FINAL PUBLISHABLE REPORT

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RMG: -		

TABLE OF CONTENTS

1 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.

2 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.

3 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.

4 Results

4.1 Objective 1, the capture of waveforms suspected of disturbing and interfering with static electricity meters.

This objective aims to determine the nature of disturbing and interfering signals present in typical electricity networks in order to define the accuracy boundary conditions for meters during use. To this end measurements were made of the current waveforms of a selection of commercially available CE marked electrical appliances as well as a selection of real meter supply points at various partner countries.

4.1.1 Digitisation Measurement System

The purpose of this work was to provide and characterise metrology grade sampling digitisers and transducers with sufficient bandwidth and dynamic range to faithfully capture disturbing signals in the LV electricity grid. Software was also developed to visualise the signals in real-time and trigger the capture of waveforms of interest. This measurement system was then used to make field measurements to capture waveforms at real meter supply points as described in Section 4.1.3.

Digitiser

A specification and selection of the digitiser was carried out by UTwente.

A suitable digitiser should be able to sample waveforms related to the current at a meter connection point in the time domain. The digitiser should have a bandwidth up to 150 kHz, with a sampling rate of the order of 1 MS/s sufficient to capture fast current edges. Single and three-phase measurements are needed, so ≥4 channels for 3 currents and neutral are required. An input range of +/- 50 V allows voltage transducers with a 10:1 ratio can be used. The waveform should be captured with an amplitude accuracy of 5 % full scale.

This led to a selection by UTwente of a commercially available PC-based oscilloscope. At the time of selection (2018), suitable models were selected from the Picoscope™ range namely: 5444B/5444D, 2406B, 4824, the characteristics of these oscilloscopes are shown in Table 1.

Table 1, Characteristics of different models of Picoscope (as 2018).

Model	**Required Specification**	**2406B**	**4824**	**5444B/5444D**
Bandwidth	150 kHz	50 MHz	20 MHz	200 MHz
Accuracy	+/- 5%	+/- 1%	+/- 1%	+/- 0.5%
Input range	0-50 V	0-20 V	0-50 V	0-20 V
Sampling rate	1 MS/s	1 GS/s	80 MS/s	62.5 MS/s
Buffer memory	-	32 MS	256 MS	512 MS
Vertical resolution	8 bits	8 bits	12 bits	16 bits

Input channels	4	4	8	4
Dimensions (mm)	Small enough for a meter cabinet	130 x 104 x 18.8	190 x 170 x 40	190 x 170 x 40
Price	-	€509	€1955	€2325

Current Transducers

The current transducers (CTs) to be selected should be easy to connect in small working spaces and thus be flexible, due to space limitations in meter cupboards. The CTs should be non-invasive, such that the power does not need for installation. The selected CT should be capable of measuring currents up to 100 A peak, with a bandwidth from DC to 150kHz.

Based on these specifications, three different current transducers were tested by JV and UTwente for their frequency response and step response from fast current pulses. Following testing, the Power Electronic Measurements Ltd. PEM CWT3, a flexible Rogowski coil, was selected. This device has a bandwidth of 16MHz and can be used up to 600A. Its sensitivity is 10 mV/A, highly suitable for connection to the Picoscope digitizer.

Traceability

The frequency response of the CT was tested by JV and UTwente using a commercial calibrator suppling a Clarke-Hess transconductance amplifier. For the selected PEM CT, the response is flat within specification for the entire investigated frequency range.

In common with all Rogowski coils, the output stability of the PEM device is susceptible to position and rotation on the conductor, however this does not affect the frequency response or the ability to capture waveshapes.

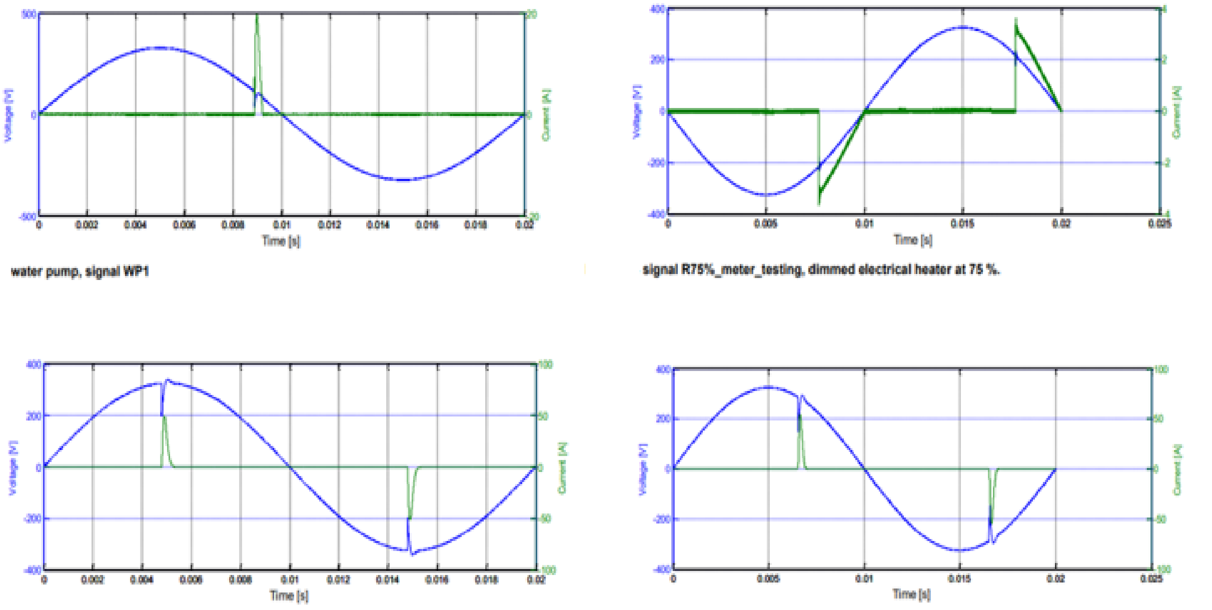
In order to test the response to fast current changes, the CTs were compared to a JV resistive current shunt directly connected to the current circuit. The current shunts have AC-DC differences below 20 ppm up to 100 kHz, and within 100 ppm up to 1 MHz, well within the accuracy range needed for the tests. A fast relay switch was used to switch the signal source of the amplifier from 50 Hz to 100 kHz, and the signals from the JV current shunt and the PEM were recorded using two channels of the Picoscope 5444D. Figure 5 shows the responses of the three CTs, compared to the JV reference current shunt. The response of the PEM followed that of the JV shunt within the required specification.

Based on these results, the PEM CT demonstrates both a fast step response to current pulses and has a flat frequency response in the frequency range of 10 Hz to 1 MHz, furthermore it delivers Type A uncertainty of 0.1%. It also allows easy connection to cables with space limitations due to its flexibility.

4.1.2 Capture of appliance waveforms in the laboratory

In an attempt to understand the type of waveform produced by consumer electrical products, a selection of commercially purchased appliances were tested by VSL in the laboratory and their current waveforms were measured. The appliances will be chosen for their potential to generate switching currents. Reference was also made to the technical report CLC/TR 50627:2015 which lists reported interference problems in the 2-150kHz range. The selected appliances are as follows: Laptop, PC + monitor, smart-TV, refrigerator + freezer, microwave, USB chargers, DVD players, Induction cooker, Blender, Vacuum cleaner, drilling machine, patio heater, Coffee machine, water pump, solar Inverter and lamps: CFL, LED.

This testing was carried out by VSL and the waveforms were captured using wideband current transducers and fast sampling equipment to record the current waveform time series. Four of the captured waveforms are shown in Figure 1. More captured waveform information is available at [1, 2] http://empir.npl.co.uk/meteremi/wp-content/uploads/sites/47/2019/11/Measurements-of-Appliances-in-the-lab-to-the-capture-waveforms.pdf



water pump, signal WP1

signal R75%_meter_testing, dimmed electrical heater at 75 %.

signal CL50%_meter_testing, Combination of multiple dimmed CFL and LED lamps, dimming lev 50 %.

Signal CL75%_meter_testing. Combination of multiple dimmed CLF and LED lamps, dimming level 75%.

Figure 1, Selection of waveforms captured from appliances

4.1.3 Capture of waveforms on-site at metering supply points

The impedance of the supply source will determine the shape of the current pulse induced by an appliance. For example, the source inductance will limit the rate at which the current can change and cause the rise time of the pulse to be reduced. So, it is important to examine waveforms at typical meter connection points in a variety of settings to observe the types of waveforms that meters are exposed to in the real world.

A total of 61 test sites in The Netherlands, Spain and Norway were identified and measurements were carried out by VSL, UTC, UTwente and JV where digitiser measing equipment described in Section 4.1.1 was installed at meter connection points to collect waveform data over a representative period of time depending on variable loading conditions. Sites include urban and rural domestic settings, PV installations and EV charging stations.

A total of 25717 different waveforms were captured at supply points and automated post-processing was used to select those waveforms which contained features associated with meter errors [3]. More information of site testing can be found at [4,5,6] and:

http://empir.npl.co.uk/meteremi/wp-content/uploads/sites/47/2021/04/02_MeterEMI_M36_workshop_-_Onsite_waveforms_UT1.pdf

A total of 74% of the waveforms contained features that have been related to meter errors. A total of 5 waveforms were selected for further testing as detailed in Section 4.4. An example of On-site test waveform #1 is shown in Figure 2.

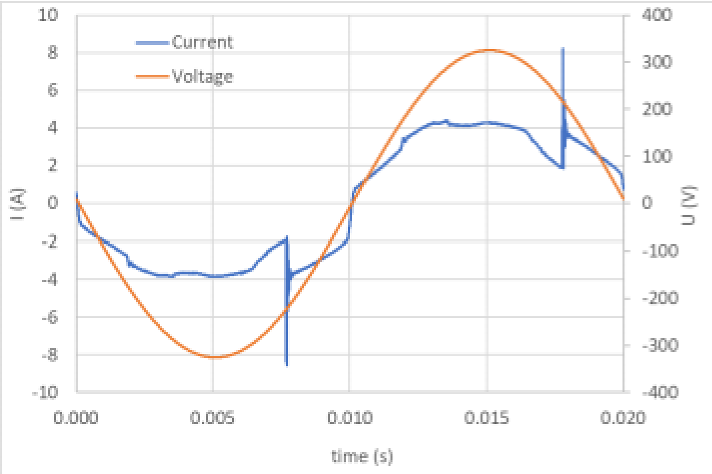


Figure 2, Onsite Waveform #1, voltage is a pure sinewave added to show level of distortion.

4.1.4 Summary

The work in this section has described the capture of disturbing and interfering signals and can be summarised as follows:

- An on-site waveform capture digitiser system was specified and charactered suitable for the capture of disturbances at real meter supply points.
- Recommended digitiser used at 1MS/s: Picoscope™ models: 5444B/5444D, 2406B.
- Rogowski coil CT was selected and characterised for frequency response and step change response. This device can be connected around “meter tails” to measure currents at typical supply points with interrupting the power.
- Recommended Rogowski coil: Power Electronic Measurements Ltd. PEM CWT3
- Current waveforms from 17 commercial domestic appliances were recorded in the laboratory.
- 25,717 current waveforms were recorded at 61 meter supply points in The Netherlands, Spain and Norway.
- Post processing was used to select the waveforms with the most potential to cause meter errors.

This work meets the requirement of the objective.

4.2 Objective 2, algorithms to specify test waveforms in an efficient and unambiguous way suitable for inclusion in an international standard

This objective aims to develop and test new waveform transforms and decomposition signal analysis techniques that can be used to efficiently and accurately represent the critical features of current waveforms that have been shown to cause errors in some electricity meters. These transforms essentially simplify the waveforms so that they can be written down with much reduced information, whilst maintaining the essential error inducing properties of the original waveforms. Two different approaches are described in the following sections.

4.2.1 Wavelet methods to specify waveforms

Wavelet transforms are a signal processing technique that are often used to represent and analyse complex waveforms, particularly those with discontinuities. The discrete wavelet transform (DWT) can be used to sparsely extract the dominant features of signals with highly impulsive characteristics, which have been linked to the occurrence of errors in static electricity meters. The discrete Fourier transform, which is the more conventionally used frequency analysis tool, produces broad spectra for these impulsive signals, making specification in terms of harmonic components impractical. In contrast, wavelet-based specification offers high rates of compression compared to the original time domain data.

Wavelet decomposition derives from the continuous wavelet transform, which is a mathematical operation that allows the representation of a signal as the combination of a basis of functions, obtained by shifting and scaling one fundamental function, called mother wavelet. The DWT is the digital equivalent, where the representation is given in terms of a set of coefficients (called the approximation and the detail coefficients), obtained through a series of digital filtering operations. These coefficients are representative of the frequency content of the original signal and of the time at which specific frequencies appear.

For a suitable choice of mother wavelet, the inverse discrete wavelet transform (IDWT) can perfectly reconstruct the original signal from the set of coefficients (energy is conserved). In this work [7] NPL utilised the useful property is that in the case of a very impulsive signal, the DWT coefficients are *sparse,* i.e., most of the coefficients have negligible amplitude, and the relevant signal information is concentrated in a few coefficients. This means that in the reconstruction process, only few coefficients can be defined, while the rest of them can be set to zero, and the reconstructed signal, although not exact, will be very accurate. This strategy is widely employed, e.g., in data compression applications, where the amount of stored data can be greatly reduced. Figure 3 illustrates the process developed by NPL.

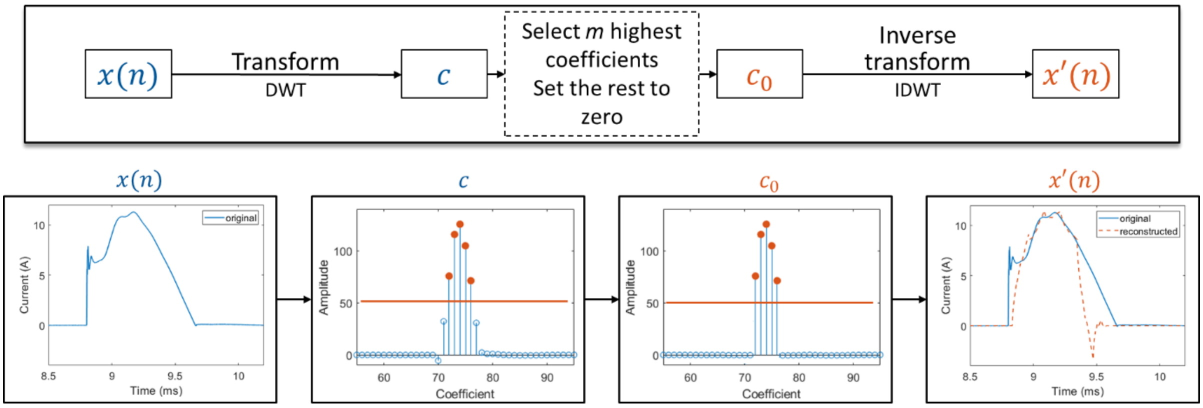


Figure 3, Wavelet-based feature extraction.

At the bottom of it can be seen in Figure 3 that the original waveform on the left is transformed to a modified version on the right, but only using 4 wavelet coefficients, a fraction of the original waveform data size. The optimisation required is to minimise the amount of coefficient whilst maintaining sufficient accuracy to reveal the meter errors. NPLs work showed that 20 wavelet coefficients were sufficient to represent the waveform with the required accuracy; a full power cycle at 1MS/s of a captured waveform can be generated using 20 wavelet coefficients as shown in Figure 4, along with the original measured signals.

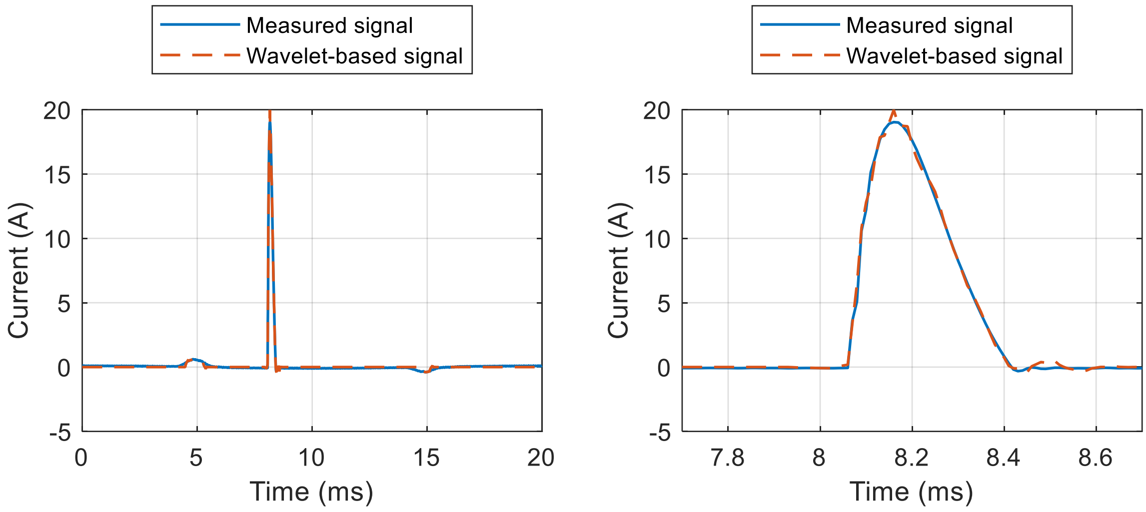


Figure 4, One entire power cycle (left) and the detail of the pulse (right) of a current waveform including the original signal measured from a specific water pump and its reconstruction from 20 wavelet coefficients.

When applied to a "faulty" electricity meter, the wavelet produced waveform gave the same result as the original waveform (1M samples), within the inherent variation of the electricity meter. This demonstrates that wavelet coefficients are highly suitable to represent complex waveforms in future normative standards. The disadvantage being that the underling maths is unfamiliar and quite difficult to quickly understand although pseudo code can be used to aid implementation by users.

4.2.2 Piece-wise linear methods to specify waveforms

As a more intuitive method to wavelets, artificial test waveforms can be represented by time-domain parameters. The time domain modelling of the interfering waveforms has the potential to reduce of complexity of data while preserving the relevant waveform features that are highly correlated to static energy meter errors. By complexity reduction, it is meant,

- **Data compression**: Time-domain modelled waveforms result in shape-preserving/parameter-preserving artificial test waveforms comprising a reduced number of change-points. Specifically, suitable artificial test waveforms comprise between 6 to 12 change-points.
- **Linearization:** Complex real-world waveforms are highly non-linear, therefore, defining a standard analytical expression for them is not a trivial problem. Through the algorithms proposed here, it is possible to segment those measured waveforms into optimal piecewise linear segments defined in between the changepoints. Therefore, the analytical expression of the artificial test waveforms simplifies to a linear combination of trapezoidal pulses.
- **Robust:** The interfering waveforms from a single source (appliance/site) are not exactly periodic and may be subject to jitter. Likewise, the on-site measurement dataset comprises noise and other superposed signals that make it more difficult to isolate the interfering waveforms. The developed time-domain modelling algorithm can detect the interfering events and extract their multiple occurrences in the recorded dataset. Then a unified representation of the interfering waveform is obtained considering the mean effect of all the detected occurrences.
- **Parametrisation:** Similar interfering waveforms will result in comparable metering errors. The similarity between the complex real-world waveforms and the artificial test waveforms is determined with regards to their critical parameters. Parameters such as the waveform charge (Q), maximum rising slope ($\Delta I/\Delta t$), crest factor (CF), peak current (I_{max}), duration ($t_{duration}$) and width (t_{width}) are considered. Since all the parameters mentioned before are defined in the time-domain, no domain transformation is required.

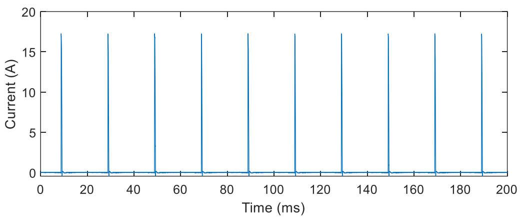
The complete details about this time-domain modelling approach and the measurement processing required to derive the proposed artificial test waveforms can be consulted in [8, 9]

To illustrate the time-domain modelling of complex real-world waveforms, a step-by-step example will be developed in Figure 5 below.

Step 1: Gathering the data.

Either measured from a single household appliance in laboratory conditions or the surveyed metered points, complex current waveforms are collected.

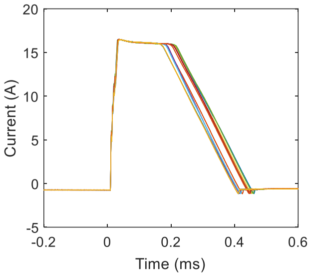
Impulsive type of waveforms triggers the acquisition.



Step 2: Extracting the current pulses

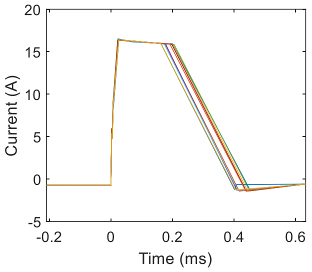
The different occurrences of the impulsive waveform are detected, segmented and aligned in time. The intervals without any relevant event can be discarded.

The similarity and differences in between waveform occurrences are observed at full detail.



Step 3: Linearizing individual waveforms

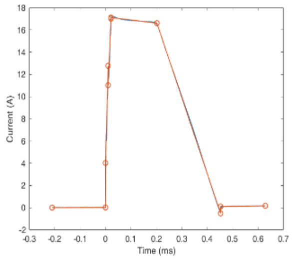
Optimal changepoints are calculated and, each instance of the current pulse is modelled using the piecewise linear approximation.



Step 4: Modelled waveform

The set of the piecewise linear approximations of the waveform occurrences are combined obtaining the mean position of each changepoint.

This process results in a shape-preserving modelled waveform.



Step 5: Parameter calculation

For each modelled waveform, its set of waveform parameter are calculated.

For those parameters that are highly correlated to the errors in the static meters, a critical range is defined.

Based on its parameters, an interpolation algorithm estimates the error caused by the modelled waveform.

Parameter	***Value***	***Critical range***
Charge	Q	4 - 8 mC
Max. rising slope	$\Delta I/\Delta t$	> 0.1 A/µs
Crest factor	CF	> 5
Peak current	I_{max}	N.A.
Duration	$t_{duration}$	0.2 – 1.2 ms
Pulse width	t_{width}	N.A.
Phase angle	PA	N.A.

Step 6: Trapezoidal waveform

A further simplified trapezoidal waveform is fitted to match the waveform parameter above using the minimum number of waveform features.

This final artificial waveform is said to be parameter preserving, and therefore, very similar regarding its impact in the metering errors.

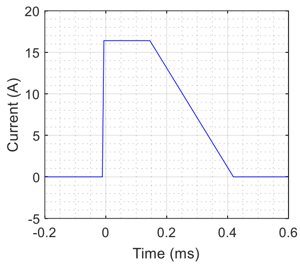
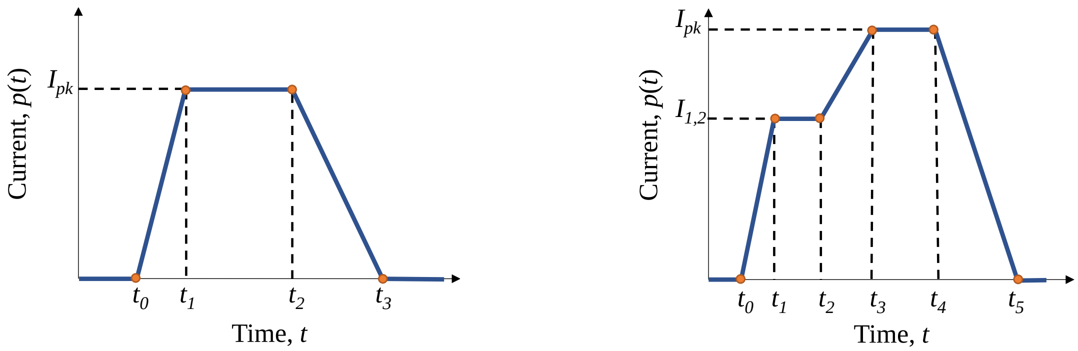


Figure 5, Trapezoidal waveform simplification process

Both, modelled and trapezoidal artificial waveforms could be used as test type waveforms for standardising purposes as both approximations result in similar metering errors for those static meters that are sensible to this kind of current pulses.

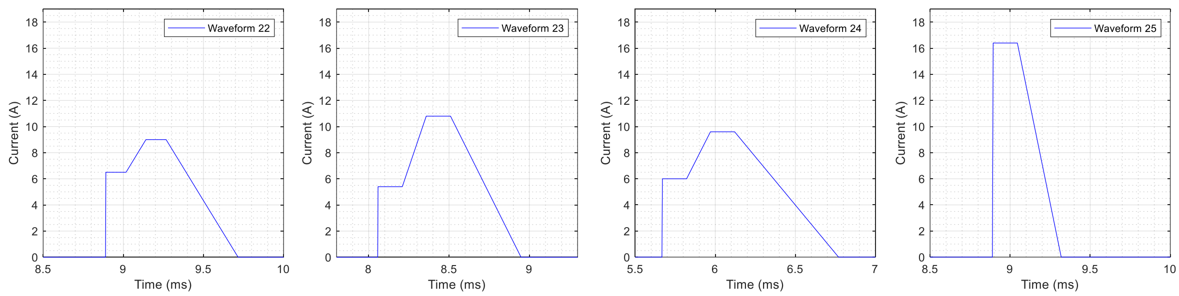
For simplicity, most test type waveforms can be reduced to the case of a single or double trapezoidal pulse shown in Figure 6Figure 5. In this case, it sufficient to specify the change-points as a series of (time, amplitude) pairs as in classical sampling.



a) Single trapezoid b) Double trapezoid

Figure 6, Specification of the single and double trapezoidal pulses as artificial test waveforms

Figure 7 shows four examples of candidate type test trapezoid waveforms based on the current drawn by a water pump at the conditions found to induce metering errors.



a) b) c) d)

Figure 7, Example trapezoidal waveforms based on a water pump signal, referred to as waveforms 22-25.

The waveform specification with regards to the changepoints is given in the table below.

Specification of waveforms 22-25.

Waveform	**I_{pk} (A)**	**$I_{1,2}$ (A)**	**$t_1 - t_0$ (µs)**	**$t_2 - t_1$ (µs)**	**$t_3 - t_2$ (µs)**	**$t_4 - t_3$ (µs)**	**$t_5 - t_4$ (µs)**
22	6.5	9	2.8	125	125	125	450
23	5.4	10.8	2.55	150	150	150	440
24	6	9.6	3.1	150	150	150	650
25	16.4	-	5.9	150	275	-	-

The waveform specification with regards to the time-domain parameters is given below.

Waveform parameter values for waveforms 22-25.

Waveform	*Q* (mC)	*CF*	*dI/dt* (A/us)	I_{pk} (A)	$t_{duration}$ (ms)	PA (degrees)
22	4.9	6.78	2.32	9	0.828	160
23	6.0	6.88	2.12	10.8	0.892	145
24	6.6	6.16	1.93	9.6	1.103	102
25	4.8	9.05	2.78	16.4	0.431	160

For the two parametrized waveforms representing the afore-mentioned water pump, a comparison was made between meter errors caused by the original waveforms and their modelled representation, using the VSL arbitrary-waveform testbed (See Section 4.3). The conclusion was that for all four waveforms investigated, the simplified versions caused similar errors on the “faulty” meters. This shows that the simplified waveforms can be used to efficiently specify test waveforms in a future international standard.

4.2.3 Summary

Two parsimonious methods are presented that are capable of a significant reduction in the data needed to accurately represent waveforms that can be used for electricity meter testing. In both cases, the simplified waveform gave similar errors on a “faulty” electricity meter compared with a similar test with the original recorded waveform that used 1M data points. The wavelet work is highly elegant and its level accuracy is readily set by varying the number of coefficient. The piece-wise linear method is highly intuitive and can be more readily understood and implemented. Either method could be used in future international standards to accurately specify waveforms with a few key parameters rather than producing tables with hundreds of thousands of data points.

This work meets the requirement of the objective.

4.3 Objective 3, laboratory testbeds for testing static electricity meters

Assuming there is a need to test the immunity of electricity meters to this type of fast rise time current, a suitable test bed is required for routine testing of new meter designs. Testbeds are used to generate current and voltage ac waveforms with a synchronised phase relationship for the type-approval testing of meters. The aim of this objective is develop and test suitable designs for future testbeds that can be used to type-approve electricity meters.

Existing MID approval testing in the EU consists of simple stationary waveforms mostly consisting of the fundamental components with limited low frequency harmonics as specified in IEC 62052-11 [10]. This standard outlines all the requirements a meter has to fulfil as well as the test methods used to demonstrate they have been achieved. Immunity testing to interference up to 150 kHz is already specified in IEC61000-4-19 [11] which specifies simple tests to inject swept and modulated tones and testing laboratories already have testbeds for this. The adequacy of these existing 4-19 tests has been called in to question by recent publications on meter errors. However, it is highly desirable to redeploy and many aspects of the existing apparatus as possible in new testbeds to save money for testing laboratories.

In order to develop new testbeds capable of testing using real-world signals, two different approaches have been pursued in this work; the first uses a split signal generation method (separately by METAS and CMI) similar to that specified and implemented for existing IEC61000-4-19 testing. The second method (separately pursued by VSL and NPL) uses an arbitrary waveform technique replaying complex waveforms using a digital-to-analogue convertor and transconductance amplifier. The “split signal” method has the advantage of using existing apparatus already used by testing laboratories, but the difficulty of synchronising the split signals makes this a high-risk approach. The “arbitrary waveform” method should produce better fidelity and accuracy but would require new investment by testing laboratories if it were adopted for normative testing.

Comparing two independent methods is a core principle of metrology and if the “split signal” method can be made to work, the “arbitrary waveform” method will be a key tool for verifying its performance. If the “split signal” method proves impractical, the “arbitrary waveform” method can be specified for future normative type testing. To make the comparison and to demonstrate the capabilities of the testbeds, a round robin comparison was performed using two meters that were shown to be particularly sensitive to the applied test waveforms.

4.3.1 Arbitrary waveform phantom power testbeds

To perform these measurements, the testbed generates a voltage and current signal which are both supplied to a static electricity meter separately. This ‘phantom power’ combination results in energy being registered by the static electricity meter. Through comparing the energy registered by the electricity meter to the energy measured by the testbed, the electricity metering errors, or in other words, the sensitivity of the static electricity meter to the applied disturbances is determined.

A diagram of the VSL testbed layout is shown in Figure 8. A step-up transformer added to the voltage amplifier provides isolation and increases the output voltage to the desired range. A linear wideband power amplifier in combination with a suitable load resistance, in this case 1.5 Ω, is used to generate the current signal. A wideband transconductance amplifier can also be used for this purpose. Both amplifier inputs are supplied by an arbitrary waveform generator with synchronized outputs.

The outputs of the voltage and current amplifiers are connected to the meter under test (MUT) in a phantom power configuration. Current connections are kept short to minimize inductance and the remaining reactance is compensated to achieve a bandwidth of at least 150 kHz. Note that voltage amplifier connections are reversed so that voltage is applied to the neutral connection of the MUT. This reversal is done for equipment safety and does not affect the MUT output. The voltage amplifier has a power rating capable of delivering the non-linear currents drawn by the internal power consumption of the static electricity meter without introducing significant distortion to the applied voltage signal.

A wideband precision voltage divider and a wideband AC/DC shunt measure the voltage and current applied to the MUT. Since the voltage supplied to the MUT is floating in this configuration, a digitizer capable of differential measurement is used to read out the transducers.

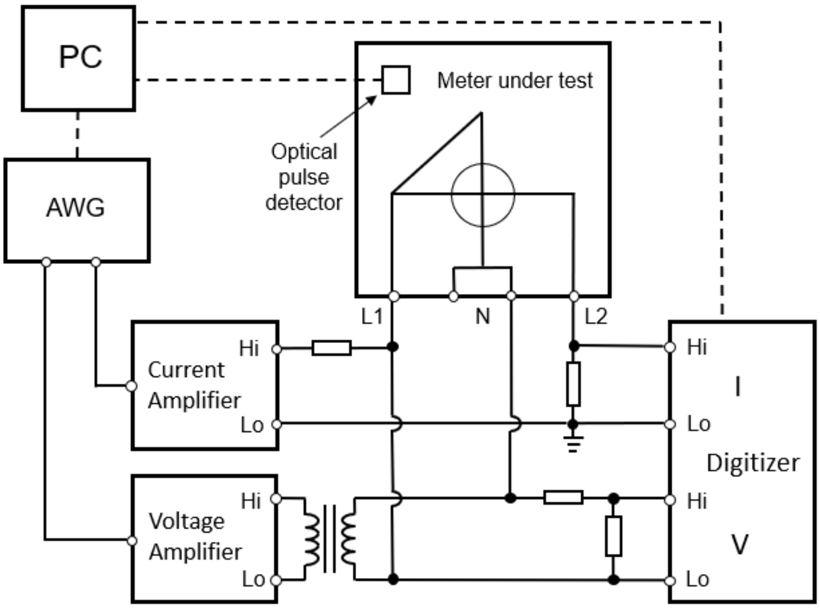


Figure 8, Schematic of the VSL arbitrary waveform testbed.

The product of voltage *V(t)* and current signal *I(t)* as function of time *t* is integrated over the time interval [T_1, T_2] between two or more adjacent optical output pulses emitted by the electricity meter under test is used to calculate the reference energy consumption E_{ref},

$$E_{\mathrm{ref}} = \int_{T_1}^{T_2} V(t) \cdot I(t)\, dt \; . \qquad (1)$$

An optical pulse sensor registers light pulses emitted by an LED on the static electricity meter under test. These light pulses correspond to a certain number of Wh units registered by the MUT. The metering error $\varepsilon_{\mathrm{MUT}}$ is then calculated as a percentage error by comparing the MUT registered energy E_{MUT} with the reference measured energy E_{ref} using the following equation:

$$\varepsilon_{\mathrm{MUT}} = \frac{E_{\mathrm{MUT}} - E_{\mathrm{ref}}}{E_{\mathrm{ref}}} \times 100\ \% \qquad (2)$$

The VSL testbed is capable of generating and measuring highly distorted arbitrary voltage and current waveforms with peak currents up to 50 A and containing frequency components up to 150 kHz. It can measure the active power with an uncertainty of 0.06 % for 50 Hz signals and a total uncertainty of 0.2 % for the worst-case relevant distorted signals larger than 20 W. Typically the uncertainty is within 0.1 % for most applicable waveforms investigated.

The test bed was validated by comparing the meter errors caused by the recorded and regenerated waveforms with the meter errors that occurred with the real loads. The table shows that the test bed agrees closely and within the standard deviation due to the variation of results on the meter, which after-all was not designed as a precision transfer standard.

METER READING ERRORS FOR DIFFERENT LOADS

Applied test signal	Power (W)	Real load MUT error (%)	Test Bed MUT error (%)
R0	798	0.4	0.4
R75	148	51	46
CL75	297	136	142
WP4	34	1257	1261
WP4-M	35	1947	2038
WP9	67	145	143

The NPL version of the arbitrary waveform testbed is quite similar to Figure 8. One of the main differences is that the isolation is achieved by use of an electronic switching isolator [12] . The switching capability is required to cancel out (to a first order approximation) the phase angles errors introduced by the isolators.
For the NPL testbed, phase angle between voltage and current is the dominant component which worsens at higher frequencies. The estimated uncertainty is 0.14 % at 20 kHz and 0.32 % at 150 kHz.

4.3.2 Split signal test beds

METAS and CMI both built split-signal testbeds which were essentially retro-fits to the already existing IEC 61000-4-19 test bed, by modifying it and adding components to it. The key components are missing from the existing test bench to achieve the desired reproducibility of the MeterEMI waveforms are as follows:

- The existing test bench lacks a synchronization between the clean 50 Hz and the perturbation signal
- The existing test bench error measurement is meant to measure the immunity of a meter to some perturbations. It is not meant to measure the power of the perturbation directly.
- The existing test bench is limited to 20 A in its perturbation generation.
- The existing test bench can only generate a sinusoidal perturbation on the current channel

To solve those limitations, the following modifications were done to the existing 61000-4-19 test bench:

- To synchronize the perturbations to the 50 Hz source, a Phase Locked Loop system was designed and implemented in Labview in order to issue a trigger signal to the waveform generator as well as the acquisition device.
- To measure the error based on the arbitrary waveform applied to the meter, the frequency of the pulses issued by the meter is measured with the use of a precise frequency counter. The current and voltage signals are acquired over one period with a PC based oscilloscope and then the power is calculated from the waveform with the use of a Matlab analysis. From there, it is trivial to compare the power to the meters frequency and obtain the error.
- To overcome the 20 A limitation of the previous system, a more powerful and precise transconductance amplifier was used.
- In order to reproduce accurately any waveform on the current perturbation of the test bed, an arbitrary waveform generator synchronized to the system was used to generate the specific waveforms for the test.

The complete block schematic of the system is represented in Figure 9 and the components specifications are reported in the table below.

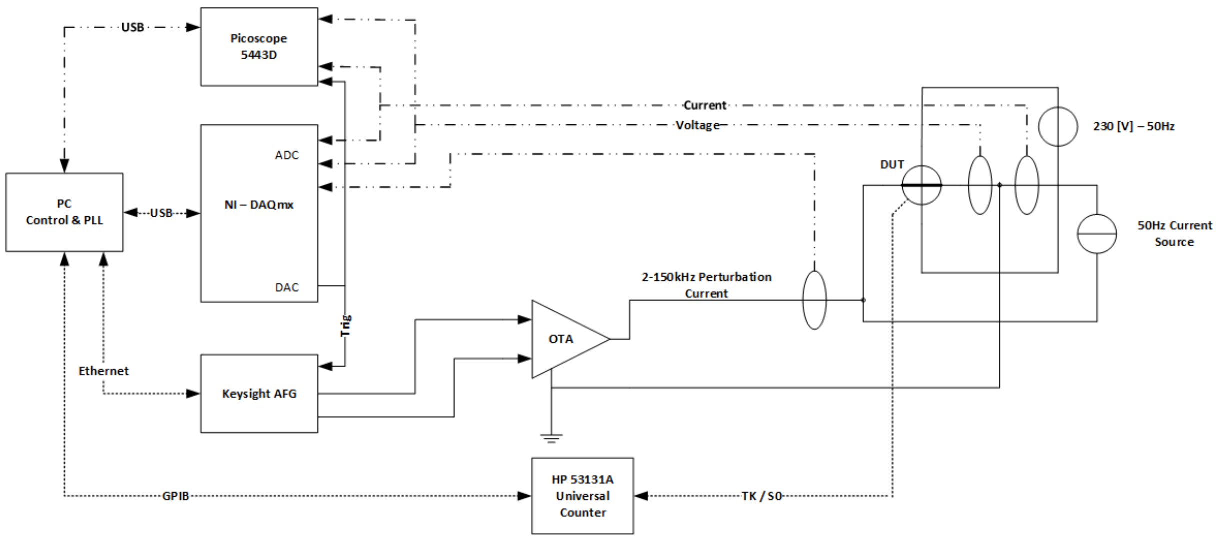


Figure 9, METAS Split Signal Testbed schematic

The 50 Hz voltage and current source used for the IEC 61000-4-19 test was also used in the MeterEMI split-signal test bed without the need to modify it. This source is a METAS custom made instruments capable of delivering up to 300 V and 50 A on three phases. It conveniently has isolation transformers on its output allowing the use of the transconductance amplifier on the current channel by bringing the phase to potential zero.

As the 50 Hz source does not offer any synchronization signal, an external triggering solution had to be built in order to fire precisely the arbitrary waveforms. This external synchronization system was essentially a classic Phase Locked Loop implementation which has proven to be very reliable to lock onto the voltage source frequency and bringing the trigger system to a near zero phase with the 50 Hz source. The jitter on the trigger signal was measured to be of approximately 3 mrad.

The perturbation source consists in a transconductance amplifier capable of delivering up to 100 A at 100 kHz fed by an arbitrary waveform signal loaded with signals defined for the MeterEMI project. The high current signal is connected to the meter under test without any risk of damaging the amplifier output stage with a high voltage because of the isolation transformers of the 50 Hz source

The CMI design has many similarities with the METAS split signal system. Current circuits and voltage circuits were power supplied from two electrically separated sources which in-turn both separated also from power supply mains. Voltage on the voltage circuits was 230 V (±2 %), current in the current circuit under test was defined by MeterEMI test waveforms which were generated by an arbitrary waveform generator (AWG) and amplified by a precision power amplifier. The generation of current is synchronised via the AWG with an additional channel of voltage source. Some limitations on the magnitude of the current pulses was caused by the limited range of the power amplifier.

The resulting phantom power was measured by commercial reference wattmeter. The magnitude of the disturbing current was measured using 1 Ω shunt resistor and sampling.

4.3.3 Comparison of Testbeds

To demonstrate the capabilities of the four testbeds, a round robin comparison was performed using two meters that were shown to be particularly sensitive to the applied test waveforms. The comparison was blind in the sense that the meters under test were sent around and the measurement results were not shared before presentation of the results.

The test current waveforms were recorded from household appliances in the laboratory as well as artificial waveforms based on recordings at real metering points in houses. The voltage waveforms used were sinusoidal. It turned out that the split signal method was unable to generate some of the very highest current peaks that were included in the recommended test waveforms, so a subset of the test waveforms were used in the comparison.

The results of the intercomparison showed good agreement between the four test beds in most cases within the combined measurement uncertainty. Where agreement was not reached, the cause was traced to unreliable output by the meter under test.

4.3.4 Summary

This objective was to provide possible designs of test bed to type approve meters using fast edge current waveforms. Two designs principles have been presents including development details. These designs compare well in an intercomparison, all cases revealing the gross errors that have occurred on some meters with this type of waveform. The split-signal design is convenient for test labs as in principle they can retrofit existing rigs, however it should be emphasised that the test waveforms as strongly non-linear as the ones presented here cannot easily be generated using the split-signal testbed due to the large broadband frequency contents, i.e., the sharp high-amplitude peaks without a clearly dominant fundamental component. Instead, an arbitrary waveform testbed using proper amplifiers and measurement equipment is preferred for some of the projects recommended test waveforms.

This work meets the requirement of the objective.

4.4 *Objective 4, methods to determine static meter errors*

This objective is concerned with demonstrating how the facilities and infrastructure developed in this project can be applied in practice to the testing of static electricity meters to determine their susceptibility to the sort of EMI that is the subject of recent problems with some makes of meter. This leads to the aim of this objective to develop methods that can be used to determine electricity meter errors.

This is mainly achieved by testing an ensemble of European meters using the projects recommended test waveforms, which were obtained from waveform recordings at real meter points in various countries as described in Objective 1, these waveforms were simplified using the methods developed in Objective 2, and generated using the test beds in Objective 3. So this objective brings together all the various strands of the project to demonstrate to standards committees how a future type-approval system could work and be implemented by testing laboratories.

4.4.1 Meter Test Waveforms.

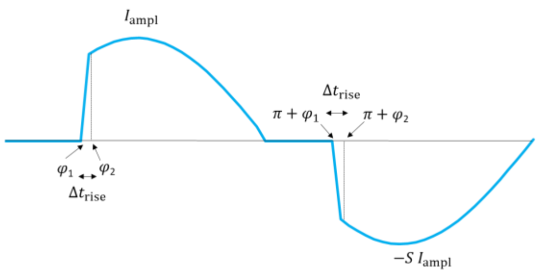
From the most error-inducing waveforms recorded when using individual household equipment, the typical patterns encountered were highly-peaked pulses and phase-fired sine waves. The most important parameter was found to be the current slope dI/dt, which should be at least 0.2 A/µs to be potentially harmful.

Waveforms recorded on-site have been obtained from several grid operators at more than 50 different metered supply points by VSL, UTwente, UTC and JV using the equipment developed in Objective 1. These waveforms have been analysed by VSL and typical patterns have been identified leading to “parameterised waveforms” with associated specific parameter values are suggested for meter testing. These parameterised waveforms are represented using the piece-wise method described in Section 4.2.2.

Many of the suggested waveforms have caused meter errors for some specific meters as demonstrated during investigations at VSL. For these investigations, 16 different static electricity meters were used, built by 10 different manufacturers, rolled-out in six different European countries between 2008 and 2019, and using the most common types of current sensors (Rogowski coil, Hall sensor, CT, shunt). From these meters, three turned out to be particularly sensitive to the applied disturbance signals. The following Figure 10 summarise these parameterised waveforms which are represented using the techniques described in Objective 2 in Section 4.2.2. Figure 10 also summarises the range of results that were obtained from the 16 tested electricity meters for each of the waveforms.

<table>
<tr><th>Parametrized Test Waveform</th><th>Proposed parameter values for testing meters and range of results found in the 16 tested meters for each waveform.</th></tr>
<tr><td>

<u>Phase-fired waveforms</u>



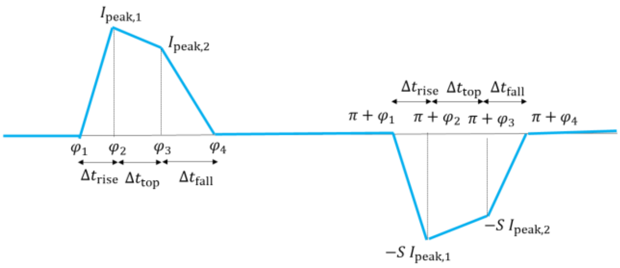
</td><td>

<table>
<tr><th>Parameter</th><th>Proposed parameter values for testing</th></tr>
<tr><td>φ_2</td><td>15°, 30°, 45°, ... , 90°, ... , 165°</td></tr>
<tr><td>I_{ampl}</td><td>10 A and 40 A</td></tr>
<tr><td>Δt_{rise}</td><td>10 µs</td></tr>
<tr><td>S</td><td>0 or 1, where $S = 0$ is suggested only in combination with $I_{\mathrm{ampl}} = 40$ A</td></tr>
</table>

Large errors of a few dozen to several hundred percent were found for three of the 16 meters investigated using these waveforms.

</td></tr>
</table>

Pulsed waveforms

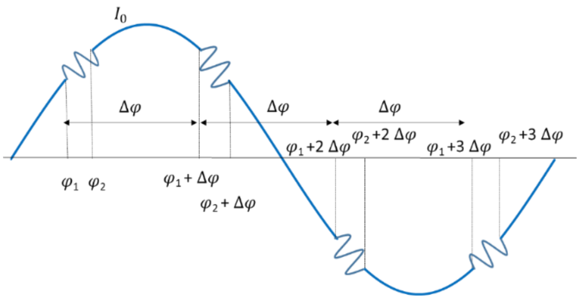


φ_2	15°, 45°, 90°, 135°, 165°
S	S = 1 for $\varphi_2 = 15°, 45°, 165°$, S = 0 for $\varphi_2 = 90°, 135°$

Parameter	TK1	TK2	TK3	TK4	TK5
$I_{\mathrm{peak,1}}$ [A]	50	50	13	25	7
$I_{\mathrm{peak,2}}$ [A]	50	10	25	21	7
Δt_{rise} [µs]	70	90	4	50	8
Δt_{top} [µs]	100	500	22	2	90
Δt_{fall} [µs]	300	5000	400	3000	180
Parameter	**TK6**	**TK7**	**TK8**	**TK9**	**TK10**
$I_{\mathrm{peak,1}}$ [A]	15	6	50	12	20
$I_{\mathrm{peak,2}}$ [A]	23	3	50	22	10
Δt_{rise} [µs]	1	2	66	12	4
Δt_{top} [µs]	2	4	300	110	8
Δt_{fall} [µs]	10	100	2000	360	200

Huge errors of a few dozen to several thousand percent were found for nine of the 16 meters investigated using these waveforms.

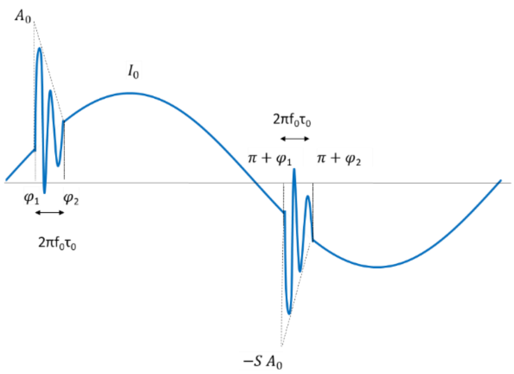
Bursts of Constant High-Frequency Ripple



Parameter	continuous ripple	bursts of ripple
I_0	0 A, 10 A	0 A, 1 A
φ_1	0°	0°
φ_2	360°	0.36°
$\Delta\varphi$	N.A.	0.90°
f_{HF}	20 kHz, 80 kHz, 150 kHz	20 kHz, 80 kHz, 150 kHz
I_{HF}	3 A and 6 A	2 A and 6 A

Errors of a few dozen percent were found for three of the 16 meters investigated using these waveforms.

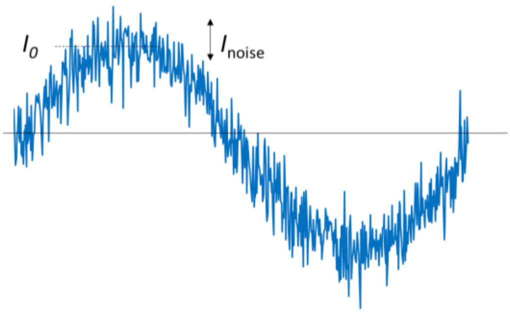
Decreasing High-Frequency Ripple



Parameter	Proposed parameter values for testing
I_0	0 A, 5 A
φ_1	15°, 45°, 90°, 135°, 165°
f_{HF}	60 kHz, 100 kHz
A_0	20 A
τ_0	50 µs
S	1

Minor errors below ten percent were found for three of the 16 meters investigated using these waveforms.

High-Amplitude Noise



Parameter	Proposed parameter values for testing
I_0	1 A, 10 A
I_{noise}	0.2 A, 0.5 A

Errors of a few dozen percent were found for one of the 16 meters investigated using these waveforms.

Figure 10, Recommended parametrised Test Waveforms

For the parametrised waveforms shown above, especially two parametrized waveforms representing the afore-mentioned water pump, a comparison was made between meter errors caused by the original waveforms and their modelled representation, using the VSL arbitrary-waveform testbed (Objective 3, Section 4.3.1). The conclusion was that for all four waveforms investigated, the simplified versions caused similar errors on "faulty meters". This shows that the simplified parameterised waveforms, are suitable candidates for improved standardization of type testing of electricity meters.

4.4.2 Benchmark Meter

The aim of the benchmark meters is that it should be immune to the above-mentioned test waveforms and other similar distorted signals. Benchmark meters are intended to be installed in parallel with the existing meter under dispute at metered supply points, such that the energy readings of the meter under dispute can be verified and the potentially harmful waveforms can be recorded. Two possible approaches have been investigated: one by UTwente based on an existing power quality analyser and one by VSL based on a digitizer with minicomputer and built-in data acquisition, storage, and analysis software. The power-quality-analyser-based instrument designed by University of Twente did not pass all tests, whereas the custom waveform recorder developed at VSL turned out to be successful and provides the most suitable candidate to be used as a benchmark meter in case of metering disputes.

The VSL custom benchmark meter has been developed based on a 3-phase waveform-capturing device that has been modified to function as a static electricity meter. This VSL-built electricity meter uses an 8-channel 16-bit digitizer unit with 1 MHz sampling rate, suitable for performing three-phase voltage and current measurements. Digitizer channels can be either DC or AC coupled, where AC coupling is performed by introducing a series capacitance of around 160 nF, introducing a high-pass filter with a lower cut-off frequency of about 1 Hz for low-impedance voltage sources. An on-board computer with dedicated software is used to process the measurement data, to apply filtering techniques to calculate the active energy and to store the corresponding voltage and current waveforms. Gain settings of the different channels are calibrated and corrected using the reference testbed. Trigger mechanisms are built in to record potentially harmful waveforms for further investigations later.

A photograph of the VSL benchmark meter is shown in Figure 11. Voltage measurements are performed using integrated high-ohmic capacitively-shunted resistive voltage dividers. The shunt capacitance put in parallel with the 10 MΩ input resistance of the divider is chosen such that the combination and the input impedance of the digitizer unit (which is also used as the output of the divider) leads to an almost flat frequency spectrum [13]. When using the digitizer in AC-coupling mode, the impedance of the corresponding coupling capacitor of around 160 nF is dominated by the divider high-ohmic input resistance of 10 MΩ for the lower frequencies. Consequently, due to the high input resistors the digitizer input is effectively DC coupled. The current is measured using a Rogowski coil with a high-pass lower cut-off frequency of 0.3 Hz and a bandwidth of 1 MHz. The Rogowski coil is suitable for recording current variations as fast as 30 A/μs.

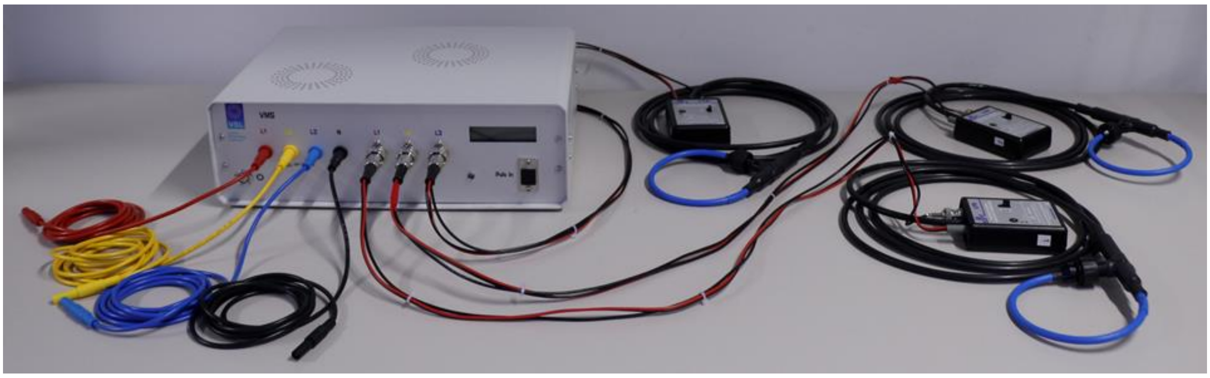


Figure 11, VSL benchmark meter and waveform recorder. The four voltage inputs (L1, L2, L3, N) are on the left, and the three current inputs on the right of that. The voltage signals are scaled down with internal voltage dividers. The high-precision current probes are shown on the right. The optical sensor for reading the pulse output of the electricity meter under test is not connected.

To compensate for the different transfer functions of the current and voltage input stages of static electricity meters, usually a time-shift correction is applied. This time-shift correction is suitable for sinusoidal signals with little distortion, but introduces misalignment of the high-frequency disturbances, and, consequently, miscalculations of the energy in equation (1) and hence metering errors in equation (2) for non-sinusoidal signals. For highly distorted waveforms, these miscalculations can in fact increase the reading errors rather than improve the energy readings. Therefore, two alternative methods have been investigated to avoid these errors and to correct the errors introduced by the time-shift method [13].

In the first method, the inverse-filtering method, the voltage and current channels' inverse transfer functions are implemented in the software to correct for their filtering behaviour. The inverse-filtering method was shown to be the most powerful leading to the best measurement results, especially when using lower-bandwidth voltage dividers. This method is rather computationally intensive, however, which makes it less suitable for simple implementation in electricity meters but might be beneficial in high-accuracy power meters or waveform recorders.

The second method, the equivalent-filtering method, instead, does not correct for the transfer functions but simply ensures that the voltage and current signals effectively propagate through equivalent input stages by implementing a digital filter in one of the channels, such that the instantaneous voltage and current values are properly multiplied in (1). The equivalent-filtering method showed very good results as well and was selected for use in our benchmark meter because of its simplicity and low computational burden. Note that because of the same reason this method might be a good candidate for implementation for instance in inexpensive electricity meters or less-accurate power meters as well.

The VSL-built benchmark meter is designed for an accuracy of 0.5 % for sinusoidal signals at 50 Hz and the target was to reach an accuracy of 2.0 % for highly-distorted waveforms that are known to cause metering errors in some specific static electricity meters. The benchmark meter has an optical pulse output that generates 1000 pulses per kWh as well and can therefore be investigated using a reference testbed that can generate and measure the requested voltage and current waveforms. The reference testbed has a bandwidth of approximately 150 kHz and is able to measure the waveforms with an uncertainty of less than 0.10 % with a 95 % confidence level (or 0.05 % standard uncertainty). Artificial waveforms as well as waveforms recorded for real loads were selected. The waveforms used for the validation include real-load waveforms, such as those caused by the earlier mentioned water pump as well as the artificial test waveforms reflecting critical parameters of those waveforms. From experience, the waveforms investigated here show some of the most deteriorating waveforms, with peak currents up to 55 A and maximum dI/dt up to 4 A/μs, and significant broadband frequency content up to around 50 kHz with crest factors up to 14, providing the largest error readings for electricity meters found so far.

Measurement errors of the benchmark meter used in AC coupling mode are determined for four different compensation methods: no correction, the time-shift correction, the inverse-filtering method, and the equivalent-filtering method. The results are presented in Figure 12 for waveforms that have been shown to cause huge meter errors for some other electricity meters. The time-shift correction seems to only improve the PF0.866 and R75 signals, which are the only two signals where the fundamental current is the dominant component, at a cost of decreased accuracy for the other signals which all have a more sharply-pulsed waveform. Obviously, the inverse-filtering method and the equivalent-filtering method provide results withing the target accuracy of 2 %.

TABLE I

METER ERRORS FOR THE VSL-BUILT BENCHMARK METER

Label	None	Time	Inverse	Equivalent
PF0.866	-2.3 %	0.2 %	0.2 %	0.1 %
R75	7.2 %	-0.6 %	-0.5 %	-0.7 %
CL75	2.4 %	10.6 %	0.0 %	-0.1 %
CL50	0.0 %	7.4 %	0.2 %	0.1 %
WP4	5.2 %	4.0 %	-1.2 %	-0.5 %
WP9	0.5 %	2.2 %	-0.5 %	-0.3 %
TK90	0.3 %	4.7 %	0.1 %	-0.1 %
TK135	5.0 %	7.0 %	-0.4 %	-0.3 %

TABLE II

EXPANDED UNCERTAINTY OF THE VSL-BUILT BENCHMARK METER FOR DIFFERENT COMPENSATION METHODS

Waveform	None	Time	Inverse	Equivalent
Sinusoidal	3.5 %	0.5 %	0.5 %	0.5 %
Highly-distorted	8.8 %	13.0 %	1.9 %	1.8 %

Figure 12, Testing the Benchmark Meter Design

4.4.3 Summary

A set of recommended test waveforms have been presented based on simplified parameterised current waveforms obtained from on-site recordings at seven real metered supply points, mainly at residential houses. The original waveforms have been obtained from grid operators and were selected from on-site recordings from over 50 metered supply points.

The waveform simplifications are such that the waveforms can be unambiguously and simply written in a documentary standard, whilst still exhibiting the same defining characteristics that give rise to gross errors in some meters. The simplification is based on linear piece-wise approximation which can be used to reconstruct the test waveform, so that it can be generated using an arbitrary-waveform testbed to test electricity-meter immunity to this type of disturbance.

SDOs are encouraged to update existing standards using the findings presented here. A decision on which waveforms to include is beyond the scope of this report.

A benchmark meter design by VSL was validated by measurements and an uncertainty calculation was compiled. It is concluded that the VSL-built digitizer-based waveform recorder modified to operate as an electricity meter, is immune to the investigated newly found distortion waveforms. It correctly determines the energy consumption to well within the uncertainty aim of 2 % for all waveforms investigated. Furthermore, it allows to record potentially harmful waveforms for further investigation afterwards. Therefore, it is very well suitable to serve as a benchmark electricity meter in case of disputes between energy providers and customers.

This work meets the requirement of the objective.

5 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.

6 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

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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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