Current waveforms of household appliances for advanced meter testing

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***Abstract*—Recent studies showed that static electricity meters can generate wrong metering results when exposed to conducted electromagnetic inference caused by electronic appliances, consisting of waveforms with very steep rising edges in combination with large peak amplitudes. To identify more waveforms that can cause errors, we captured a large series of waveforms of common household appliances, and after analyzing these waveforms we selected a number of waveforms for testing a static electricity meter.**

Keywords—Electromagnetic compatibility, static meters, interference, accuracy, testing, household appliances

I. INTRODUCTION

Throughout Europe traditional electromechanical electricity meters are being replaced by a new generation of static electricity meters. In total over 300 million electricity meters are replaced in Europe. It is therefore of importance that the static electricity meters are reliable and insensitive to interference.

Due to increased use of power electronics the amount of unwanted interference signals on the electricity grid increased. Previous research from the university of Kassel and university of Eindhoven already showed that single frequency high current tones in the 2 – 150 kHz range can cause metering errors [1,2]. Updated standards for testing static electricity meters now include tests that deal with these single frequency high current peaks [3].

More recent studies executed by the University of Twente and verified by VSL showed that electromagnetic interference caused by certain household appliances also cause metering errors, resulting in too high or too low registration of consumed energy [4,5]. In both studies a laboratory setup has been developed, based on commercially available dimmers, LED and CFL lamps and heaters, to generate these signals. The current waveform of these new interference signals is different than the signals found in the earlier work. These new interference signals are strongly-distorted waveforms in the time domain, characterised by very steep rising edges and high peak amplitudes. In the frequency domain, this results in a broad spectrum of higher harmonics starting at the 50 Hz fundamental mode and up to 2 – 50 kHz. These signals strongly differ from the earlier-found interference signals in the 2 – 150 kHz range. The questions that arise is how realistic and relevant these new signals generated by the laboratorium setups are, and whether there are other household appliances that can generate comparable signals.

Therefore, in this paper we would like to answer the following questions. How do the waveforms of modern household appliances look like, and are they comparable with the earlier found inference signals? Can the most disturbed waveform found in an actual household appliance generate metering errors? To answer these questions the following strategy is developed. With the help of a number of literature sources a selection of household appliances is made. From each of these household appliances the voltage and current waveform is measured. The gathered waveforms are then analysed by determining three parameters which give a good description of the waveforms causing metering errors at certain static electricity meters. After measuring the waveforms, a sensitive electricity meter will be tested with the household appliances which according to the earlier calculated parameters could generate metering errors. During these tests the metering error of the static meter will be determined. In the final part of the paper we further analyse the waveforms that caused metering errors in order to find a mechanism that causes the metering errors.

II. MEASUREMENT SETUP AND TEST METHOD

A. *Setup for capturing waveforms*

To avoid interference of other electronic equipment and to ensure reproducibility at a voltage of 230 V rms at 50 Hz, a separate power source is used. The output impedance of the power supply is verified to be comparable to the impedance of the mains socket in the laboratory. The technique to simultaneously measure voltage and current is used in recent work in testing of static electricity meters and is proven to be a reliable technique to capture waveforms [6-8].

The applied voltage over the household appliance under test is recorded by measuring the voltage between the phase and the neutral. A 150/1 voltage divider is used to scale the voltage down. A 50 mΩ current shunt is used to convert the current in a measurable voltage [8]. The voltage from both the voltage divider and the current shunt is digitized by a broadband synchronized 24-bit 2-channel ADC at a sampling rate of 1 MSa/s. For each waveform 10 cycles at 50 Hz are captured [9].

B. *Selection of test objects.*

For this series of tests, a selection of household appliances is made which can typically be found in a modern European household. The equipment is selected with the help of the equiPment hArmoNic DAtabase (PANDA) set up by the university of Dresden [10]. In this database a large collection of waveforms from household appliances are collected and analysed. With help of the database we selected a number of household appliances with high total harmonic distortion current (THDi). Electronic equipment with a high THDi are characterised by a strongly distorted waveform and are thus interesting for further analysis. Based on high THDi, two groups of electronic appliances are found in the database: LED and CFL lamps and small electronic devices (P < 50 W) with a switching power supply such as chargers for mobiles phones and other mobile devices.

Based on previous work [4,5] also electronic equipment, were electronic power is controlled with an electronic circuit such as a dimmer, is selected for the waveform capturing. Examples of appliances in this category are vacuum cleaners, kitchen appliances such as blenders, and electric power tools such as drilling machines. In total 29 pieces of electrical household appliances were selected for waveform capturing: three patio heaters, three electric drills, three vacuum cleaners, four blenders, three induction cookers, four USB-chargers, one water pump for pond applications, two wall mounted dimmers for lighting purposes, and an array of eight dimmable LED lamps. All appliances measured in this work claim to be in compliance with the present CE regulations on electromagnetic emissions.

C. *Test conditions for waveform capturing.*

All equipment is measured in a way that resembles normal operation.

The three heaters are measured at multiple modes of operation and the waveforms of each heater are captured after waiting a few minutes. In this time window the heater power consumption could stabilize.

The drills are measured at various settings of the output power and the revolutions per minute (rpm) by controlling the pressure on the trigger.

The vacuum cleaners are measured with an open hose and the hose closed. Two of the measured vacuum cleaners have the capability to control the output power of the vacuum pump. The test with open and closed hose entry is then repeated for various amounts of set power.

All measured blenders have the capability to set the output power/rotation speed. The current and voltage waveforms are captured for various rotation speeds.

The induction cookers are measured for various power settings while heating a pan filled with water.

The USB-chargers are measured with ohmic loads of 5 Ω, 2.5 Ω and 1.67 Ω, to simulate charging an electronic device. Some of the chargers can also be connected to multiple devices; these chargers are also tested with multiple ohmic loads.

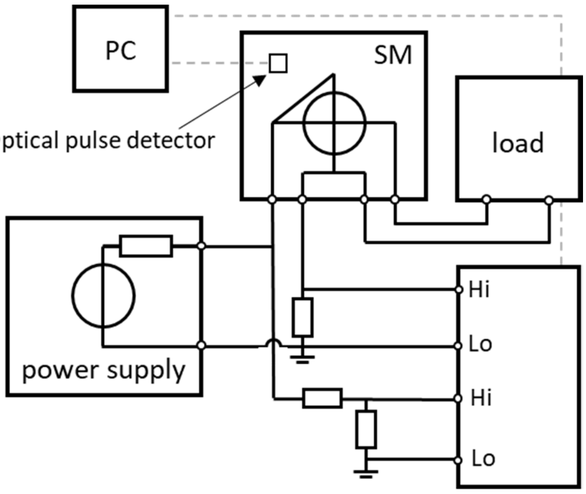

Figure 1. Schematic overview the setup used for test static electricity meters(SM) with a household appliance as load . The digitizer in combination with shunt for current measurement and the resistive divider for voltage measurements forms the reference electricity meter.

The water pump for outdoor pond applications is submersed in a container filled with water and measured on all possible settings of the corresponding external dimmer. A similar pump was recently also investigated at the university of Twente [11].

The dimmers are commercially available dimmers designed for installation inside walls. Both measured dimmers are designed for operation with dimmable LED lamps as load, and both have a maximum load capacity of 400 W. These dimmers are measured in combination with 8 dimmable LED lamps, with a power consumption of 1 W. The dimmable LED-lamps are also measured without the dimmers.

D. *Testing of electricity meters*

After recording the waveforms of the household appliances, a static electricity meter is tested with a selected number of these household appliances as load. The specific static electricity meter chosen for this test is one that proved to be sensitive for conducted electromagnetic interference such as those in previous studies [5,6]. The static electricity meters use a Rogowski coil as current sensing element. In the past, a test method has been developed at VSL to test static electricity meters on metering errors due to electronic equipment as load [5]. A schematic of the test setup can be found in Fig. 1. The voltage and current are measured by using the same voltage divider, current shunt and digitizer as used for capturing the waveforms. In the control software the energy consumption is calculated based on these values.

The energy reading of the static electricity meter under test (MUT) is determined by measuring the optical pulses emitted by the LED output. The time T between two or more adjacent pulses is used to calculate the reference energy from the measured voltage and current:

$$E_{ref}(T) = \int_0^T V(t) \cdot I(t) dt \tag{1}$$

The reference energy is then compared to the measured energy measured by the MUT, between the same adjacent

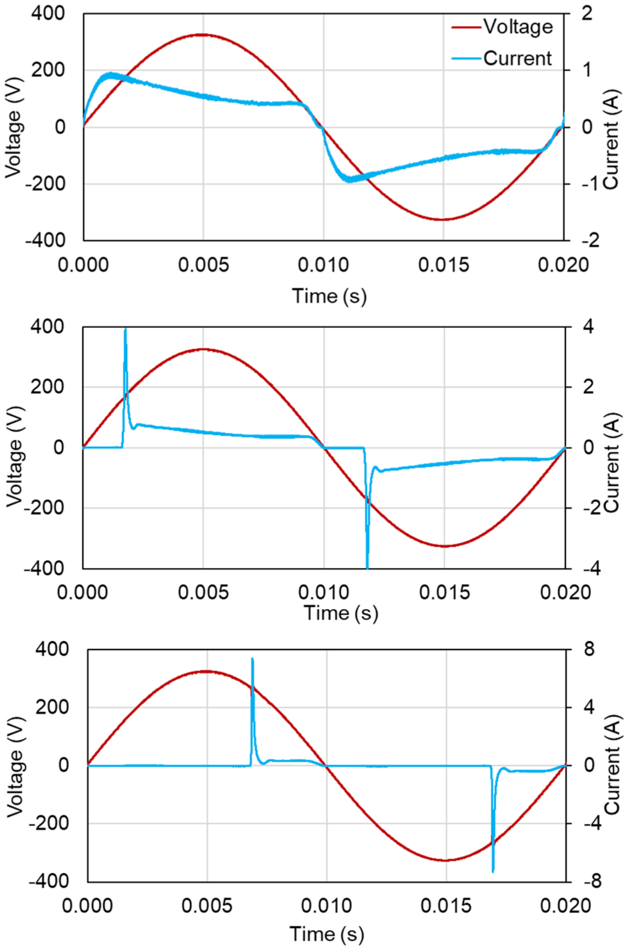

Figure 2. Measured waveforms for a wall mounted dimmer with eight dimmable LED lamps. The top panel shows the waveform when only the LED lamps without dimmer are connected (121 W *power consumption). The middle panel shows the lamps and dimmer in the lowest dimming mode (highest output power, 108* W*), the bottom panel shows the situation when the dimmer is set to the highest dimming mode (lowest output power 33* W*).*

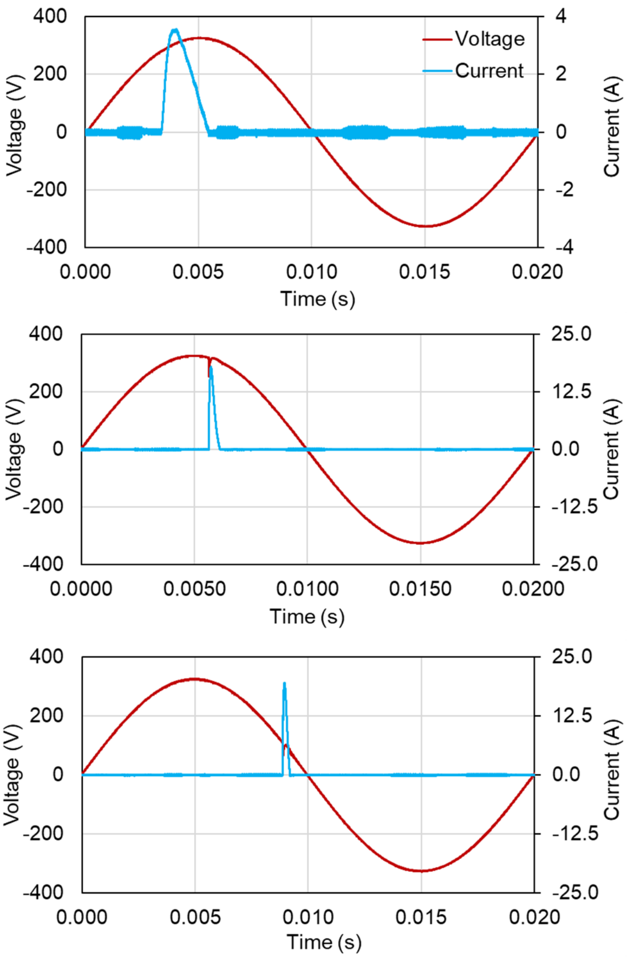

Figure 3. Measured waveforms for the water pump and dimmer. The top panel shows the waveform when the water pump is set to the highest setting (68 W *power consumption). The middle panel shows the waveform when the pump is set in the second highest setting and the bottom panel shows the measured waveform when the water pump is in the lowest setting (65* W *and 17* W *respectively).*

pulses. The energy corresponding to each emitted pulse is 2 W. The metering error of the meter under test is calculated with the formula:

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

The reference energy meter has an uncertainty smaller than 0.5 % for all tested signals and smaller than 0.02 % for 50 Hz sinusoidal signals [5].

III. MEASUREMENT RESULTS

A. *Categorising of measured waveforms*

A total of 161 waveforms are collected from the 29 selected household appliances. Examples of captured waveforms are shown in Fig. 2 and Fig. 3. Fig. 2 shows the measured waveforms of a wall-mounted dimmer in combination with an array of eight dimmable LED lamps for three different dimmer settings. The top panel of Fig. 2 shows the waveform of only the array of eight dimmable LED lamps The middle panel of Fig. 2 shows the measured waveform of the same array of the eight dimmable LED lamps in combination with a dimmer at a small phase firing angle (< 45°) resulting in an output power of 108 W. The bottom panel shows the measured waveform when the output power of the LED lamps is further reduced due to the dimming. Fig. 3 shows the measured waveforms of the water pump with dimmer, again for three different dimmer settings. Both figures show that the applied voltage does not change significantly with the applied load, whereas the measured current does vary significantly for each measured appliance and setting. Further analysis will therefore be focused on the measured current signals.

The interference signals found in earlier work [2,3] that causes metering errors are characterised by very steep rising edges and high peak amplitudes. Parameters that describe these parameters are the maximum amplitude, the maximum current derivative (maximum dI/dt), and the crest factor ($cf_I = \frac{I_{peak}}{I_{rms}}$). For all 161 measured waveforms these parameters are determined. Fig. 4 shows two graphs where the maximum dI/dt values are plotted versus the maximum peak amplitude and the crest factor, respectively.

The green triangles in these two graphs correspond to the waveforms, found in the earlier work by VSL [4,5], known to

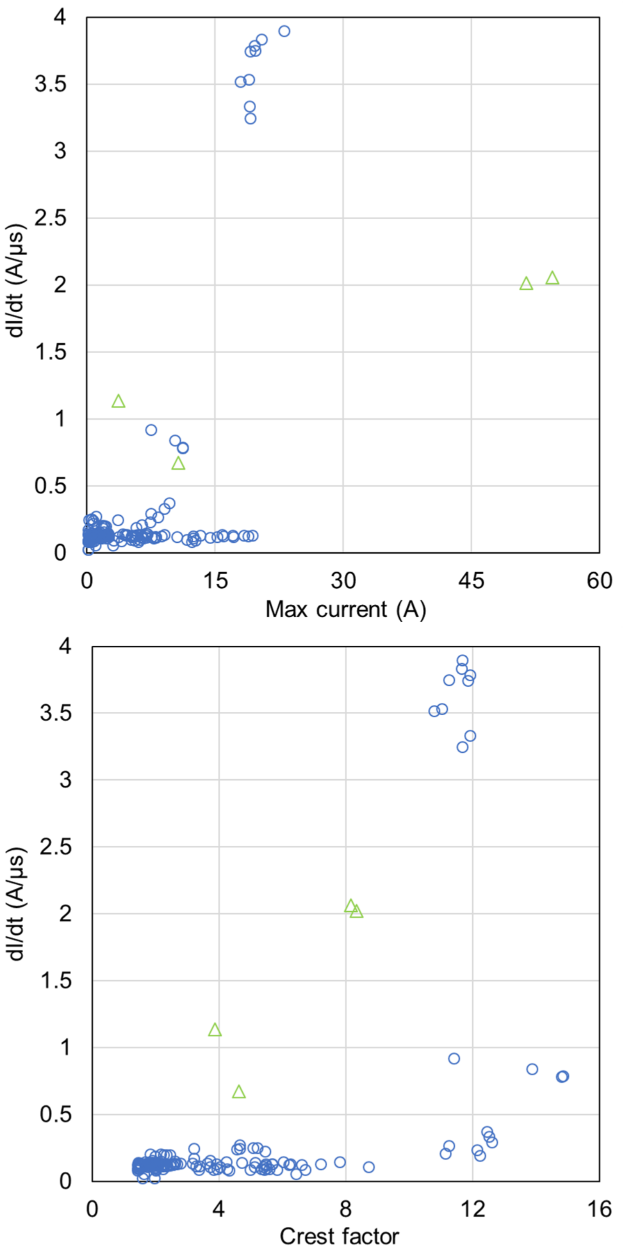

Figure 4. The maximum current derivative d*I*/d*t* *as a function of maximum current (top) and crest factor (bottom). The datapoints of the devices already tested in previous research and known to cause problems are indicated with the green triangles [4,5].*

Table 1. Metering reading deviation for a static electricity meter tested in combination with household appliances.

test setting	**Meter error**	
	[%]	**[W]**
only Dimmable LED lamps 121 W	0.2	0.0
Dimmer A at 33 W	45.4	15.0
50 W	120.2	60.1
65 W	25.4	16.5
90 W	-62.2	-56.0
108 W	0.5	0.5
Dimmer B at 71 W	-74	-52.5
78 W	-25.5	-19.9
90 W	16.5	14.9
100 W	-80	-80.0
Water pump with dimmer setting 10 (68 W)	1.2	0.8
Setting 9 (65 W)	139.9	90.9
Setting 1 (17 W)	2589.2	440.2

cause metering errors. The blue circles correspond to the waveforms measured in this work. Both graphs show that the waveforms known for causing metering errors have high maximum d*I*/d*t*, larger than 0.5 A/µs, and in two cases high peak amplitudes up to 51 A. Another point that can be noticed is that the majority of measured household appliances have a maximum d*I*/d*t* smaller then 0.25 A/µs, a peak amplitude not higher than 20 A and a crest factor smaller than 8. A number of datapoints can be identified that have a higher maximum d*I*/d*t* and crest factor. The highest maximum d*I*/d*t* found is 3.9 A/µs and corresponds to the waveform measured when running the water pump. The other household appliances that generate high peak amplitude, maximum *dI/dt,* and crest factor are the two dimmers in combination with the dimmable LED lamps. The waveform of the measured dimmers with LED lamps shows very high crest factors, of more than 10, indicating very narrow peaks.

B. Testing a static electricity meter

As a demonstration of the effect of highly distorted waveforms caused by household equipment, in the next part of this work a sensitive static meter will be tested with appliances that have a maximum d*I*/d*t* > 0.25 and a crest factor > 10. During these tests, the metering error of the static electricity meter is measured with these appliances as load. The static electricity meter selected for the next series of tests can be found in European households and is compliant with the MID and relevant EN standards but has been proven to be very sensitive for conducted electromagnetic interference signals resulting in significant metering errors [5].

In the first test, the metering error of the static electricity meter is determined with an array of eight dimmable LED lamps as load. Although this appliance has only a peak amplitude of 1.0 A and a maximum dI/dt of 0.06 A/µs this combination is interesting because it will also function as load in combination with a wall-mounted dimmer in two other tests. In the second test and third test the static electricity meter is loaded with a wall-mounted dimmer and the array of dimmable LED lamps. The static electricity meter is tested with two different dimmers from different manufacturers. In both tests, the metering error is determined for multiple settings of the dimmer. In the fourth test, the static electricity meter is tested with the water pump and dimmer as load. Also in this series of tests the metering error is determined for various settings.

The measured metering errors can be found in Table 1 for the various test settings. The table shows that all tested appliances except the array of LED lamps cause metering errors for at least one or more dimmer settings. In Fig. 5 the parameters characterising the waveforms used in testing the static electricity meter are plotted. The figure shows that the

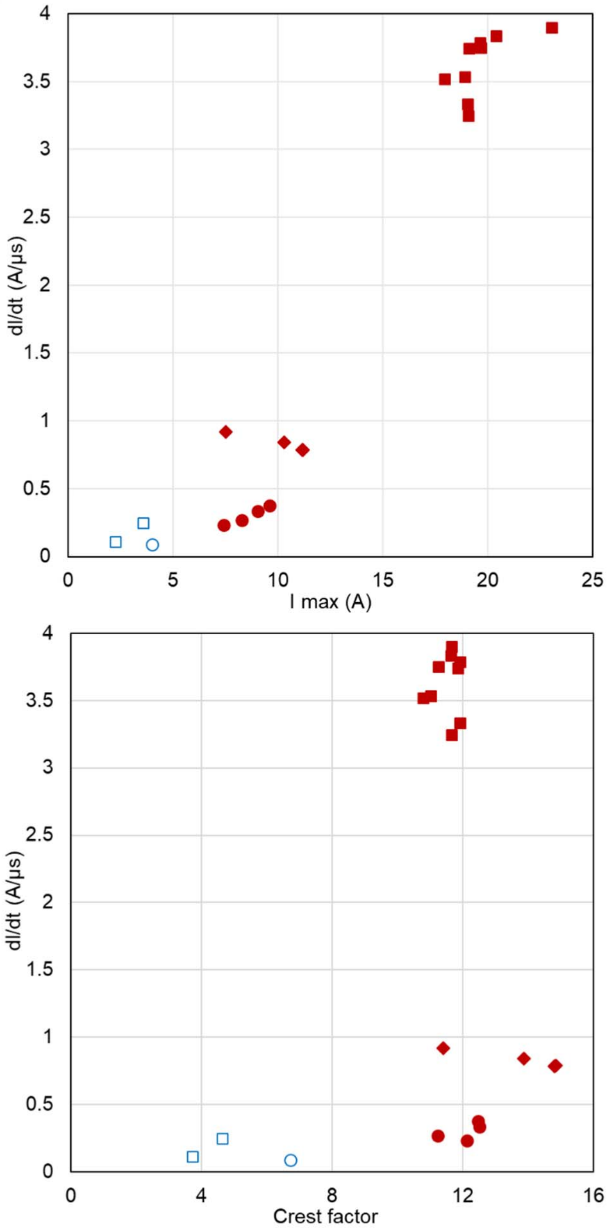

Figure 5. The maximum current derivative dI/dt *as a function of maximum current (top) and crest factor (bottom), for the appliances used as load for testing the static meter. The solid symbols correspond to the waveforms causing metering errors, and the open symbols when no error has been measured.. Squares represent the water pump with dimmer. The circles represent the first model wall mounted dimmer with 8 dimmable lamps. The diamonds represent the second type of wall mounted dimmer with 8 dimmable lamps, from a different manufacturer.*

lowest maximum dI/dt that causes metering errors is 0.25 A/µs, which is measured for one of the combinations of dimmer and dimmable LED lamps. The highest value for the maximum dI/dt is found for the water pump for pond applications in combination with a dimmer. Here, the dimming causes peak amplitudes as high as 23 A and a high maximum dI/dt of 3.9 A/µs, although power consumption is relatively low: 68 W at maximum pumping speed and 17 W at minimum pumping speed. The high peak current, high maximum dI/dt and low power consumption result in high metering errors, as can be seen in Table 1.

IV. DISCUSSION

In all cases observed in this survey the appliances causing metering errors are combinations of electrical appliances with a dimmer to control the amount of power. Electric dimmers often contain an electric circuit with a thyristor. The operating principle of a dimmer is based on controlling the phase-firing angle, this is the point where the thyristor in the dimmer starts conducting current. For undimmed LED lamps the current load is smooth over the entire period, without major peaks or rapid increases in current, as can be seen in the top panel of Fig. 2. When a dimmer is inserted, a peak appears at the beginning of the curve as can be seen in the middle panel of Fig. 2. This is the point where the thyristor in the dimmer starts to conduct current. When the phase firing angle is further increased (> 90°) the current peak shifts further to the right and becomes larger, as can be seen in the waveforms in the bottom panel of Fig. 2. From this figure it can be concluded that the dimmer forces the current load, intrinsically spread out over the whole period, to concentrate in a very narrow peak at the point where the thyristor in the dimmer is switched from non-conductive to conductive state. This peak, dependent on the connected load, can result in metering errors when the slope is steep enough and a certain peak amplitude value is reached. A maximum dI/dt of 0.23 A/µs combined with a peak amplitude of 7.4 A is already enough to cause metering errors.

Similar behaviour can be observed for the water pump in combination with the dimmer to control the flowrate, as can be seen in Fig. 3. The top panel of Fig. 3 shows undimmed operation. This mode of operation will not result in an error on the tested meter. The middle panel of Fig. 3 shows the measured waveform when the pump power is reduced by 1 step to 65 W. This results in a substantially different current waveform. In the figure it is visible that the peak becomes narrower, and the maximum amplitude rises to a value of 18 A. Also the rising edge becomes much steeper and reaches values up to 3.5 A/µs. This measured waveform will cause metering errors on the tested meter. The bottom panel of Fig. 3 shows the measured waveform when the pumping speed is further reduced to the lowest possible setting, using only 17 W. In this panel it becomes visible that the peak is shifted further to the right relative to the voltage curve without a change in peak shape or amplitude. Also, this waveform results in meter errors for this tested meter. The combination of this specific water pump and dimmer for pond applications is in a later stage withdrawn from the consumer market because of a violation in EMC standards.

V. CONCLUSION

In this paper, the current waveforms of 29 household appliances are presented. The obtained waveforms are analyzed by determining the maximum amplitude, the maximum derivative dI/dt and the crest factor. With these three parameters we identified the waveforms that are most likely to cause metering errors in some static electricity meters. A total of three household appliances has been identified with substantially higher maximum dI/dt, peak amplitude and crest factor than the majority of the measured equipment. As a demonstration, in a next series of measurements these three appliances were used as load for the testing of a static electricity meter that is known to be sensitive to high distortions from earlier work [5]. For this meter we found that all three household appliances cause metering errors in one or more modes of operation. All three appliances are characterized by the fact that a dimmer is used to control the output power of the connected load.

For future work also electromagnetic interference of PV-inverters, EV-charges and air conditioners on static electricity meters will further been investigated. The results obtained in this survey can be used in a later stage as input for new test signals for type testing and for updating test standards for testing static electricity meters [3,12].

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