the Netherlands</td><td>Chief Stakeholder Contact: Janine Rumph</td></tr>
<tr><td>Internal Funded Partners:
1 NPL, United Kingdom
2 CMI, Czech Republic
3 JV, Norway
4 METAS, Switzerland
5 VSL, Netherlands</td><td>External Funded Partners:
6 UPC, Spain
7 UTwente, Netherlands</td><td>Unfunded Partners:</td></tr>
<tr><td colspan="3">RMG: -</td></tr>
</table>