Practical Papers, Articles and Application Notes

Kye Yak See, Technical Editor

In the smart grid era, conventional electromechanical meters will be replaced by electronic energy meters. There are concerns from consumers on potential electromagnetic interference (EMI) that may affect the accuracy of readings taken from these electronic energy meters. Frank Leferink and Cees Keyer from University of Twente and Anton Melentjev from University of Applied Sciences Amsterdam, the Netherlands have performed an investigative study on possible reading errors taken from these meters based on controlled laboratory experiments. The experimental results are presented in the first paper, "Static Energy Meter Errors Caused by Conducted Electromagnetic Interference". With more nonlinear and fast switching loads connected to the power grid, the types of current sensors used in electronic energy meters do have an impact on the variations in the meter readings. Such investigative study will be a useful reference for electronic energy meter manufacturers to improve the electromagnetic immunity of these meters.

The second paper "Characteristic Mode Analysis of Radiating Structures in Digital Systems" was contributed by Qi Wu, Heinz-Dietrich Brüns and Christian Schuster from Hamburg University of Technology, Germany. This paper adopts the characteristic mode analysis (CMA) to analyze radiating structures in digital systems up to 3 GHz. Through visualization of the CMA, it provides useful insight into the optimal placement of signal and power routing, grounding and placement of loads. Some examples presented in the paper show that a significant reduction of radiated power is achievable by using CMA and hence, illustrate its usefulness for EMC design of digital systems.

The third and last paper, "Comparison of Injected and Radiated EMC Testing of Active Implanted Cardiac Medical Devices at the Boundary Frequency of 450 MHz", is authored by Howard Bassen and Gonzalo Mendoza from U. S. Food and Drug Administration Center for Devices and Radiological Health. They compared testing via radiated versus injected susceptibility methods specified in the ISO 14117 standard for EMC of implantable cardiac medical devices. Experimental and computational studies were performed to determine voltages induced in a model of an implant. At the border frequency of 450 MHz separating the two methods, the radiated and injected tests do not agree well in terms of the voltage induced at the input of an implanted device. They present a very detailed study and analysis in this paper for the cause of disagreement.

As this is the last issue of the magazine in 2016, I would like to take this opportunity to wish all our readers a Happy New Year! I thank all the authors who have contributed the wonderful papers in 2016 and I look forward to receiving more good papers in the year ahead. Do drop me an e-mail at ekysee@ntu.edu.sg if you have a good paper in mind and would like to share it with our readers.

Static Energy Meter Errors Caused by Conducted Electromagnetic Interference

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Abstract - Static, or electronic, energy meters are replacing the conventional electromechanical meters. Consumers are sometimes complaining about higher energy readings and billing after the change to a static meter, but there is not a clear common or root cause at present. Electromagnetic interference has been observed between active infeed converters as used in photo-voltaic systems and static meters. Reducing the interference levels eliminated inaccurate reading in static meters. Several field investigations failed to identify a clear root cause of inaccurate readings of static energy meters. Experiments were performed in a controlled lab environment. Three-phase meters showed large deviations, even when supplied with an ideal sinusoidal voltage from a four-quadrant power amplifier. Large variations could be observed when non-linear, fast switching, loads were connected. A deviation of +276 % was measured with one static energy meter, +265% with a second and -46% with a third static energy meter. After dismantling it was revealed that the meters with the positive deviation used a Rogowski coil current sensor. The meter with a Hall effect-based current sensor gave the -46% deviation. The fourth meter, with a current transformer, resulted in -10% in one experiment and +8% in another experiment, where the deviations are with respect to a conventional electromechanical meter. Measurements were repeated with more meters and supplied from standard, low internal impedance, mains supply in the laboratory. Deviations of +475%, +566%, +569%, +581%, +582% and -31% and -32% were registered, with again the positive deviation for Rogowski coil current sensors and negative deviations for the Hall sensors.

Keywords: Electromagnetic Compatibility, Static Meter, Smart Meter, Electronic Meter, Interference

I. Introduction

Electromechanical energy meters with moving parts, based on the Ferraris principle, are rapidly being replaced by static, or electronic, energy meters. These static meters can also measure other electrical parameters such as phase voltages and currents, frequency, power factor, active, reactive and apparent power. By adding a communication link, either via a wireless interface, a data line, or through Power-Line Telecommunication (PLT), these static meters are also capable of transmitting measured data. The target is a rollout of at least 80% in Europe by 2020, with the aim to use energy data in a smart grid.

Some consumers are complaining about their energy bills after replacement of the energy meter, because the registered energy is higher with the static meter compared to the old Ferraris meter. The utility companies use the argument that the old meters were incorrect because of mechanical wear and consumers should be happy because they have been under-charged for many years.

Generation of energy through Photo-Voltaic (PV) installations has become very popular. Energy generated through the PV is fed into the power grid using Active Infeed Converters (AIC). The lack of proper Electromagnetic Interference (EMI) standards, especially in the range 2-150 kHz, created possibilities to generate high interference levels, causing EMI [1]. Two neighboring farmers using the same PV system observed that on sunny days one PV generated only 40% of the energy generated by the other. Measurements have been carried out and it was found that the power drive systems for the fans in the barn generated high conducted interference on the power lines. As a result, the static energy meter failed to register the actual value. The problem could be solved by replacing the power drive system [2]. A similar case was observed during experimentation with PV installations in Germany. In other cases high interference levels generated by AICs were also observed, which caused faulty readings of the static energy meters [3], [4], [5]. This observation, possibly combined with a higher number of complaints and failures, resulted in faster publication of the TR50579 [6] technical report and IEC 61000-4-19 standard [7]. Specifically the voltages generated by PLT and currents generated by other equipment connected to the grid are taken into account. These requirements can be considered as an extension for the EN 50470-1 [8] and EN 50470-3 [9], which were made in reply to the Measurement Instruments Directive (MID) [10]. The MID of 2004 has been superseded by the new MID [11]. The tests as described in [6] are developed to achieve immunity against disturbing currents between 2 kHz and 150 kHz. In [7] it is stated that in several cases electricity meters registered only a part of the energy factually fed into the public supply network from a PV inverter. The investigations showed that this malfunction was caused by the ripple current of the inverter in the frequency range 3 kHz to 150 kHz, stemming from the switching frequency of the inverter (several tens of kHz) and its harmonics.

After observing the PV interference as described above and in [2], and later replying to complaints and requests from consumers, several audits and field survey measurements have been performed by us to investigate possible interference causes of potentially faulty higher static energy meter readings. Investigations showed that no basic mistakes were made, such as incorrect readings or faulty connections, before experiments were conducted. No obvious cause was identified during field investigations, although the current consumed was often highly distorted, the energy consumption was highly unbalanced, and relatively high PLT signals were measured. To investigate the possible cause of EMI influencing the static energy meter reading, measurements were performed in a controlled laboratory environment on 1- and 3- phase meters.

II. Constraints

When a consumer makes a complaint about the meter reading, he/she can request re-calibration of the meter. If the meter performance falls within the specified values, the consumer has to pay for the re-calibration. Our research revealed, however, that calibration is carried out using an ideal sinusoidal voltage of 50 Hz, and a linear load. Only the effect of phase lag and phase lead (cos ϕ) is investigated. The effect of non-linear loads and switching equipment is not investigated during the recalibration. For example, in case of a faulty capacitor the EMI filtering effect is reduced in the meter, which will not be revealed during such recalibration. The other problem is that faulty meters are scrapped and are not available for further research and no information is given on a probable cause. A third problem is that static meters are supplied by the utility companies and are not freely available on the market in the Netherlands. We had to purchase static energy meters used for the experiments in another European country. The fourth problem is that meters are sealed and documentation is extremely limited. After opening meters the seal has to be broken, and we observed that all manufacturers use their own specific digital signal processor with proprietary software. In [12] an overview of techniques used by integrated circuit manufacturers such as Texas Instruments, Analog Devices, ST and Maxim, shows that there are various options for signal processing. In case the reactive power and energy are measured, the different metrics corresponding to different mathematical models can provide conflicting results for non-sinusoidal conditions [13], e.g. 90° shifting of the voltage by means of an integrator, or by means of a time shift of a quarter of a period, or digital implementation of the definition of the “non-active power”. Measurements showed differences of up to 52% [13], and -61% to +47% [14]. It is also stated in the IEEE 1459 standard [16]: ‘VARmeters that use 90° phase shift in time of fundamental may measure correctly the reactive power under sinusoidal conditions. When the voltage and current waveforms are highly distorted, such meters yield a reading that has questionable significance’. No data could be obtained on the active power reading, the processing of the data, and neither the technology for the sensors being used by the manufacturers.

III. Simple Energy Monitor

The effect of faulty readings due to conducted electromagnetic interference has been demonstrated using low-cost energy monitors. Four energy monitors were connected to a four-quadrant amplifier generating an ideal sinusoidal voltage, and a distorted voltage. The distorted voltage is shown in Figure 1, and it is an exact replica of the measured voltage waveform in a modern building as described in [2]. The load was a string of 30 Compact Fluorescent Lamps (CFL) and 20 Light Emitting Diode (LED) lamps. Using the ideal sinusoidal voltage the measured power and energy consumption was the same for all four meters. In this case the orthogonality, i.e. the RMS value of a sum of two orthogonal currents or voltages contains no cross-products and the squared total RMS value is equal to the sum of the squared RMS values, resulted in a valid reading. But when the distorted voltage was supplied, the reading was 361 W, 8 W, 349 W and 0 W, while a calibrated energy meter stated 360 W. The meter with 8 W reading also measured 107 Hz, instead of the supplied 50 Hz fundamental frequency, which supports the idea that the algorithm uses zero-voltage detection, causing the misreading in this meter. A picture of the display is shown in Figure 2.

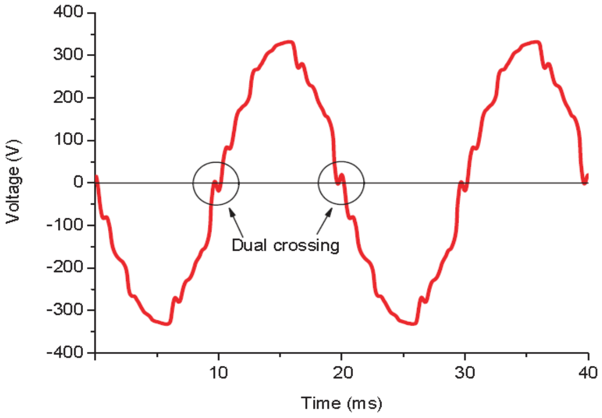

Fig. 1: High level of harmonic distortion

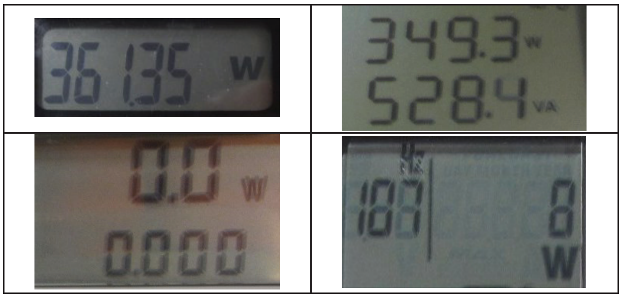

Fig. 2: Readings of the 4 energy monitors

Most static meters use an analog to digital converter (ADC) based on audio sigma delta technology. To reduce power consumption in the meter chip itself the sample rate can be reduced. If all signal content was at the line frequency then in theory a second order sigma delta with a 500 Hz, or 600 Hz sample frequency would be adequate. But a switched mode power supply for instance, especially under a light load, would consume a lot of power at higher frequencies, resulting in a misread by a low sampling frequency ADC.

PLT is used in several static meters to allow communication for developing a Smart Grid. PLT systems use the 2-150 kHz band and the modulation system can vary while voltage levels of up to 10 Vpp are present. These signals need to be removed before the ADC by a low-pass filter. Cheaper systems may not contain such a filter, which could result in inaccurate readings. In [17] an inaccurate reading of 1600% was observed at a frequency of 10 kHz and at 20 kHz. The reason for these susceptibilities was traced back to aliasing effects that are connected to a sampling frequency of 10 kHz. Due to aliasing, disturbing frequencies close to the sampling frequency can appear as low frequencies, that is, with a sampling frequency of 10 kHz a disturbing frequency of 9.95 kHz can appear as a 50 Hz signal that is recorded by the static meter [17]. However, this should not occur in properly designed energy meters, because they should be fitted with low-pass filters.

PLT signals have been shown to interfere with various systems, like touch-dimmer lights [5]. In case of low-impedance loads, the PLT voltages can cause high amplitude current at the consumer premises. This could also be a cause of misreading of static energy meters.

IV. Single-Phase Energy Meters

Several single-phase static energy meters were measured in various setups. The generator was a four-quadrant amplifier from Spitzenberger & Spies (S&S) PAS 5000, driven by the SyCore generator, also from S&S. This equipment can perform EMI measurements according several standards such as the IEC 61000-4-11 [18]. Measurements with ideal sinusoidal and with distorted voltage waveform have been performed. Furthermore, interfering signals were injected using the CS101 test setup of MIL-STD 461E [19]. The frequency range was 30 Hz up to 150 kHz, and levels were around 10 Vpp. This setup replicates the IEC 61000-4-19 [7] test. The loads used during the tests were power resistors, strings of CFL and LED lamps, a power drive system, and a dimmer driving these lamps. A Dranetz PowerXplorer PX5-400, and an oscilloscope were used for reference energy measurements. The results can be summarized in one sentence: no deviation beyond the specification could be observed; no influence of interference due to interfering or distorted voltage, and no influence caused by interfering currents were observed.

V. Three-Phase Energy Meters

Four different three-phase static energy meters have been tested in series with an electromechanical meter. The accuracy class of the static meters is defined by the IEC 62053.21-22 standard [20] and are either class 1 or class 2. The variations in percentage error limits for the specific classes are shown in Table I. The meters used in all tests were rated at 80, 85, 100, 120 A, except for the electromechanical Ferraris meter which was rated at 30 A for I_{max}.

Table 1: Accuracy of static meters

Range for test current	Power Factor	Class 1	Class 2
$0.05I_n < I < I_{max}$	1	± 2.0%	± 2.5%
$0.2I_n < I < I_{max}$	0.5 inductive	± 2.0%	± 2.5%

The three-phase meters were used in a three-phase test setup using normal mains supply, and in a single-phase test setup using the programmable power source with the four-quadrant amplifier from Spitzenberger & Spies (S&S) PAS 5000. The S&S SyCore generator and the PAS 5000 are used to generate a controlled distortion-free ideal sinusoidal voltage waveform. The internal impedance of this source is less that 0.4+j0.25 Ω, as defined in the standard [18]. The test setup is drawn in Figure 3.

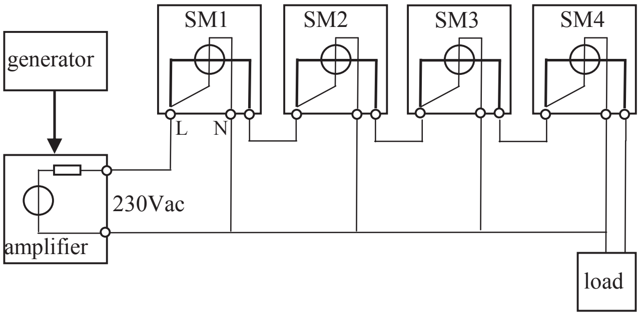

Fig. 3: Test setup

Various loads were used, including an electric heater (resistive load), a string of CFL lamps and a string of LED lamps. These loads were controlled by a dimmer creating a chopped part of a sinusoidal waveform, in case a resistive load would be used. The waveforms for a dimmer at 45^0, and at 135^0, when using the electric heater and 30 CFL and 20 LED are shown in Figures 4 and 5 respectively.

The voltage dips in the voltage waveform are caused by the internal impedance of the four-quadrant amplifier, which is less than 0.4+j0.25 Ω. Tests were performed during at least 24 hours, and sometimes over the weekend, over a 48 hour period. The registered energy of the static meters was measured using an Arduino microprocessor and optical sensors for detecting the pulses from the LED on the static meter fronts. The readings were verified using the liquid crystal display (LCD) reading on the meter. For example, the LCD displayed 18 kWh, and the Arduino measured 17902 Wh, while on another meter the display showed 7.43 kWh, and the Arduino measured 7430 Wh. A conventional electromechanical meter based on the Ferraris principle was used as reference, because consumers are also using this as reference. Most experiments have been repeated to confirm the conclusions, and repeated again, and again, because some of the static energy meters gave large differences. In Figure 6 the deviation with respect to the Ferraris meter is shown, using

$$deviation_{\%} = \frac{E_{SM} - E_{ferraris}}{E_{ferraris}} 100\%$$

The test results are also listed in Table II.

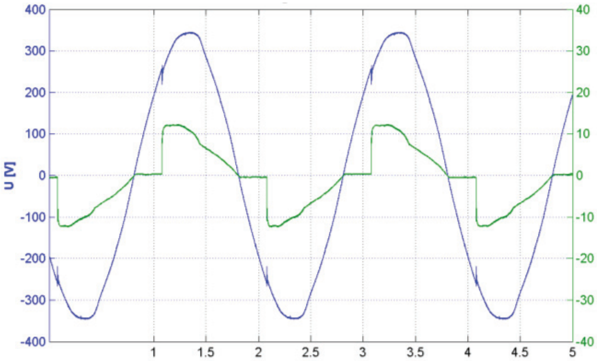

Fig. 4: Voltage and current, for heater, CFL and LED as load, dimmer at 45^0

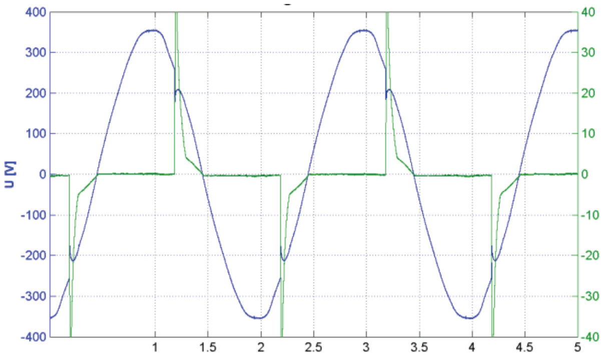

Fig.5: Voltage and current, for heater, CFL and LED as load, dimmer at 135^0

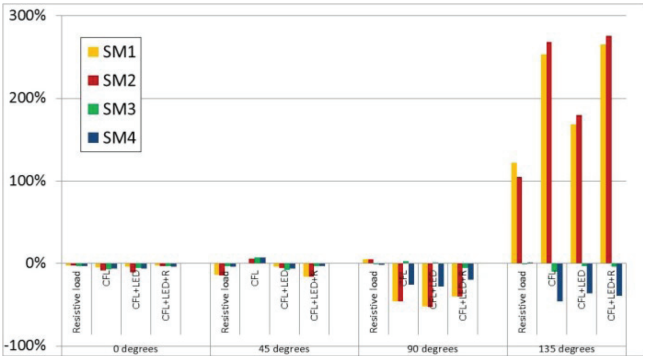

Fig.6: Deviation of static meter (SM) 1 to 4, referenced to an electromechanical (Ferraris) energy meter

Table II: Deviation of static meter (SM) 1 to 4, referenced to an electromechanical energy meter

Dimmer		Resistive	CFL	CFL+ LED	CFL+ LED+ Resistive
0^0	SM1	-2%	-4%	-4%	-3%
	SM2	-3%	-9%	-11%	-3%
	SM3	-3%	-7%	-6%	-3%
	SM4	-3%	-7%	-6%	-4%
45^0	SM1	-14%	0%	-4%	-16%
	SM2	-14%	6%	-5%	-16%
	SM3	-3%	7%	-8%	-3%
	SM4	-4%	7%	-6%	-3%

90^0	SM1	5%	-46%	-52%	-40%
	SM2	5%	-46%	-53%	-40%
	SM3	-1%	3%	1%	-6%
	SM4	-2%	-26%	-28%	-20%
135^0	SM1	122%	253%	169%	265%
	SM2	105%	268%	180%	276%
	SM3	-1%	-10%	-3%	-4%
	SM4	2%	-46%	-36%	-39%

These measurements have been performed using a standard non-distorted voltage generated by the four-quadrant amplifier with a defined low-impedance internal impedance. The observed effects are due to the pulsed currents consumed by the loads.

VI. Root Cause Analysis

Four types of current sensors are widely used in static meters: the shunt resistor, current transformer, Hall effect-based current sensor, and Rogowski coil. Static Meter 1 (SM1) and SM2 are from the same manufacturer. SM1 was produced in 2013 and SM2 in 2007. After opening it was revealed that both are using the Rogowski principle. SM3, from 2007, used a current transformer, and SM4, 2014, the Hall sensor. The current transformer is the most expensive technique, and SM3 is the most costly meter, it results in the best reading, very similar to the reading of the electromechanical meter. The meter with the Hall sensor, SM4, is the best for the consumer because it resulted often in a negative reading, with a maximum of -46%. Readings taken by Rogowski coil meters are dramatically higher, at +265 % for SM1 and +276% for SM2. The effect was consistent over the three phases, as is shown in Figure 7. Tests were repeated several times and the results were very repeatable, within a few percent.

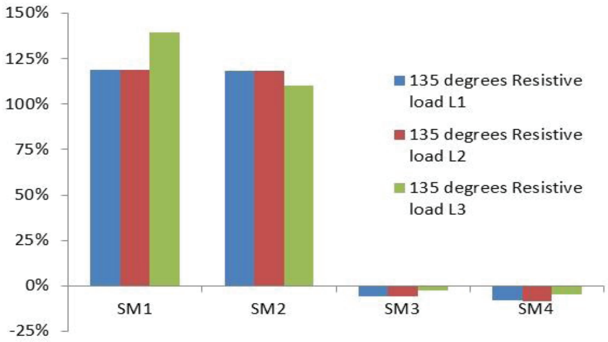

Fig. 7: Deviation of static meter (SM) 1 to 4, with resistive load (heater) and dimmer at 135^0, for all three phases

Measurements were also performed using the mains supply and a balanced load over the three phases, but with the dimmer circuit in only one single phase. The deviations were consistent, but only a factor 3 lower because of the balanced loading.

VII. Extended Experiments On More Meters

A series of experiments have been tested over a period of 6 months, with tests lasting at least 1 week, sometimes several weeks. The tests have been performed using standard mains supply. In this series, 9 static meters were connected in series with 1 electromechanical energy meter, and 1 phase was used, because some of the meters are single-phase types. The test setup is shown in Figure 8. Also measurements using energy and power meters for lab use have been performed. One static meter is using a shunt, others are using a Rogowski and Hall sensors. The fabrication dates are 2004, 2007 (2), 2009, 2011, 2013 (2), 2014 (2). The meters are representative of the installed base of energy meters in The Netherlands. The following experiments have been performed, and the key results are noted:

· Resistive load 1800 W	<3%
· 20 LED + 30 CFL	<3%
· 20 LED + 30 CFL + C_x	<3%
· Dimmer 90^0, LED+CFL	-28%, +64%
· Dimmer 90^0, LED+CFL + line choke	<3%
· Dimmer 135^0, LED+CFL	-32%, +575%
· Dimmer 135^0, LED+CFL repeated	-32%, +582%

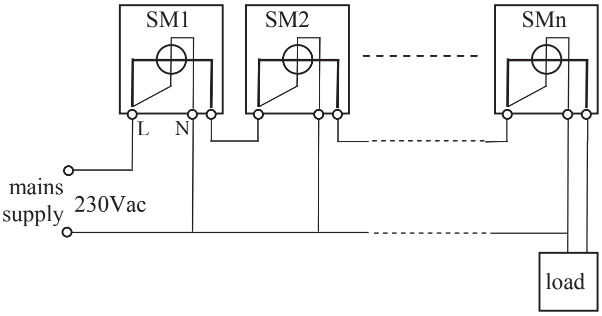

Fig. 8: Test setup

The C_x is a capacitance of 200μF between phase and neutral to create a very low mains impedance. This did not result in extreme high inrush current using the LED and CFL lights. The series inductance of 1.2 mH reduced the inrush current rise-time, as shown in Figure 9.

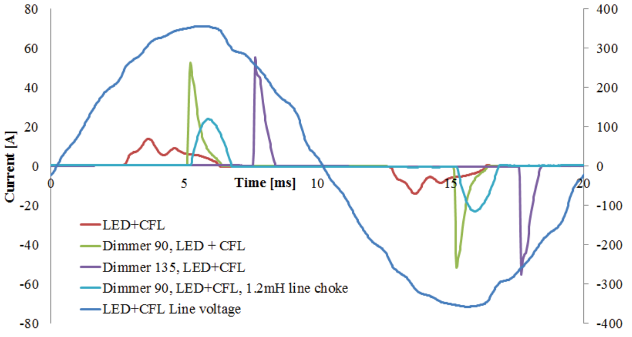

Fig. 9: Current waveform LED+CFL lights, with dimmer at 90o and dimmer at 135^0, and with additional line choke

The rise times are

· Dimmer 90^0, LED+CFL and line choke	0.086 A/μs
· Dimmer 90^0, LED+CFL	0.67 A/μs
· Dimmer 135^0, LED+CFL	1.1 A/μs

The deviations for the experiment with the dimmer and LED+CFL are shown in Table III.

SM8 is a meter using the shunt principle. We could not confirm, without breaking the seals, if SM5 is also using the shunt, but it is likely. SM1, SM2, SM6, SM7 and SM9 are using the Rogowski coil and SM4, and we expect also SM10, are using the Hall principle.

Table III: Deviation of energy meters

Meter	Year of production	Dimmer 90º	Dimmer 135º	Dimmer 135º, repeat
SM1	2013	60%	559%	566%
SM2	2007	64%	574%	581%
SM4	2014	-28%	-32%	-32%
SM5	2004	0%	-5%	-6%
SM6	2007	60%	563%	569%
SM7	2009	61%	575%	582%
SM8	2011	1%	0%	0%
SM9	2013	28%	480%	475%
SM10	2014	-25%	-31%	-31%

The deviation shown in Table II is based on the calculation using

$$deviation_{\%} = \frac{E_{SM} - E_{ferraris}}{E_{ferraris}} 100\%$$

If the reading would be listed, using

$$reading_{\%} = \frac{E_{SM}}{E_{ferraris}} 100\%$$

then the reading of, for instance SM7, is 682% (deviation 582%), and for SM4 it is 68%.

VIII. Discussion

Many experiments were performed to find out if static energy meters can provide inaccurate readings. Based on our own experience [2] the large conducted interference caused by power drive systems or some active infeed converters, as well as the high PLT levels, were assumed to be a potential culprit. This interference can be solved by reducing the emission level of the interference sources, often simply by replacing the power drive system [2] or the AIC [21]. Large harmonic distortion of the mains supply could be another source of misreading, but, although observed for low-cost energy monitors, this could not be confirmed for the static energy meters.

The reason for faulty readings appears to be the current sensor, and the associated circuitry. As a Rogowski coil results in a time-derivative of the measured current, the measured voltage has to be integrated. Probably active integration is used instead of passive integration, and the input electronics are pushed in saturation caused by the high rise-time of the current. Although the peak current level is below the maximum level stated for the meters. As stated before, no information or documentation at all is available from meter manufacturers.

The recently introduced standards [6], [7] only assume a damped sinewave current and voltage as potential interference. These signals are actually the pulse response of a larger system formed by the cabling. The experimental results presented in this paper show that static energy meters can be pushed into faulty reading (positive and negative) if sufficiently fast pulsed currents are drawn by the consumer. The actual response (damped sinewave) is not of interest anymore.

The observations of a consumer that were reported on an internet forum are consistent with the results contained in this paper: a small electronic circuit consumed only a very small amount of peak current, but caused the meter to read 500 W, resulting in a yearly additional energy ‘consumption’ of 4380 kWh [22].

IX. Conclusion

Conducted electromagnetic interference can cause misreading of static electronic energy meters. This was already observed in the past, but only for cases with lower energy reading. In one actual case the cause of this misreading is the interfering currents caused by active infeed converters for renewable energy. In this paper it is shown that also higher readings are possible. Electromagnetic interference tests have been introduced so that static meters will be immune against this type of interference. The static energy meters are used for billings and if a customer files a complaint the meter can be calibrated. However, this is done using ideal sinusoidal voltages and currents, while in our current living environment the currents deviate substantially due to the non-linear loads of modern equipment.

Controlled experiments performed on static energy meters confirm that they can present still faulty, and substantially higher, readings. The main cause of interference appears to be the current sensor. Meters with a Rogowski coil current sensor showed a positive deviation of 276%, or an increased reading of 376%, using a controlled power supply with undistorted voltage and defined impedance, compared to the reading of a conventional electromechanical meter based on the Ferraris principle. Meters with a Hall sensor showed a deviation of registered energy of -46%, or a decrease in energy reading to 54%.

Using the mains supply in the laboratory, from 9 static meters 5 showed positive deviations of up to 582%, which is a higher energy reading of 682%, and 2 showed deviations of around -30%, equivalent to a reading of 68%.

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