# 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 will determine the extent of this problem by measuring the interference at a representative selection of meter installations and electrical products. Advanced digital signal processing methods will be developed to analyse the nature of these interference waveforms so that they can be accurately reproduced using new testbeds to assess the range of smart meters. These methods and apparatus will form the new type-approval tests and normative protocols to restore confidence in electricity metering.

## Need

With 200 million smart meters rolling out across Europe, the suggestion in recent studies of over-billing by some 500 % when meters are exposed to certain interference, threatens to undermine consumer confidence in this €45 billion EU mandated roll-out. This is 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 are 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 are needed to trigger its capture and to break the resulting waveforms into their constituent parts. This requires 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 must then 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 will require 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 are needed to resolve consumers billing disputes and can be selected from these tests.

## Objectives

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 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 will look to advance the current 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 will comprise of several advances, namely: digitising real world waveforms at Metered Supply Points (MSP), developing advanced digital signal processing (DSP) algorithms to accurately characterise complex, non-stationary waveforms, performing accurate synthesis of complex, non-stationary current signal 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 5$^{th}$ 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 will be accurately captured using high bandwidth sampling instruments and wide-band transducers. These waveforms will augment the present idealised MID tests.

A digitiser has been selected with sufficient bandwidth, resolution and accuracy to capture the sort of current waveforms that are thought to cause EMI issues with static electricity meters. It is a commercial device which has been tested, characterised and multiple units have been purchased by project partners so that they can be deployed in several on-site measurements at MSPs. Current probes or transducers with enough bandwidth and range to be capable of measuring the high dI/dt currents have been selected and have been assessed and characterised. Associated software to capture, analyse and visualise the digitised waveform data has been written and tested.

A selection of mass-market electrical appliances have been 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 have been made on this collection of appliance and the digitised waveform data has been stored in data files.

Contacts with utilities, industrial companies and authorities have been 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 have been stored for analysis.

Work to undertake a root cause analysis on the component parts of electricity meters has been 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. These results are now being analysed in advance of publication.

A collection of current transducers (CTs) typical of those used in meters have been identified. These technologies include magnetic CT, Hall Effect, Rogowski coil and magneto-resistive. The CTs are being 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 will be used in the root cause analysis.

*Algorithms to trigger capture and visualise events in the presence of highly implosive signals, and for the parsimonious specification of waveforms:*

Capturing sporadic events of interest at MSPs requires the collection and the time-consuming analysis of very large data sets. This makes site measurements difficult, as the investigator is not sure whether any signals of interest have been captured until off-line analysis has been completed. To avoid this, new triggering algorithms based on various methods (rate of change of current, Gaussian filtered dI/dt, wavelets with four different mother functions with various taps) have been developed and have been incorporated into software to detect, capture and visualise each event as used in the above site measurements at MSPs.

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. Building on the triggering algorithms described above, new transforms based on wavelets and time-frequency distributions have been developed and tested building on work in other fields of applied mathematics. Using thresholding techniques commonly used in data compression, it has been shown that it is possible to represent and generate a test waveform to induce meter errors, but with much reduced waveform information (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 achieves 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 are now being tested using test rigs (see below) with a series of meters to see if they induce the same level of errors as the original waveform.

Feature extraction methods as used in pattern recognition and machine learning are also being investigated as a means of finding the waveform features that cause meter errors. Alternative metrics are being used to categorise the waveforms using energy and entropy and find correlations of waveform features to meter errors. To perform well, these techniques require larger data sets which will be provided by the on-site measurements.

These new methods will lead to the efficient, yet accurate representation of long captured time series, suitable for accurate regeneration and inclusion in normative standards.

*New testbeds for MID meter type approval:*
Currently testbeds sweep a single frequency tone to 150 kHz to test a meter response. New testbeds are being developed, capable of accurately and repeatedly reproducing fast switching real world signals with a target uncertainty of 0.1 %. A specification for a new test bed has been agreed building on the normative specification published in IEC61000-4-19.

Where possible new testbeds will be achieved by modifying existing IEC61000-4-19 testbeds which mix interference with the mains frequency waveform in a so-called “split-signal” method, however signal alignment is critical to avoid distortion of fast edges. To do this, a system is being developed to generate a fast-edge current waveforms which will be injected into the circuit and superimposed on the sinewave current that is normally used in this test bed. The generated signals will have a fixed and controllable alignment with existing sinewave.

An arbitrary waveform method has been developed as an alternative testbed and compared to the split-signal method. The digitised waveforms captured from appliances and real MSPs are loaded into the arbitrary waveform generator and can be replayed to produce voltage signals that are applied to current (transconductance) amplifiers. Current amplifiers with sufficient rise time to produce the required dI/dt levels have been investigated and tested resulting in the selection of a suitable amplifier. An optical isolation amplifier has been 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 to investigate whether the errors are improved or worsened by certain changes to the waveform features. This waveform editing capabilities are closely linked with the waveform transform work described above.

These testbeds will form the basis for future testbeds to be used in MID meter approvals. The testbeds will then be used to test a representative selection of EU smart meters which is currently being collected-together from manufacturers and electricity suppliers. These meters will then be tested using regenerated versions of the captured waveforms and the level of errors assessed. The testing will lead to new normative procedures for the future routine type-approval testing of meters in the presence of realistic interference. The results will reveal the extent of metering errors and determine the scope and degree of the standardisation response.

*Testing electricity meters and specifying “Benchmark” meters to settle customer billing disputes:*

Having tested the European installed meters with realistic waveforms, a comparison table of meters will result from an ensemble of electricity meters from around Europe. This will reveal the extent of the problem and will be an important input to the decision whether to update the MID related normative standards.

Work in in progress to develop a benchmark meter that will be used by electricity supply utilities to settle any customer disputes related to the billing accuracy of their installed electricity meter. The benchmark meter must be 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.

Several benchmark meters approaches have been investigated and a solution based on a commercial power quality analyser suitably modified for this application has been selected. This selection was made based on a combination of accuracy, utility and being of compact size for meter enclosures. Work to modify the benchmark instrument including the provision of a safety enclosure with suitable safety connection terminals, has been completed. The remaining issue is selection and characterisation of current transducers of sufficient band width performance.

**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. The presentations are available here.

Several 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.

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.

*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 will develop new type-testing protocols that will 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 will be provided to help them settle customer meter disputes and safeguard their reputation with their customers. Regulators and standard development organisations (SDOs) are charged with upholding the integrity of the MID which is under debate now. This project will provide new evidence of the extent of meter errors when exposed to real-world interference. New testbeds for future MID testing using realistic waveforms will be available to quickly implement an evidence-based response through new protocols. 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 urgently require an early resolution to this issue and the new hardware, protocols and norms will underpin the smart meter rollout.

The project is working 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 are currently working with the project to provide a range of electricity meters used in several countries. These meters will be 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 will become 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 will result 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.

*Impact on relevant standards:*

New testbeds and protocols developed in the project will 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 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.

*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 will be assured by the meter tests carried out in this project, avoiding unnecessary replacement. By developing exacting but fair normative tests, the project will restore confidence without overburdening stakeholders with costs based on unnecessary restrictions.

Industry and Europe 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 on new meters or will passively refuse of 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 Europe 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 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

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