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Control meter for static energy meters used to validate the readings in cases of EMI issues

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Abstract

Static, or electronic, energy meters are replacing old fashioned electromechanical energy meters based on the Ferraris principle. Renewable energy and the large variations in energy supply and demand as function of time resulted in a need for smart energy meters. A smart energy meter has communication capabilities added to the standard static energy meter. Previous research showed that static meters can give faulty energy readings. Many cases have been reported where static meters give very high energy readings, which cannot be explained based on the residence situation. It is of great interest to investigate this kind of cases and find the source that causes interference on static meters. For that reason, a control meter is developed which can act as a reference for installed static meters. This control meter is placed next to the static meter and can: measure the energy consumption in a verified and correct manner, readout the static meter, measure the electromagnetic environment, and log the data. Furthermore, it is designed such that it is hardened against the electromagnetic environment. This control meter is now already in use to investigate possible deviations and their causes in static meters.

Contents

Abstract **iii**

List of acronyms **vii**

1 Introduction **1**

2 Analysis of design options **5**
2.1 Available loggers and meters . . . 6
2.2 Current sensor . . . 9
2.3 Monitor energy consumption static meter . . . 11

3 Design control meter **13**
3.1 Design criteria . . . 13
3.2 Functional design . . . 15
3.2.1 Power quality analyzer . . . 15
3.2.2 Installed static meter monitor . . . 17
3.2.3 EM environment monitor . . . 18
3.2.4 Implementation of the subparts . . . 19

4 Measurement Method **21**
4.1 Instrumentation . . . 21
4.2 Setup elements . . . 22
4.2.1 Static meter setup . . . 22
4.2.2 Reference meter . . . 23
4.2.3 Load . . . 24
4.3 Measurement procedure . . . 26
4.3.1 Energy consumption of the static meters . . . 26
4.3.2 Linear load . . . 27
4.3.3 Non-linear load . . . 28
4.3.4 Static meter readout . . . 29
4.3.5 EM environment measurement . . . 30
4.3.6 Trigger events . . . 31

4.3.7 Sampling rate adjustment 32

5 Results 33

5.1 Energy consumption static meters 33
5.2 Linear load 34
5.3 Non-linear load 35
5.3.1 Dimmer set to 0° 36
5.3.2 Dimmer set to 45° 37
5.3.3 Dimmer set to 90° 38
5.3.4 Dimmer set to 135° 39
5.4 Readout static meter 40
5.5 Measure EM environment 41
5.6 Trigger events 42
5.6.1 Snapshot 43
5.6.2 Voltage Sag 44
5.7 Sampling rate 45

6 Discussion 47

7 Conclusion and recommendations 49

References 51

Appendices

A Arduino code static meter setup 53

B Matlab code static meter setup 57

C Paper submitted to EMC Europe 2018 63

List of acronyms

PV	photo voltaic
CFL	compact fluorescent lamp
LED	light emitting diode
EM	electromagnetic
AC	alternating current
EMI	electromagnetic interference
LDR	light-depending resistor
RMS	root mean square

Chapter 1

Introduction

Smart grid technology has led to the development of smarter methods for energy metering. The old fashioned electromechanical energy meters, based on the Ferraris principle [1], are replaced by static energy meters. These meters are called smart meters if a communication link is added to transmit the recorded data to the utility company. In such a way, a smart meter assists in remote billing and can give load feedback to the utility for load forecasting.

Some consumers, who use these static meters, are complaining about the energy readings given by their meter [2]. They claim that the static meter gives higher readings compared to the old electromechanical meter. The electric utilities claim that because of wear the old meters gave incorrect, too low, readings and the customers should be happy that they paid too less for years.

In a specific case, [3], two neighboring farmers installed the same photo voltaic (PV) system, but on sunny days there was a difference of 40% between the two PV systems. Experiments show that high interference levels on the power lines were caused by the power drive systems of the fans. This resulted a faulty reading of the static meters. Faulty readings of static energy meters due to PV systems were also observed in Germany [4], [5]. In this case it was a low reading, and this was also caused due to high interference levels generated by active infeed converters of a PV system.

In [6], [7], and [8] experiments are done in a lab environment to mimic faulty energy readings due to realistic loads attached to static meters. During the experiments the screens of the static meters are monitored manually. The tests are performed during a long period, because the energy consumption of light emitting diode (LED) and compact fluorescent lamp (CFL) lights is low. That was also the reason why an array of 50 lamps is used. However, this amount of lamps is not a realistic household situation anymore. Furthermore, with this experiment it is not possible to analyze shorter intervals within the experiment, only the final results are presented. In [9] an improved setup is proposed to do these kind of measurements in a lab situation by measuring the power instead of the energy consumption, which results in faster measurements.

This research [6], [7], and [8] has showed that in some cases static meters can give faulty energy readings, positive and negative, if static meters are loaded with fast pulsed currents. In [6], controlled experiments on static meters show that they can present faulty readings. When using static meters in a three-phase setup, loaded with a string of CFL and LED lamps in combination with a dimmer, static meters show a positive deviation of 276% and negative deviation of -46% compared to conventional electromechanical energy meters. The experimental results in [7] and [8] show that tested static meters gave maximal positive deviations of +582% and negative deviations of -32% when loaded with CFL and LED lamps in combination with a dimmer for a one-phase test setup.

In [8] it is stated that the reason for faulty energy readings in static meters can be caused by the current sensor used in the meter. A Rogowski coil results in a time-derivative of the measured current, the measured voltage must be integrated. It suggests that active integration is used instead of passive integration. There is come up with a solution to prevent higher and lower readings of the static meters: either proper current sensors, a passive integrator instead of the currently implemented active integrator, or a faster sampling time.

However, still a lot of cases are present where static meters give extremely high energy readings which cannot be explained based on the residence situation. It is of great interest to investigate these kinds of cases and find the source that causes interference on the static meters. The best way to do so, is by analyzing the behavior of installed static meters for these specific on-site situations. There have been indications that electromagnetic (EM) fields generated by transmitting antennas of an antenna mast, could be a source of interference, therefore it is also important to measure the EM environment. Therefore, a control meter is developed which can act as a reference for installed static meters. This control meter should be able to monitor the installed static meter continuously and compare these results with a reference measurement done by the control meter. When extreme situations are measured, researchers should be alarmed by the control meter with the corresponding data to analyze it. These extreme situations include: a difference between energy consumption as measured by the installed static meter and control meter, high electric fields in the environment and deformation in voltage waveform and frequency.

The purpose of this research is to develop a suitable control meter which is able to: measure the energy consumption in a verified and correct manner, readout the static meter, measure the electromagnetic environment and log the data. Furthermore, the design is made such that it is hardened against the electromagnetic environment. Finally, the control meter must be tested in realistic situations of energy consumptions in household situations.

The upcoming chapters are organized as follows: Chapter 2 analyses options for the control meter, including commercial available devices to monitor energy consumption, Chapter 3 describes the design criteria and functional design of the control meter, Chapter 4 gives a description of the measurements performed for the validation of the design, Chapter 5 shows the results of the measurements, in Chapter 6 the results of the measurements are discussed and in Chapter 7 the study is concluded and final recommendations are made.

Chapter 2

Analysis of design options

This chapter analyses the options that can be used to develop a suitable control meter. This includes an analysis of commercial available power analyzers used to monitor the energy consumption and power quality.

For the development of a control meter, two options can be considered. The first one is to build a complete new device and the second option is to use an existing power analyzer to which additional functionalities can be added. Functionalities that at least should be added is the monitoring of the installed static meter and the measurement of the EM environment. The latter option is the preferred one, because the development of a complete new design is a time-consuming assignment and would not fit within the time allocated for this project.

A power analyzer measures various parameters of an electrical power distribution system. The analyzer might measure the following parameters for single- and/or three-phase systems: voltage and current waveforms, RMS-values, power factor, instantaneous power, average and maximum powers, harmonic distortion, energy consumption and phase angles. Power analyzers exist roughly in two categories:

- Meters used to measure the power characteristics directly. Examples are the Yokogawa WT500 power analyzer and the PicoScope. These devices are used to directly view the mains power waveforms and analyze them, and are not suitable to log the grid for longer periods. Furthermore, most of these devices are bulky and therefore not suited to install in a meter cabinet.

- Portable loggers, which are more compact and used to observe energy consumption patterns in real-time. These record the consumed energy and log it periodically, for example every minute, over a longer period.

For the control meter a device that is more in between these two categories is needed. The device should have the functionalities of a logger to log the data periodically, but also the analysis of the waveforms is important in cases unexpected phenomena in power quality occur.

2.1 Available loggers and meters

A comparison between commercial available loggers and meters is done. The results are shown in Table 2.1. The purpose is to find a suitable power analyzer that can be used as a control meter when some additional functionalities are added. The power analyzers are compared one five different aspects:

1. Power configuration. Some mains systems use three-phase, while others use single-phase. The power analyzers are checked if it is possible to measure single- or three-phase power configurations or both.

2. Sampling rate. For the conversion from an analog to a digital signal, the sampling rate is an important parameter. In some cases, the current waveform might not look like a proper sine and hence an increased sampling rate is needed for the digital reconstruction.

3. Accuracy. The power analyzer is intended to do accurate measurements. The accuracy should be at least class A [10], which means that the energy readings of the analyzer are within $\pm$2.5% accuracy based on full load conditions and unity power factor.

4. Logging. Power analyzers are able to store the data locally or by uploading or logging it to the user. To make sure that it is not necessary that the user is at the test site, uploading or logging to the user is preferred.

5. Analog output. The availability of an analog output port for the power analyzers is an important thing to check. This can be used to connect sensory systems to the power analyzer. Such sensory systems could be able to monitor the installed static meter and/or measure the electromagnetic environment close to the static meter.

It is found that the commercially available power quality analyzers are able to make a lot of detailed plots of the voltage and current waveforms. But do not have the option to add additional functions. These analyzers are made specific to monitor the energy consumption in a grid. Therefore, these analyzers are not suitable and the search area is limited. The PQube2, PQube3 and the Fluke 1736 are the only analyzers that have the option to add extra sensors using analog ports. Also the analyzers of OpenEnergyMonitor could be tweaked to add extra sensors, since those use Arduino microcontroller or Rasberry Pi.

The analyzers included in the comparison have decent accuracy and sampling rate. Except for the analyzers made by OpenEnergyMonitor, these did not specify these parameters. All of the other power analyzers compared have a decent sampling rate. These sampling rates are assumed to be appropiate for the digital reconstruction of the analog signal. The analyzers of OpenEnergyMonitor are the only ones that are not capable of measuring three-phase power configurations.

Table 2.1: Comparison of commercially available power quality analyzers [11], [12], [13], [14], [15], [16], [17], [18], [19]

Company	**Model**	**Power configuration**	**Sampling rate**	**Accuracy**	**Remote logging**	**Analog output**
Power Standards Lab	PQube2	1- and 3-phase	6.4 kHz	Class A	Ethernet	2
Power Standards Lab	PQube3	1- and 3-phase	12.8 kHz	Class A	Ethernet	4
Fluke	1736	1- and 3-phase	10 kHz	Class A	Ethernet	2
Unilyzer	9000	1- and 3-phase	12.8 kHz	Class A	WLAN	0
Chauvin Arnoux Pel	103	1- and 3-phase	6.4 kHz	Class A	Ethernet	0
Unilyzer	902	1- and 3-phase	12.8 kHz	Class A	Ethernet	0
OpenEnergy Monitor	EmonTx V3	1-phase	-	-	Ethernet	Yes
OpenEnergy Monitor	emonPi	1-phase	-	-	Ethernet	Yes
Smappee	Pro	1- and 3-phase	16 kHz	Class A	Ethernet	0

2.2 Current sensor

When the energy consumption in a mains power system is measured, the current waveform should be measured. For measuring the mains current, a current sensor should be used to transform the current into a voltage which can be read by the power quality analyzer. This current sensor should be clamped around the wire for which the current should be known. To do so two methods exists:

1. Current transformer principle. The current transformer principle transforms an alternating current (AC) from its primary to its secondary conductor. In the secondary conductor, the current is transformed into a voltage by means of a resistor, such that this voltage is proportional to the current in the primary coil.

2. Rogowski coil principle. The current flow through the wire encircled by the Rogowski coil induces an output voltage in the coil proportional to the derivative of the current flow. This output voltage is integrated so that it is proportional to the current in the wire.

A comparison between commercially available current sensors is made in Table 2.2. The current sensors are compared on the following parameters: current range, accuracy, linearity, measurement method, and dimensions. The dimensions of the sensors using the Rogowski coil principle are given as the diameter of the loop. For the current transformers the dimensions in length times height times width of the complete sensor are given.

All of the sensors included in the comparison measure current within the range that is expected for household situations. The accuracy and linearity of the sensors is appropiate to measure the current for this purpose. It will measure with some inaccuracy, but large deviations between control meter and installed static meter are expected. Such that this inaccuracy is negligible. From the dimensions it can be seen that there are big differences between the sensors. This will be a heavily weighing parameter for selecting the current sensors. In some meter cabinets there is limited space, such that a small current sensor is preferred.

Table 2.2: Comparison of commercially available current sensors [20], [21], [22], [23], [24]

Company	**Model**	**Current range**	**Accuracy**	**Linearity**	**Measurement method**	**Dimensions (in mm)**
Power Standards Lab	PSL SCS-075	1-200A	± 1%	-	Current transformer	50.6x53.8x15.6
Power Standards Lab	FCT XX-3000A	0-3000A	± 0.5%	± 0.2%	Rogowski coil	d=190
Power Standards Lab	Precise CT	0-300A	± 0.2%	-	Current transformer	60.4x90.0x29.4
Magnelab	RCT-1200-00	0-15000A	-	± 0.5%	Rogowski coil	d=305
Efergy	819-9779	0.5-95A	-	-	Current transformer	-
Hobut	SC CT 60A	0-60A	±1%	-	Current transformer	28.7x41.7x26.4
YHDC	SCT-013-000	0-100A	± 1%	± 3%	Current transformer	32x57x22

2.3 Monitor energy consumption static meter

This section describes how the energy consumption as measured by the static meter can be monitored by an optical sensor. The static meters have a blinking LED integrated. This LED blinks if a certain amount of energy is consumed. For most meters, this is one blink per 1 or 2 Wh of energy consumed in the circuit. This LED pulse can be monitored by attaching it to an optical sensor. Such an optical sensor should give a voltage dependent on whether the LED is on or off. Such that this blinking LED can be translated into an analog voltage signal.

In [9] three different kind of optical sensors are described that can do this kind of translations from an optical pulse to an electrical voltage pulse. The sensors that are described are: a light-depending resistor (LDR), a TSL261RD and a TSL257 light-to-voltage sensor. The response of these three sensors can be seen in Figure 2.1.

A light-to-voltage sensor is a packet which contains a photodiode together with a transimpedance amplifier. Photodiodes have a quicker response time compared to an LDR. The rising edge and falling edge of the electrical voltage pulse is much shorter. This behavior of the sensors is also visible in Figure 2.2. A quicker response time can become handy if a lot of energy is consumed. Or in cases of interfering sources on the installed static meter. These cases will result in a high frequency at which the pulses occur. And fast detection is needed. Therefore, the optical sensors using a photodiode are preferred over an LDR. The difference between the two light-to-voltage sensors as described in [9], is the spectral responsivity. The intensity and the wavelength of the LEDs on the static meters are different. The TSL261, which has a small spectral responsivity range, was not able to monitor the LEDs of all static meters tested. Therefore, it is not a suitable sensor to use. Sensors with a broader spectral responsivity range should be used.

Another method to measure the blinking LED on the static meter is to use a commercially available sensor, made specific to monitor the energy consumption as measured by a static meter. These sensors work on every static meter, since they are designed for it specifically. However, electrically the sensor does the same thing as a photodiode: translate an optical pulse into an electrical voltage pulse. And the costs of a commercial available sensor are ten times higher.

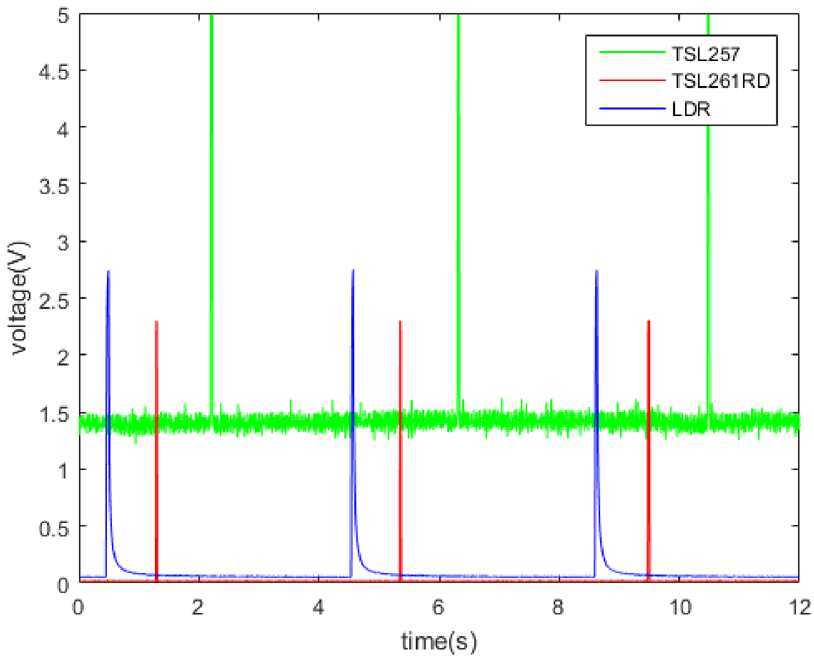

Figure 2.1: Response of the optical sensors connected to a LED on a static meter when loaded with 850 W resistor. For optical sensors: TSL257 in green, TSL261RD in red and LDR in blue.

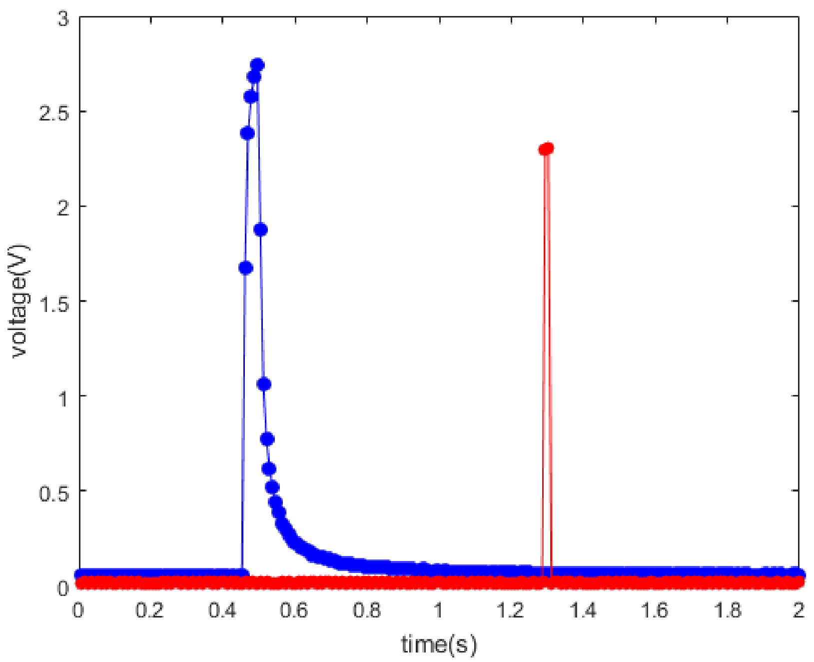

Figure 2.2: Zoomed version of the response of the optical sensors connected to a LED on a static meter when loaded with 850 W resistor, dots indicate the data points. For optical sensors: TSL261RD in red and LDR in blue.

Chapter 3

Design control meter

This chapter describes the design criteria and the functional design of the control meter, based on the findings in Chapter 2.

3.1 Design criteria

The design to be made for the control meter should met a couple of criteria, such that the meter can be used for the purpose of monitoring a static meter, as described in Chapter 1. The design should be made such that the following criteria are met:

- Monitor the installed static meter
- Measure the energy consumption in one- and three phase systems accurately
- Measure the EM environment
- Be hardened against the EM environment
- Remote logging of the obtained data
- Be installable by a local electrical engineer

First of all, the control meter should be able to monitor the energy consumption as indicated by the installed static meter. This result should be compared by the energy consumption measured by the control meter itself. The control meter should be able to measure single- and three phase systems. In that way it can be used in multiple occasions. The measured energy consumption should be compared to the monitored consumption as indicated by the installed static meter. Therefore, the measurement of the energy consumption should be accurate enough to do so, but a very accurate (golden) meter is not needed. This means that an accuracy of $\pm$ 5% should be enough for this purpose. When deviations between the energy consumption measured and monitored by static meter occur, the user of the control meter should be alarmed. The aimed output is a graph or table in which both the consumption as measured by the installed static meter and the control meter are compared. Such that deviations can be seen fast. Furthermore, the control meter should be able to measure the EM environment. Since there are indications that EM fields generated by antenna masts could interfere with static meters. In order to verify this theory the control meter should be equipped with this functionality. The control meter to be designed should be hardened against EM fields generated in realistic situations around houses. Such that the measurement results are not disturbed. The data obtained by the control meter should be logged to the user remotely. Then the user does not have to be at the test site and it is warned automatically if unexpected behavior occurs at the test site. A last point that the control meter should met, is that it should be installable by a local electrical engineer. Such that there is no need that a researcher has to travel to the test site to install the control meter. Therefore, the design should be made simple and easy to install. Furthermore, it should be robust and flexible, such that the control meter is not destroyed easily.

3.2 Functional design

This section shows the functional design that is made for the control meter. It starts with the used power quality analyzer. Then, the monitoring of the installed meter is covered. After that the method to measure the EM environment is shown. Finally, the implementation of all the subparts is shown.

3.2.1 Power quality analyzer

The control meter exists of a power quality analyzer which forms the backbone of the design. The purpose of a power quality analyzer is to measure the power quality of a grid. The rest of the wanted functionalities of the control meter are added to this power quality analyzer. The power quality analyzer used for this purpose is the PQube2 of Power Standards Lab. This device meets all the criteria needed as indicated in Chapter 2. It is used, because there was already some experience on working with this analyzer, and it was directly available. The PQube2 is used including the CTE1 and PS1 module. These are used to measure the current channels, do remote logging via Ethernet, and fed the device with 230 VAC instead of 24 VDC. The specifications of the PQube2 including these modules can be seen in Table 3.1.

The PQube2 has a voltage divider circuitry inside, such that mains voltage channels can be directly connected and measured by the device. To measure the current, external current transformers are used. The PQube2 needs a nominal input of 0.333, 1, 5 or 10 V_{rms}. The PSL SCS-075 current transformers of Power Standards Lab are used for this purpose. These are appropiate to use and test the functionality of the device in a lab environment, but when meter cabinets with limited space should be analyzed those are too bulky and smaller ones need to be used.

Table 3.1: Specifications of the PQube2 including CTE1 and PS1 module

Mains voltage measuring channels	
Magnitude accuracy	± 0.05% rdg ± 0.05% FS typical
Sampling rate (at 50 Hz)	256 samples/cycle
Current input channels	
Accuracy (excl. CT)	± 0.02% rdg ± 0.2% FS typical
Sampling rate (at 50 Hz)	256 samples/cycle
Analog input channels	
Nominal input	High range: ± 60 VDC to Earth Low range: ± 10 VDC to Earth
Accuracy	± 0.2 rdg ± 0.2 FS typical
Power quality measurements	
Fully compliant and certified to IEC 61000-4-30 Ed. 3 Class A	
Instrument power supply	
AC input range	100 ∼ 240 VAC ± 10% 50/60 Hz
Power required	25 VA max
Storage	
Removable SD card	Capacity 16 GB standard (up to 3 years of data under normal use)
Communications	
Ethernet Port	standard RJ-45 socket (wired Ethernet)
Physical connections (mains voltage, current and analog input channels)	
Pluggable screw terminal block	
Operating environment	
RF field strength immunity	3 V/m (IEC 61000-4-3 Test level 2)
Magnetic field strength immunity	30 A/m (IEC 61000-4-8 level 4)

3.2.2 Installed static meter monitor

The readout of the static meter is done by means of a TSL257 optical sensor. This photodiode translates an optical pulse into a voltage pulse, this voltage is connected to analog port, AN1, of the PQube2. In the software of the PQube2 a threshold is set, which detects the pulse. When this happens, a counter increments. This counter can be translated to the energy consumption by knowing the number of pulses the installed static meter gives for a certain amount of consumed energy. Figure 3.1 shows the optical sensor attached to the installed static meter.

Figure 3.1: Optical sensor attached to a static meter.

3.2.3 EM environment monitor

The measurement of the EM environment is done by means of a homemade electric field strength sensor, shown in Figure 3.2. The antenna has three orthogonal sensor plates to make it less oriention dependent.

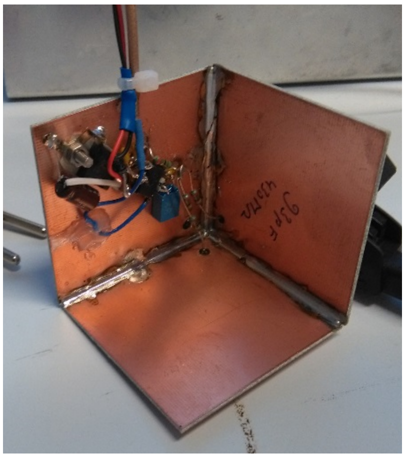

Figure 3.2: Electric field strength sensor

This field strength sensor gives an output voltage depending on the field strength:

$$V_{out} = -0.5 + 0.5log(E_{incident}) \tag{3.1}$$

where V_{out} is the output voltage given in V and $E_{incident}$ is the incident electric field strength given in V/m. This relation can be seen in Figure 3.3.

The output of the sensor is attached to analog input channel 2 (AN2) of the PQube2. This voltage can be calculated back to the electric field strength:

$$E_{incident} = 10^{2V_{out}+1} \tag{3.2}$$

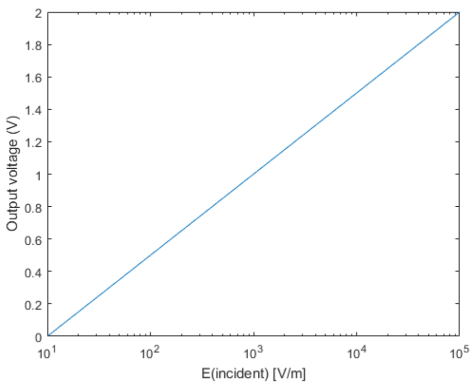

Figure 3.3: Expected response of the sensor versus the incident E-field

3.2.4 Implementation of the subparts

All the subparts are embedded in an enclosure. This enclosure consists of a metal part and a plastic part. The plastic part contains the electric field sensor. All of the other subparts are implemented into the metallic enclosure. This metallic enclosure is used to shield the inside from disturbances created by external sources due to electromagnetic interference (EMI). The implementation of the subparts in the enclosure can be seen in Figure 3.4.

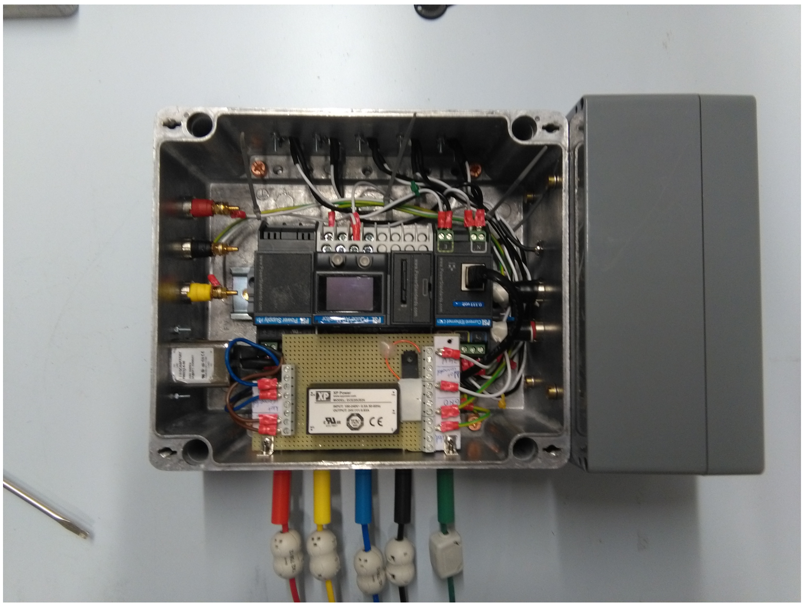

Figure 3.4: Implementation of the control meter in a metal enclosure, on the right a plastic compartment containing the electric field strength sensor is added.

The power used to supply the control meter is fed through a power line filter directly after entering the enclosure. This is done to reduce the conducted emissions on the power line. Ferrite material is clamped around the lines measuring the voltages, to attenuate radio frequency interference noise on these lines.

The control meter is configured to trigger events when unexpected phenomena occur in the behavior of: voltage, current, frequency or electric field. During such an event, detailed data is captured which can be analyzed afterwards. In normal functionality the data is logged to a daily trends file.

Chapter 4

Measurement Method

In this chapter, the method to verify the working of the control meter is described. The subchapters that are covered are: the instrumentation, the setup elements and the measurement procedure.

4.1 Instrumentation

For performing the measurements, the following equipment has been used:

- Control meter (explained in detail in Chapter 3)
- Static meter setup
- Yokogawa WT500 Power Analyzer
- Three-phase generator
- Heater
- Array of 13 CFL and 20 LED lamps
- Dimmer

4.2 Setup elements

This paragraph describes the static meter setup and the loads used when performing the measurements.

4.2.1 Static meter setup

The static meter setup that is used, is described in [9]. It consists of 10 static meters placed in series using a single-phase configuration, as in Figure 4.1 and 4.2. Meters that are included in the test setup have different types of current sensors: shunt resistor, current transformer, Hall effect-based current sensor and Rogowski coil. The meters are representative of the installed base of energy meters in The Netherlands. These static meters are readout using optical sensors which are processed by an Arduino microcontroller. The output is visualized by Matlab and it shows the energy consumed since the start of the experiment and the real power transfer measured by each static meter over a short interval of 30 seconds. All of this data is also logged to a data file. The corresponding codes can be seen in Appendix A and C.

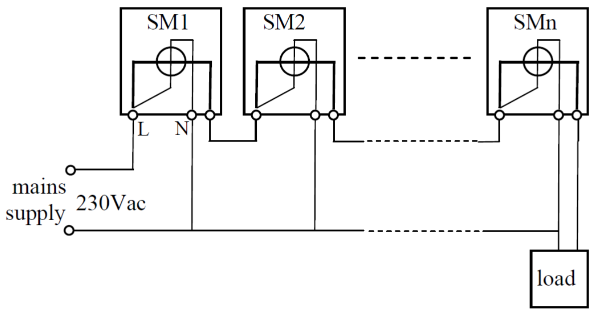

Figure 4.1: Schematic of the static meter test setup

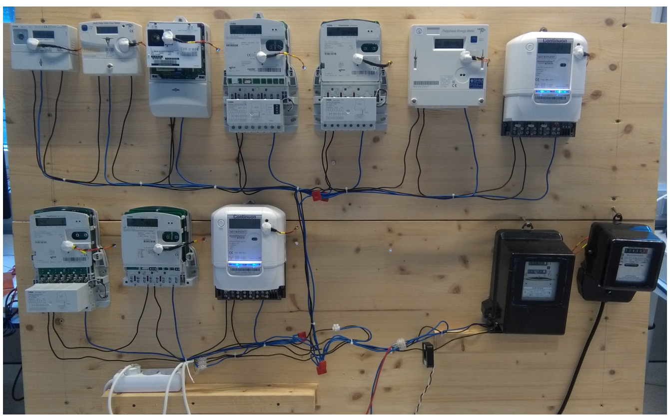

Figure 4.2: Picture of the static meter test setup

4.2.2 Reference meter

As a reference for the measurements, a Yokogawa WT500 power analyzer is used. This power analyzer has a basic power accuracy of 0.1% and can therefore be trusted as a very accurate reference for the measurements. The reference meter is attached to the setup as can be seen in Figure 4.3.

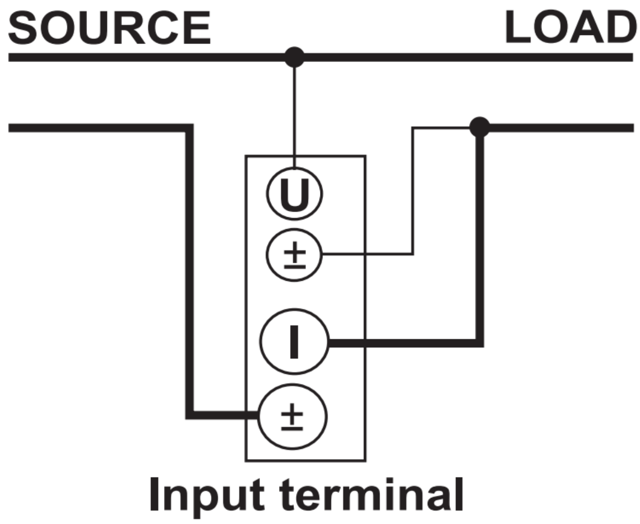

Figure 4.3: Reference meter as attached to the setup.

4.2.3 Load

For the verification of the control meter two different types of loads are used: a linear and non-linear load. A heater, shown in Figure 4.4, is used as a linear load. This heater has six stands, see Table 4.1. Only measurements with an 1800 W heater are shown, but the other stands show similar results. The non-linear load that is used is an array of 13 CFL and 20 LED lamps in combination with a dimmer, shown in Figure 4.5, this dimmer has four different stands, see Table 4.1. The difference between the two types of loads is that the linear gives a clear sine current waveform and the non-linear load gives a pulsed current waveform. These two different types are used, because then the two major load types are tested.

Table 4.1: Different loads used in the measurements

#	Load description	Type
1	Heater 190 W	Linear
2	Heater 310 W	Linear
3	Heater 500 W	Linear
4	Heater 800 W	Linear
5	Heater 1300 W	Linear
6	Heater 1800 W	Linear
7	Array of 13 CFL and 20 LED lamps with dimmer on 0°	Non-linear
8	Array of 13 CFL and 20 LED lamps with dimmer on 45°	Non-linear
9	Array of 13 CFL and 20 LED lamps with dimmer on 90°	Non-linear
10	Array of 13 CFL and 20 LED lamps with dimmer on 135°	Non-linear

Figure 4.4: Heater

Figure 4.5: Dimmer (left) and array with CFL and LED lamps (right)

4.3 Measurement procedure

This paragraph describes the measurement procedures that are used for performing the measurements. Measurements are done to measure the consumption of the static meters and to test and verify the working of the control meter. All of the tests are done with the same number of static meters, which is ten static meters, and all are installed in the same order for all of the measurements.

4.3.1 Energy consumption of the static meters

A measurement is done to correct the test setup for the consumption of energy of the static energy meters included in the test setup. This is an important measurement to calibrate the static meter test setup. For this measurement, no load is attached to the setup, such that the static meters only measure the energy consumed by the meters connected after it, so static meter 1 measures static meter 2 to n. After the last static meter a reference meter is placed. This point is taken as the zero point, which means that after a correction of the energy consumed by the static meters, all of them indicate the value of the energy consumption at this point. The measurement will run for a couple of days to make sure that the energy consumption measured is very accurate. It is assumed that all of the static meters will consume a couple of Wh. A schematic of the test setup is shown in Figure 4.6.

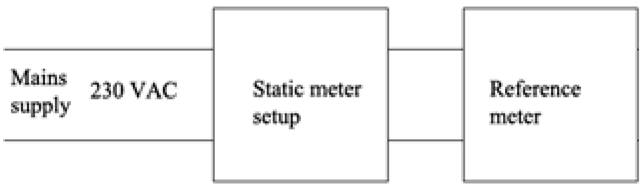

Figure 4.6: Test setup for the measurement of the energy consumption of the static meters.

4.3.2 Linear load

The control meter is tested with a linear load. This is done to make sure that the control meter can measure this situation accurate compared to the reference meter and the static meters included in the static meter test setup.

The measurement setup consists of the static meter test setup, the control meter, the reference meter and a linear load of 1800 W. The schematic of the test setup is shown in Figure 4.7. Tests are performed during a period of two hours. It is assumed that all of the meters, including the control meter, measure the same values.

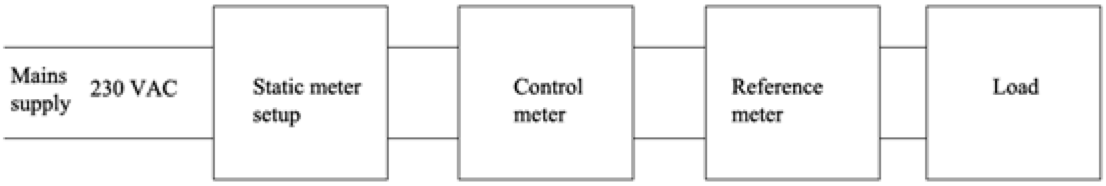

Figure 4.7: Test setup for the measurement of the control meter in combination with a linear load.

4.3.3 Non-linear load

The control meter is tested with a non-linear load, this situation is known to give faulty energy readings based on previous research. The non-linear load that is used is an array of CFL and LED lamps combined with a dimmer. It is of interest to find out if the control meter behaves correctly with respect to the reference meter when this load is applied, such that the control meter can act as a trusted reference for the static meters.

The measurement setup consists of static meter test setup, the control meter, the reference meter and the non-linear load. The dimmer of the non-linear load will be set to four different situations: 0°, 45°, 90° and 135°. Where0° indicates that the array of lamps is completely on. The schematic of the test setup is shown in Figure 4.8. Tests are performed during a period of two hours. The hypothesis is that some of the static meters will show big deviations in energy readings compared to each other, when the dimmer is set to 90° and 135° [6], [7], [8]. It is assumed that the control meter will monitor the consumed energy correctly, so that it will not show big deviations compared to the reference meter.

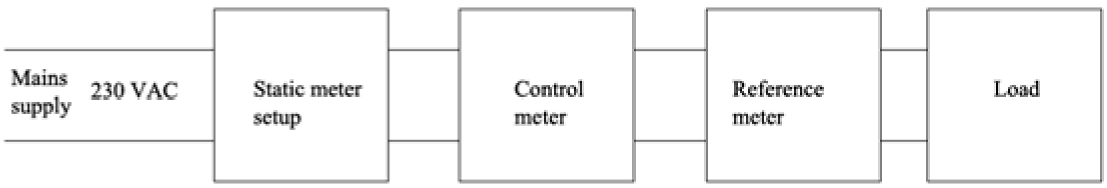

Figure 4.8: Test setup for the measurement of the control meter in combination with a non-linear load.

4.3.4 Static meter readout

The static meter is readout using a sensor which is reading the blinking LED on the static meter, as explained in Chapter 3.2.2. Measurements are done to verify which data is obtained by the control meter. For this measurement the optical sensor is connected to a static meter, a threshold is set, which indicates a LED blink of the static meter, and this reading is compared to the energy measurement as done by the control meter. In this way, the energy measured by the static meter is compared with the energy measured by the control meter.

4.3.5 EM environment measurement

A sensor is connected to the control meter, which is able to measure the EM field strength in the environment of the control meter, as explained in Chapter 3.2.3. This measurement is done to verify how the data appears in the log files of the control meter and how this can be used. For this measurement, the EM field is measured in the lab where the meter was located.

4.3.6 Trigger events

The control meter has the functionality that events can be triggered if something unexpected happens in the measured power system. For this test a 3-phase voltage is supplied to the control meter and the amplitude of the voltage waveform supplied are changed. Such a way there can be seen how the data triggered by the control meter looks like and for what purpose it can be used.

A 3-phase voltage is created by a generator and supplied to the control meter. The amplitude of the line-to-neutral voltage is 115V. This is not a standard line-to-neutral voltage that happens in practice. But the idea of this measurement was to observe how variations of the voltage from the initial state, are captured by the control meter. The control meter is connected to the 3-phase voltage generated by the generator, as can be seen in Figure 4.9. First a snapshot is made by pressing this button on the control meter, to make sure that the initial state is saved. Then the amplitude is dropped to 45V for two seconds. After this the amplitude is set to 115V again for ten seconds, these two situations are repeated a couple of times. This huge drop in voltage amplitude should trigger a voltage sag event.

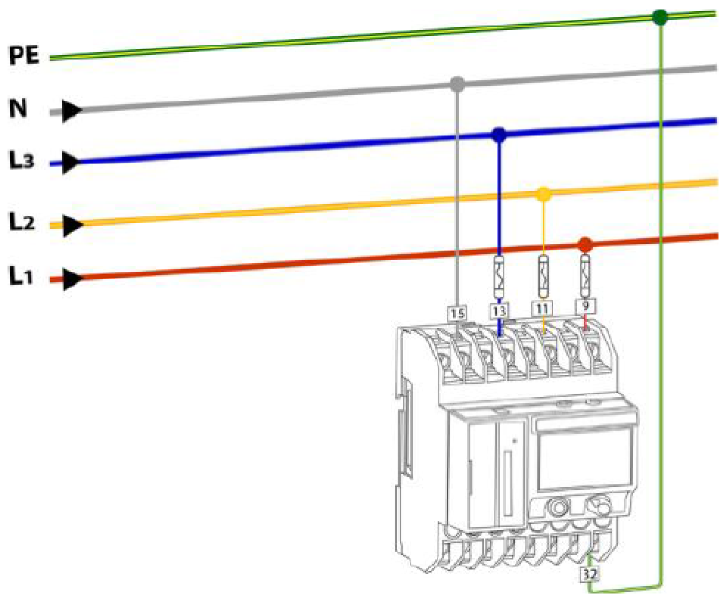

Figure 4.9: Wiring diagram for control meter connected to 3-phase generator.

4.3.7 Sampling rate adjustment

It is possible to adjust the number of samples per cycle recorded by the control meter. There is tested if this number of samples has an effect on the readings of the control meter, to make sure that this setting is set to the correct value. This is done because in [8] it was suggested that if the sampling rate is too low, the non-linear current waveform cannot be captured correctly. That is also the reason why this test will be performed with a non-linear load. Three different values for the recorded samples per cycle are tested: 32, 64 and 128 (which is the default setting).

The test setup consists of a control meter, reference meter and a non-linear load. The non-linear load that is used is the array of LED and CFL lamps with a dimmer set to 135°. The measurements took approximately two hours, and the readings of the control meter are compared to those of the Yokogawa power analyzer.

Chapter 5

Results

In this chapter, the measurement results are presented. The measurements are performed as described in Chapter 4.

5.1 Energy consumption static meters

A test is done to determine the energy consumed by each of the individual static meters. The measurement took around six days. The results can be seen in Table 5.1.

Table 5.1: Energy consumed by the static meters.

Meter	Energy consumption [Wh]
SM1	1.04
SM2	1.74
SM3	1.95
SM4	3.63
SM5	0.73
SM6	1.69
SM7	3.97
SM8	-0.47
SM9	0.64
SM10	0.63

5.2 Linear load

Tests are done to see how the control meter reacts on a linear load. For this test, the heater of 1800 W is used. Table 5.2 shows the results of this tests. The voltage and current waveforms can be seen in Figure 5.1.

Table 5.2: Consumed energy as measured by different meters, when loaded with a heater of 1800W.

Meter	Energy consumption [Wh]	Difference with control meter [%]
SM1	4788	1
SM2	4791	1
SM3	4806	2
SM4	4799	2
SM5	4789	1
SM6	4776	1
SM7	4772	1
SM8	4738	0
SM9	4812	2
SM10	4767	1
Reference	4787	1
Control Meter	4723	0

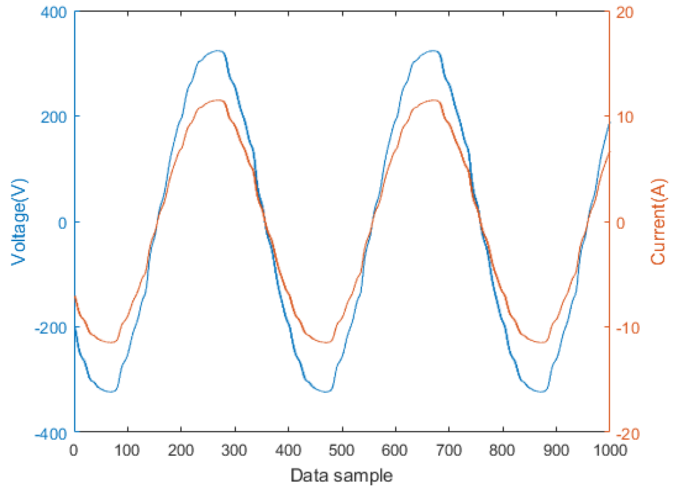

Figure 5.1: Voltage and current waveform loaded with heater of 1800W

5.3 Non-linear load

Test are performed to see how the control meter will react on a load which is known to give faulty energy readings. The control meter is compared to the static meters and the reference meter. The setup is loaded with CFL and LED lamps in combination to a dimmer. There are four tests done with different dimmer stands: 0°, 45°, 90° and 135°. Where 0° indicates that the lamps are completely on and 180° indicates that the lamps are completely off. The measurement time was approximately two hours.

5.3.1 Dimmer set to 0°

For this test, the dimmer is set to 0°. Table 5.3 shows the results of this tests. The voltage and current waveforms can be seen in Figure 5.2.

Table 5.3: Consumed energy as measured by different meters, when loaded with string of CFL and LED lamps in combination with a dimmer on 0°.

Meter	Energy consumption [Wh]	Difference with control meter [%]
SM1	372	4
SM2	371	4
SM3	370	4
SM4	370	4
SM5	374	5
SM6	373	5
SM7	370	4
SM8	365	3
SM9	375	5
SM10	368	3
Reference	370	4
Control Meter	356	0

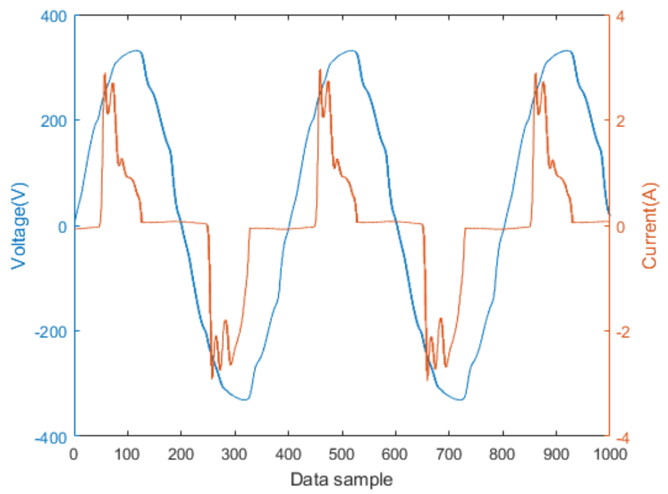

Figure 5.2: Voltage and current waveform when dimmer is set to 0°

5.3.2 Dimmer set to 45°

For this test, the dimmer is set to 45°. Table 5.4 shows the results of this tests. The voltage and current waveforms can be seen in Figure 5.3.

Table 5.4: Consumed energy as measured by different meters, when loaded with string of CFL and LED lamps in combination with a dimmer on 45°.

Meter	Energy consumption [Wh]	Difference with control meter [%]
SM1	368	4
SM2	365	3
SM3	363	2
SM4	369	4
SM5	364	3
SM6	364	3
SM7	365	3
SM8	359	1
SM9	366	3
SM10	363	2
Reference	369	4
Control Meter	355	0

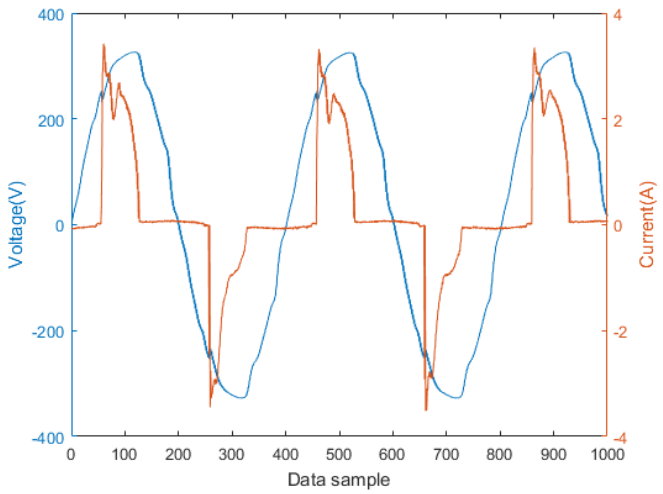

Figure 5.3: Voltage and current waveform when dimmer is set to 45°

5.3.3 Dimmer set to 90°

For this test, the dimmer is set to 90°. Table 5.5 shows the results of this tests. The voltage and current waveforms can be seen in Figure 5.4.

Table 5.5: Consumed energy as measured by different meters, when loaded with string of CFL and LED lamps in combination with a dimmer on 90°.

Meter	Energy consumption [Wh]	Difference with control meter [%]
SM1	416	1
SM2	398	-3
SM3	413	0
SM4	464	12
SM5	456	11
SM6	426	3
SM7	412	0
SM8	453	10
SM9	457	11
SM10	413	0
Reference	412	0
Control Meter	412	0

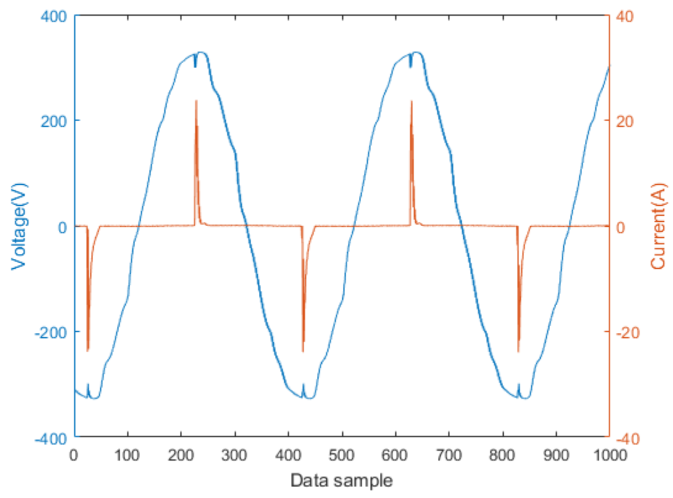

Figure 5.4: Voltage and current waveform when dimmer is set to 90°

5.3.4 Dimmer set to 135°

For this test, the dimmer is set to 135°. Table 5.6 shows the results of this tests. The voltage and current waveforms can be seen in Figure 5.5.

Table 5.6: Consumed energy as measured by different meters, when loaded with string of CFL and LED lamps in combination with a dimmer on 135°.

Meter	Energy consumption [Wh]	Difference with control meter [%]
SM1	327	1
SM2	260	-20
SM3	317	-2
SM4	2947	807
SM5	2969	814
SM6	334	3
SM7	334	3
SM8	2919	798
SM9	2961	811
SM10	270	-17
Reference	316	-3
Control Meter	325	0

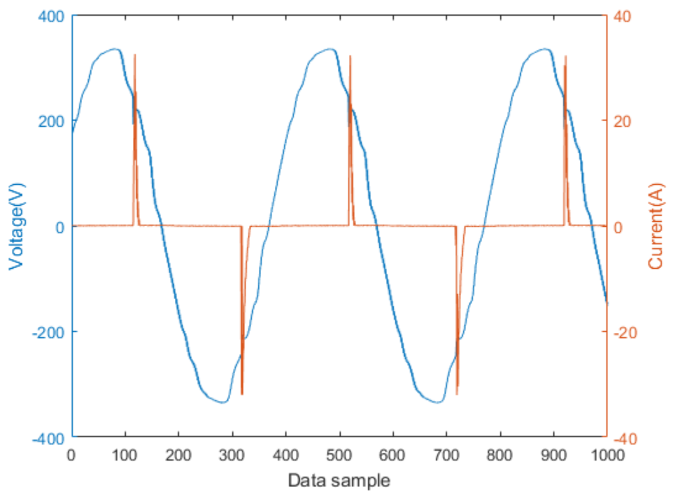

Figure 5.5: Voltage and current waveform when dimmer is set to 135°

5.4 Readout static meter

Table 5.7 shows the comparison between the static meter monitored by the control meter and the energy as measured by the control meter over a period of time.

Table 5.7: Comparison between the energy as measured by the control meter and the static meter monitored by the control meter

Date and time	Energy control meter [W]	Energy static meter [W]
8-11-2017 12:07	0	0
8-11-2017 12:08	26	27
8-11-2017 12:09	57	58
8-11-2017 12:10	87	90
8-11-2017 12:11	118	121
8-11-2017 12:12	148	152
8-11-2017 12:13	179	184
8-11-2017 12:14	209	215
8-11-2017 12:15	240	247
8-11-2017 12:16	270	278
8-11-2017 12:17	280	288

5.5 Measure EM environment

Table 5.8 shows the output as measured by the EM sensor as it appears in the data of the control meter, and the electric field strength calculated from that value, using equation 3.2.

Table 5.8: Comparison between the static meter monitored by the control meter and the energy as measured by the control meter

Date and time	Output voltage sensor [V]	Electric field [V/m]
9-11-2017 15:02	0.266	34
9-11-2017 15:03	0.271	35
9-11-2017 15:04	0.272	35
9-11-2017 15:05	0.271	35
9-11-2017 15:06	0.271	35
9-11-2017 15:07	0.272	35
9-11-2017 15:08	0.269	35
9-11-2017 15:09	0.264	34
9-11-2017 15:10	0.264	34
9-11-2017 15:11	0.264	34
9-11-2017 15:12	0.264	34
9-11-2017 15:13	0.264	34
9-11-2017 15:14	0.266	34
9-11-2017 15:15	0.264	34

5.6 Trigger events

It is tested which information is stored when the control meter is forced to trigger certain events. The events that are triggered by this experiment can be seen in Table 5.9. Event number 2 till 4 repeat for the duration of the experiment. Event 2 and 3 are triggered on the same time, indication that the sag in voltage is really big. The voltage swell indicates that after the voltage sag, the voltage is back to its original level, and thus swells from the sag situation. During these events a snapshot is made from the root mean square (RMS) values and the waveform. This can be seen in the next two subsections.

Table 5.9: Series of events triggered by the control meter.

#	Event type	Approximate duration (s)
1	Snapshot	-
2	Voltage Sag	2
3	Sag became Major Sag	2
4	Voltage Swell	10

5.6.1 Snapshot

The snapshot that is triggered shows the characteristics in the starting situation of the experiment. In the data created, the voltages and currents are captured. However, since no current is measured by the control meter during this experiment, the current captured does not give any information. During these experiments no sensors (e.g. to measure the EM environment and readout the static meter) where added, when this is the case also the values of these sensors are showed in the data captured. In the data file of the RMS values, also the power and frequency are captured. The captured data of the voltage is showed in Figure 5.6.

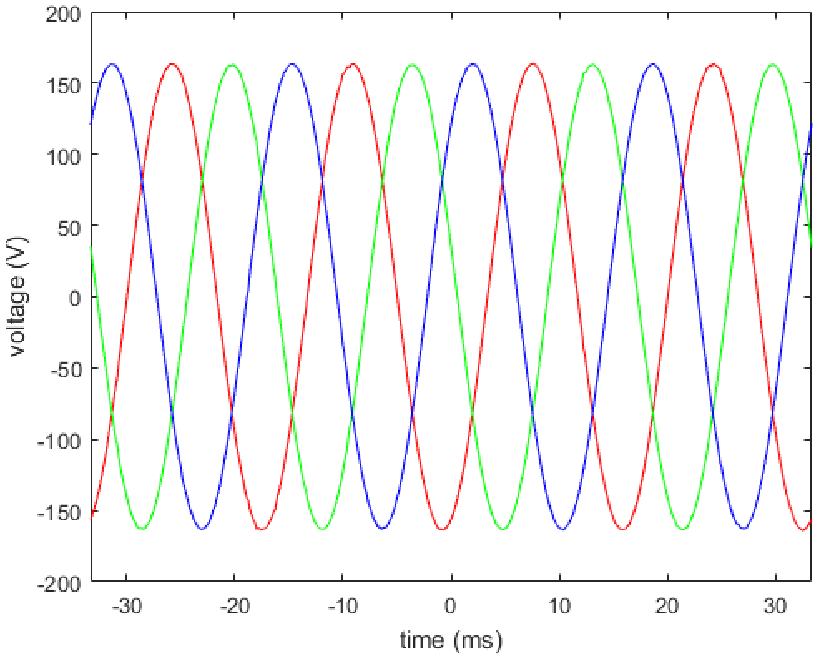

Figure 5.6: Voltage waveforms when the snapshot is triggered

5.6.2 Voltage Sag

The captured voltage data is visualized in Figure 5.7 and 5.8. Only the RMS voltage of L1 is showed, because all phases have the same RMS value.

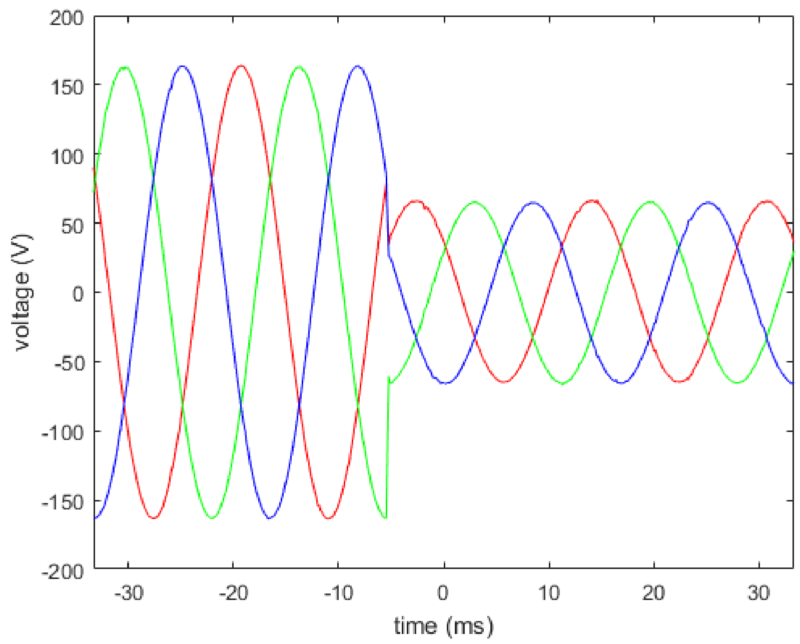

Figure 5.7: Voltage waveforms when the voltage sag is triggered

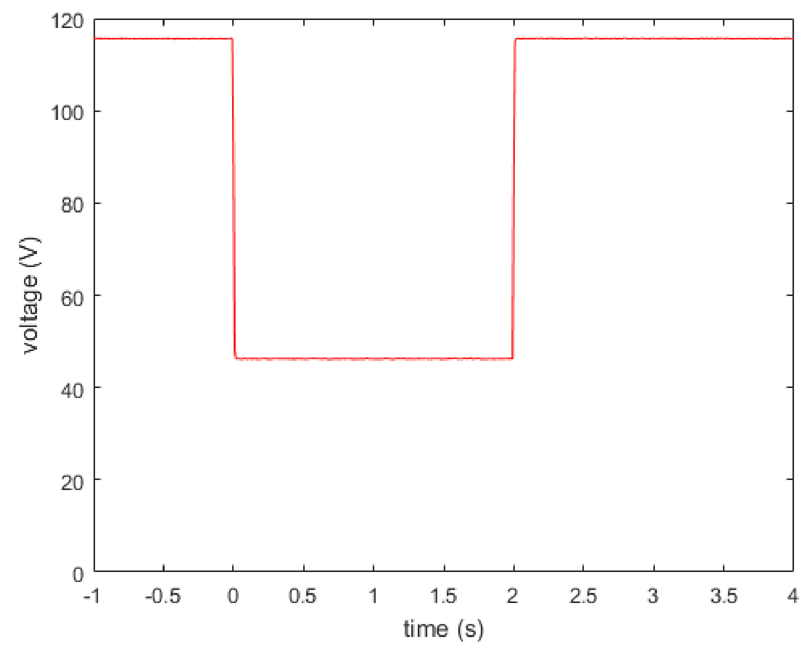

Figure 5.8: RMS values when the voltage sag is triggered

5.7 Sampling rate

Table 5.10 shows the results of the energy consumption as measured by the control meter and the reference meter for different recorded samples per cycle of the control meter.

Table 5.10: Energy consumption measured for different amount of recorded samples per cycle.

Recorded samples per cycle	Control Meter [kW]	Reference meter [kW]	Difference [%]
32	288	278	3
64	281	272	3
128	265	256	4

Chapter 6

Discussion

In this chapter the results of the measurements as presented in Chapter 5 are discussed. Furthermore some remarks are discussed about the functioning of the design for the control meter. These remarks are based on the experience of the control meter in experiments and tests performed with it.

The measurements on the energy consumption of the static meters show that all of the static meters consume a couple of watthours. There is some difference in the consumption, but all of the static meters only consume a couple of Wh. This is as was expected. However, one of the static meters, static meter 8, has a negative energy consumption. This looks strange, because it should mean that this meter delivers power to the circuit. The energy consumption of the meters is measured with respect to the meter placed after it, so it means that static meter 8 measures less energy consumed than static meter 9. All of the static meters have some inaccuracy, which can result in this behavior. Only a small amount of energy consumption is measured, this small energy consumption difference between the two meters could fit in these accuracy limits.

From the tests done to verify the readings of the control meter when loaded with linear and non-linear loads, it can be seen that the difference between the control meter and the reference meter is never bigger than 4%. When the current waveforms become more non-linear, shown in Figure 5.1 till 5.5, there are no big differences between them. However, the more non-linear current waveforms are misinterpret by the static meters. These show large deviations when the dimmer is set to 90° and 135°. This confirmes the research done in [6], [7], and [8]. From these measurements, there can be said that these tested loads do not have an influence on the readings of the control meter.

The results from Section 5.4 and 5.5 show that it is possible to monitor the installed static meter and the EM environment. It shows that this functions work properly and could be used to do on-site measurements. However, a remark has to be made on the sensory system measuring the installed static meter. During the measurements the plastic cap of the static meters was removed. These caps are included on some of the static meters, to prevent one from touching the electronics. When these are not removed, as is the case for on-site measurements, the ambient light interference with the optical sensor. Commercially available sensors should overcome this problem. The data of the EM sensor appears in the log files as the voltage measured by the sensor. This should be converted to the electric field value manually. Another option is to write software that does this.

From the results of the test, triggering certain events on the control meter, it can be seen that the data captured is useful to analyze the behavior in cases of an event. The voltage waveform is captured really detailed. When a sensor used to monitor the installed static meter or EM environment would be added (in these tests) these values can be analyzed really detailed in cases of such an event. It is also possible to trigger an event if the EM sensor gives extremely high or low values, which can become useful when analyzing the behavior of a static meter in cases of extremely high electric fields in the surrounding of this meter.

When the sampling rate of the control meter is changed, the measured energy consumption by the control meter stays approximately the same with reference to the reference meter. This shows that the control meter can also capture the pulsed current when the number of recorded samples per cycle is lowered. However, to make sure that all the data is captured correctly it is preferred to use the default setting of 128 recorded samples per cycle.

Chapter 7

Conclusion and recommendations

The control meter as designed is able to give a reasonable reference for a static meter when performing field tests. The meter is able to measure the energy consumption in the circuit, and can compare this with the readings of the static meter. Furthermore it can measure the EM environment in the surroundings of the installed static meter. The data obtained can be logged remotely and the control meter is easy to install by a local electrical engineer.

For further research it would be recommended to investigate on the current probes that are used for this control meter. The ones that are used now are too bulky. Current probes that are smaller and more flexible should be used in further research. Furthermore a more detailed look should be taken to the optical sensors that are used. It turned out that the one which is used now with a wide spectral responsivity is also sensitive for the ambient light, which can give errors. This can be solved by putting a box around the static meter, or to use another, more expensive, commercial available sensor.

Bibliography

[1] R. R. Sherburne, “Driving torque equations for the watthour meter based on the ferraris principle,” *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-90, no. 1, pp. 325–330, 1971.

[2] “Problemen met de slimme meter of met de niet-zo-slimme consument?” [Online]. Available: https://radar.avrotros.nl/testpanel/uitslagen/detail/problemen-met-de-slimme-meter-of-met-de-niet-zo-slimme-consument

[3] F. Leferink, “Conducted interference, challenges and interference cases,” *IEEE Electromagnetic Compatibility Magazine*, vol. 4, no. 1, pp. 78–85, 2015.

[4] J. Kirchhof and G. Klein, “EMV - grenzwertlücke - wechselrichter stört zähler,” *24. Symposium Photovoltaische Solarenergie, Bad Staffelstein, 2009*.

[5] J. Kirchhof, “Grenzwertlücke - wechselrichter stört elektrizitätszähler,” *EMV 2010, Dsseldorf*.

[6] F. Leferink, C. Keyer, and A. Melentjev, “Runaway energy meters due to conducted electromagnetic interference,” in *IEEE International Symposium on Electromagnetic Compatibility*, vol. 2016-November, 2016, pp. 172–175.

[7] ——, “Static energy meter errors caused by conducted electromagnetic interference,” *IEEE Electromagnetic Compatibility Magazine*, vol. 5, no. 4, pp. 49–55, 2016.

[8] C. Keyer and F. Leferink, “Conducted interference on smart meters,” in *IEEE International Symposium on Electromagnetic Compatibility*, 2017, pp. 608–611.

[9] B. ten Have, F. Leferink, and C. Keyer, “Monitoring of power transfered as measured by static energy meters,” in *IEEE International Symposium on Electromagnetic Compatibility*, 2018.

[10] “IEC62053-1,” 2003.

[11] “Specifications pqube3.” [Online]. Available: https://www.powerstandards.com/product/pqube-3/specifications/

[12] “Model pqube-02-0001-xx specifications.” [Online]. Available: https://www.powerstandards.com/product/pqube-classic/specifications/

[13] “Fluke 1736 power logger.” [Online]. Available: http://www.fluke.com/fluke/nlnl/power-quality-tools/driefasig/fluke-1736-power-logger.htm?pid=80077

[14] “Unilyzer 900 power quality analyzer.” [Online]. Available: http://unipower.se/products-and-services/portable-instruments/unilyzer-900/

[15] “Pel103 power-energy logger.” [Online]. Available: http://www.chauvin-arnoux.com/en/produit/PEL103

[16] “Unilyzer 902 network analyzer.” [Online]. Available: http://unipower.se/products-and-services/portable-instruments/unilyzer-902/

[17] “emontx v3 - electricity monitoring transmitter.” [Online]. Available: https://shop.openenergymonitor.com/emontx-v3-electricity-monitoring-transmitter/

[18] “Specifications emonpi.” [Online]. Available: https://guide.openenergymonitor.org/technical/specifications/

[19] “Smappee pro detailed product description.” [Online]. Available: https://www.smappee.com/media/wysiwyg/Manuals/Smappee%20Pro%20Detailed%20Product%20Description.pdf

[20] “Pqube3 current sensors.” [Online]. Available: https://www.powerstandards.com/product/kits-modules-accessories/current-sensors/

[21] “Rct-1200-000 flexible rogowski coil.” [Online]. Available: http://www.magnelab.com/products/ac-flexible-rogowski-coil-rct-1200-000/

[22] “Efergy split core current transformer.” [Online]. Available: https://docs-emea.rs-online.com/webdocs/154c/0900766b8154cc2b.pdf

[23] “mv split core current transformers.” [Online]. Available: https://www.hobut.co.uk/current-transformers/split-core-cts/mv-split-core-current-transformers

[24] “Yhdc product specification.” [Online]. Available: http://www.yhdc.us/ENpdf/SCT013-000-0-100A-0-50mA_en.pdf

Appendix A

Arduino code static meter setup

This appendix shows the Arduino code that is used to translate the voltage pulses obtained by the optical sensors attached to the static meters, into a counter that keeps track of the number of LED pulses, for every individual static meter included in the static meter test setup.

```
#include <Arduino.h>
//#include "../../../../../ProgramData/Anaconda3/hardware/arduino/avr/cores/arduino/USBAPI.h"
//#include "../../../../../ProgramData/Anaconda3/hardware/arduino/avr/cores/arduino/HardwareSerial.h"
//#include "../../../../../Program Files (x86)/CodeBlocks/MinGW/avr/include/stdlib.h"


const int inputPin = 0;
const int outputPin = 8;
const int pins = 16;
const long interval = 30000;


unsigned long previousMillis = 0;
unsigned long currentMillis=0;

int k[pins]={};
int counter[pins] = {};
bool curState[pins] = {};
bool oldState[pins] ={};
//only works for the mega..
int thres[pins] = {300,500,200,20,40,100,150,150,40,600,100,555,40,60,555,555};



void setup() {
```

```
    Serial.begin(9600);
    pinMode(inputPin,INPUT);
    pinMode(outputPin,OUTPUT);


}
void loop() {
     currentMillis = millis();
    randomSeed(analogRead(0));
    for (int i = 0; i < pins; ++i) {

//          curState[i] = random(0,250) > thres[i];
        curState[i] = analogRead(i) > thres[i];
        cnt(curState[i], oldState[i], counter[i]);


//          if (counter[i] % 1000 == 0) {
//              if (k[i] == 0) {
//                  {
//                      Serial.println("tot duizend geteld op pin,\n");
//                      Serial.println(i);
//                      k[i]++;
//                  }
//
//              } else {
//                  k[i] = 0;
//              }
//
//          }


    }
    //only send back the data once every xxx cycles
if(currentMillis - previousMillis >= interval){
    previousMillis = currentMillis;
    Serial.print("T = ");
    Serial.print(currentMillis/1000);
    Serial.print("; ");
    takeReading();}



}

void cnt(bool &curState, bool &oldState, int &counter){
    if (curState != oldState)
    {
```

```
        if (curState == HIGH)
        {
            counter++;

        }
    }
    oldState=curState;
//    return counter;
}

void takeReading()
    {
        for(int i =0; i<pins; ++i){
            Serial.print("Pin(");
            Serial.print(i);
            Serial.print(") = ");
            Serial.print(counter[i]);
            Serial.print("; ");
            if (i==(pins-1)){Serial.print('\n');}

        }
    }
```

:

Appendix B

Matlab code static meter setup

This appendix shows the Matlab GUI that is used to have a live view of the consumed energy as measured by the static meters, using data obtained from the Arduino. It gives the power transfer measured by the static meters over the last 30 seconds. And saves the data into a spreadsheet.

```
function varargout = gui_meters(varargin)
% GUI_METERS MATLAB code for gui_meters.fig
%      GUI_METERS, by itself, creates a new GUI_METERS or raises the existing
%      singleton*.
%
%      H = GUI_METERS returns the handle to a new GUI_METERS or the handle to
%      the existing singleton*.
%
%      GUI_METERS('CALLBACK',hObject,eventData,handles,...) calls the local
%      function named CALLBACK in GUI_METERS.M with the given input arguments.
%
%      GUI_METERS('Property','Value',...) creates a new GUI_METERS or raises the
%      existing singleton*.  Starting from the left, property value pairs are
%      applied to the GUI before gui_meters_OpeningFcn gets called.  An
%      unrecognized property name or invalid value makes property application
%      stop.  All inputs are passed to gui_meters_OpeningFcn via varargin.
%
%      *See GUI Options on GUIDE's Tools menu.  Choose "GUI allows only one
%      instance to run (singleton)".
%
```

```
% See also: GUIDE, GUIDATA, GUIHANDLES

% Edit the above text to modify the response to help gui_meters

% Last Modified by GUIDE v2.5 30-Oct-2017 16:47:51

% Begin initialization code - DO NOT EDIT
gui_Singleton = 1;
global ii
ii=0;
gui_State = struct('gui_Name',       mfilename, ...
    'gui_Singleton',  gui_Singleton, ...
    'gui_OpeningFcn', @gui_meters_OpeningFcn, ...
    'gui_OutputFcn',  @gui_meters_OutputFcn, ...
    'gui_LayoutFcn',  [] , ...
    'gui_Callback',   []);
if nargin && ischar(varargin{1})
    gui_State.gui_Callback = str2func(varargin{1});
end

if nargout
    [varargout{1:nargout}] = gui_mainfcn(gui_State, varargin{:});
else
    gui_mainfcn(gui_State, varargin{:});
end
% End initialization code - DO NOT EDIT


% --- Executes just before gui_meters is made visible.
function gui_meters_OpeningFcn(hObject, eventdata, handles, varargin)
% This function has no output args, see OutputFcn.
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
% varargin   command line arguments to gui_meters (see VARARGIN)

% Choose default command line output for gui_meters
handles.output = hObject;

% Update handles structure
guidata(hObject, handles);

% UIWAIT makes gui_meters wait for user response (see UIRESUME)
% uiwait(handles.figure1);


% --- Outputs from this function are returned to the command line.
```

```
function varargout = gui_meters_OutputFcn(hObject, eventdata, handles)
% varargout  cell array for returning output args (see VARARGOUT);
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Get default command line output from handles structure
varargout{1} = handles.output;



% --- Executes on button press in togglebutton1.
function togglebutton1_Callback(hObject, eventdata, handles)
global ii
display('drukken op knop')
if (ii==0&&get(hObject,'Value')~=0)
    display('een keer toch?')
    s = serial('COM4')
    s.Timeout = 60;
    fopen(s)
    % else
    % fclose(s)
    % ii=-1;
end
ii=ii+1;

k=0;
%initialize excell file for saving the data
filename = datestr(now);
filename(strfind(filename,' '))=['_'];
filename(strfind(filename,'-'))=[];
filename(strfind(filename,':'))=[];
filename = [filename '.xlsx'];
P = {'Time','NotCon','NotCon','1','2','3','4','5','6','7','8','9','NotCon
    ','NotCon','10','NotCon','NotCon';
     '422948','NotCon','NotCon','2120','1998','1793','1564','1138','1052',
    '854','387','442','NotCon','NotCon','367.264','NotCon','NotCon'};
xlswrite(filename,P,1,'A1')
%Second line of P indicates the correction matrix, the disipation of the
    SM
T_cor = 422948;
Pin_cor =
    [0,0,2120,1998,1793,1564*0.5,1138,1052,854,387,442*0.5,0,0,367.264,0,0];



T_old = 0;
Pin_old = zeros(1,16);
```

```
while get(hObject,'Value')

    k=k+1;
    readasync(s);
    out = fscanf(s);
    if out(1)=='T'
    %eval(out)
    i=1;
    out(strfind(out, ' ')) = [];
    for N=1:length(out)
        if out(N)=='='
            vraag(i)=N;
        end
        if out(N)==';'
            punt(i)=N;
            i=i+1;
        end
    end

    for M=1:i-1
        output(:,M)=eval(out(vraag(M)+1:punt(M)-1));
    end

    T = output(:,1);
    Pin = output(:,2:length(output));
    %
    w = calculation_watt(Pin-Pin_old,T-T_old);
    set(handles.text3, 'String', num2str(round(w)))
    row = ['A' num2str(k+2)];
    xlswrite(filename,[T Pin],1,row)

    T_old = T;
    Pin_old =Pin;
    end
    %% calculation_watt(Pin,T,k);
    % fclose(s)

    Pin2 = Pin - (Pin_cor/T_cor)*T;
    %set(handles.text2, 'String', out)
    set(handles.text2, 'String', num2str([T round(Pin2)]))
    pause(0.01)
    if get(hObject,'Value')==0
        fclose(s)
        ii=0
    end

```

```
end


% --- Executes on button press in togglebutton1.


function watt=calculation_watt(Pin,T)
    %assumed are 1000 imp/kwh
    imp_vec = [1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1];
    %imp_vec(14)=2; %A13, 2000 pulses per kwh
    imp_vec(6)=0.5; %A5, 500 pulses per kwh
    imp_vec(11)=0.5; %A10,500 pulses per kwh
    watt=(Pin./(T./3600))./imp_vec;


% hObject    handle to togglebutton1 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hint: get(hObject,'Value') returns toggle state of togglebutton1
```

:

Appendix C

Paper submitted to EMC Europe 2018

This appendix shows the paper: Monitoring of Power Measured by Static Energy Meters for Observing EMI Issues, which is written during the MSc. Thesis. This is the version which is submitted and accepted to EMC Europe 2018.

Monitoring of Power Measured by Static Energy Meters for Observing EMI Issues

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***Abstract*—Static energy meters are becoming the standard for measuring the consumed energy in households. Previous research showed that static meters can give faulty energy readings. The blinking light emitting diode (LED) in the meter gives, in many meters, a factor 1000 more accurate reading compared to the display readings. In case possible misreading has to be investigated a series energy meter would be useful, with the additional possibility to readout the blinking LED. This would allow detailed research on the behavior of static energy meters and test possible sources of interference, especially in cases where the energy consumption is low, and the risk of deviation could be high. Such a monitoring system has been designed and implemented allowing to monitor a series of static meters and the consumed energy such that a source of interference can be observed directly.**

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

I. Introduction

Nowadays, the old fashioned electromechanical energy meters, based on the Ferraris principle, are replaced by static energy meters. These meters are called smart meters if a communication link is added to transmit the recorded data. Some consumers who use these static meters, complain about their meter reading. They claim that the static meter gives higher readings compared to the old electromechanical meter. The electric utilities claim that the customers should be happy that they paid too less for years, because of wear the old meters gave incorrect, and too low readings.

In [1] two neighboring farmers installed the same Photo Voltaic (PV) system, but on sunny days there was a difference of 40% of delivered energy between the two PV systems. Experiments show that high interference levels on the power lines where caused by the power drive systems of the fans. [1], which resulted in faulty readings of the static meter. Faulty readings of static energy meters due to PV systems were also observed in [2], [3]. These where caused due to high interference levels generated by active infeed converters connected to PV systems. In all cases the energy meters gave lower readings.

Research has shown that in some other cases the static meters can give faulty energy readings, positive and negative, if static meters are loaded with pulsed currents [4], [5], [6]. In [4], controlled experiments on static meters show that they can present faulty readings. When using static meters in a three-phase standardized power supply setup, loaded with a string of compact fluorescent lamps (CFL) and light emitting diode (LED) lamps in combination with a dimmer, static meters show a positive deviation of 276% and a negative deviation of -46% compared to conventional electromechanical energy meters. The experimental results in [5] and [6] show that the tested static meters using a standard building power supply gave maximal positive deviations of $+582\%$ and negative deviations of -32% when loaded with CFL and LED lamps in combination with a dimmer for a one-phase test setup. Because the energy consumption of LED and CFL lights is low, these experiments were carried out by measuring over a period of 1 to 2 weeks. All experiments have also been repeated, so the experiments using the standardized power supply took approximately 3 months, and the extended experiments using a mains supply took 4 months to complete. An array of 50 lamps was used such that effects measured by static meters could be observed faster. But this array is not a realistic situation anymore.

Furthermore, for further research on the errors of static energy meters due to interfering sources, it would be beneficial to monitor a series of static meters. Therefore, a test setup was built that can monitor the energy consumption as indicated by around ten static meters in a short period of time. The blinking LED of the static meter is monitored, this gives a 500 to 1000 (depending of the brand of the meter) more accurate reading compared to the LCD display. Monitoring this blinking LED would allow faster experiments.The frequency at which the energy is consumed, the power, is also measured, this is the frequency of the blinking LED. When performing measurements with this setup, interference on the static meters can be observed instantaneously, instead of the 24 hours to 2 weeks as in [4], [5] and [6].

The rest of the paper is organized as follows. Section II describes the static meter setup that is used. In section III the monitoring of the energy consumption as measured by the static meter is described. Section IV describes the data processing needed for the test setup to process the energy consumption into the real power transferred over a certain period. Section V describes a simple verification of the test setup using a linear load. Section VI describes some disturbances of the setup due to injection of radio frequency signals. And finally Section VII gives the concluding remarks of the study.

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II. Static meter setup

A series of 10 static meters are connected in series using one-phase, because some of the meters are single-phase types. Fig. 1 and Fig. 2 show the static meter test setup. Meters that are included in the test setup have different types of current sensors: shunt resistor, current transformer, Hall effect-based current sensor and Rogowski coil. The meters are representative of the installed base of energy meters in The Netherlands. The meters are fed using standard mains supply, but it is also possible to feed them using a generator to create a clean supply with a standardized mains impedance.

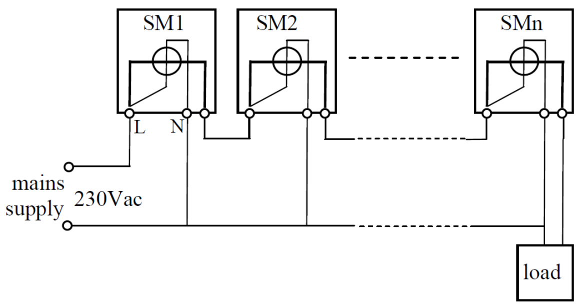

Fig. 1. Schematic of the static meter test setup

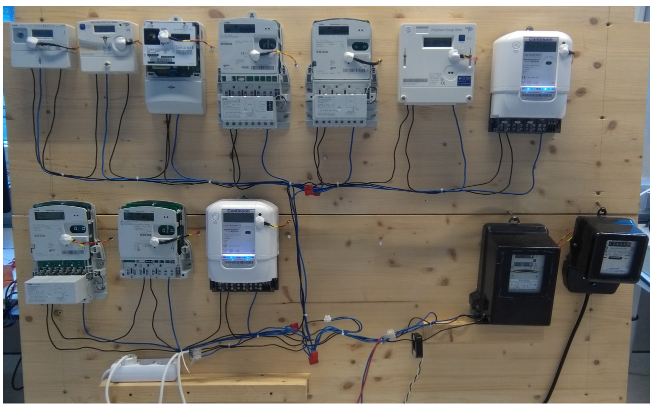

Fig. 2. Picture of the static meter test setup

In the test setup, the static meters are placed in series with each other which means that SM1 also measures the energy which is consumed by SM2 to SMn. Therefore, the energy meter reading is corrected with the consumed energy of the following meters.

III. Monitoring energy consumption

The static meters have a blinking LED integrated, which blinks if a certain amount of energy is consumed. For most of the meters this is one blink per 1 or 2 Wh of energy consumed in the circuit. This LED pulse can be monitored by attaching it to an optical sensor. Such an optical sensor should give a voltage dependent on whether the LED is on or off, such that this blinking LED can be translated into an analog voltage signal. A light dependent resistor (LDR) for which the resistance is inversely proportional to the intensity of the light it receives, can be used for this purpose. Using the LDR and a $1\,\mathrm{k\Omega}$ resistor, a voltage divider is created, such that the output voltage over the resistor can be measured. This voltage divider is fed with an input voltage of $5\,\mathrm{VDC}$ and the output is connected to an Arduino Mega microcontroller. When the LDR is connected to a static meter, loaded with a resistive load of $850\,\mathrm{W}$, meaning around 14 LED blinks per minute, the output can be seen in Fig. 3. When the LED is turned off, the output is almost zero and when the LED is on a clear voltage pulse can be seen. This configuration can translate the blinking LED into a voltage signal correctly.

However, the response time is moderate, the falling edge of the pulse is rather slow and is creating a wide pulse. Furthermore, it needs more than one data point to get to its maximum value, as can be seen in Fig 4. This can become problematic if there are a lot of pulses close to each other. Therefore, another configuration is made using so called light-to-voltage optical sensors, which is an IC packet combining a photodiode and a transimpedance amplifier. Photodiodes have a quicker response time compared to a LDR and should therefore solve this problem. The output voltage of this sensor is directly proportional with the light intensity directed on the photodiode. A TSL261RD light-to-voltage optical sensor is used, the photodiode spectral responsivity shows that it is sensitive to wavelengths around $900\,\mathrm{nm}$. Again, the output of the sensor is connected to an Arduino Mega microcontroller. Fig. 3 shows the output of the sensor when the static meter is connected to a resistive load of $850\,\mathrm{W}$. Fig. 4 shows a zoomed version of the response. It can be seen that the response time is much quicker and as a result the pulse looks much smoother compared to the LDR.

A drawback of using this specific light-to-voltage optical sensor is that the intensity and the wavelength of the LEDs is not exactly the same for the different static meters. Therefore, using this sensor, it was not possible to measure all of the static meters included in the test setup. Another light-to-voltage optical sensor was used, the TSL257. This photodiode is sensitive to wavelengths between 500 and $800\,\mathrm{nm}$. The result of using this optical sensor can also be seen in Fig. 3, it shows that the pulse is very smooth. When the LED is turned off, this sensor shows a much higher voltage compared to the other two sensors, because it is not only sensitive to the blinking LED, but also to the ambient light. However, when the sensor is interfered with ambient light, it does not give a noisy signal.

A combination of these three optical sensors is attached to the static meters test setup. The sensors are attached to the static meters using some sticky material, and can be seen in Fig. 5.

IV. Data processing

In order to process the data and count the number of pulses created by the optical sensors, these sensors are connected to an Arduino Mega microcontroller. To verify when there is a pulse, the output voltage of the optical sensors should

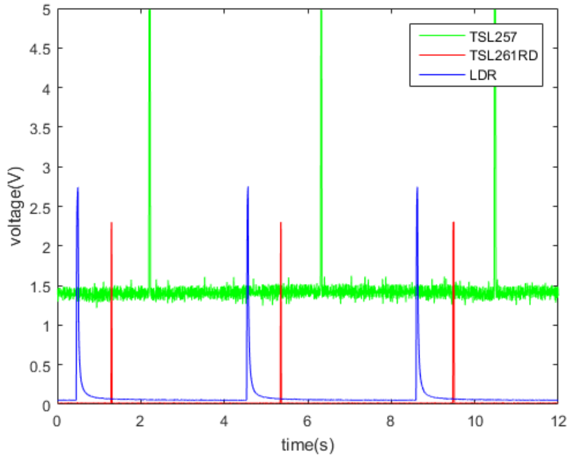

Fig. 3. Response of the optical sensors connected to a LED on a static meter when loaded with 850 W resistor. For optical sensors: TSL257 in green, TSL261RD in red and LDR in blue.

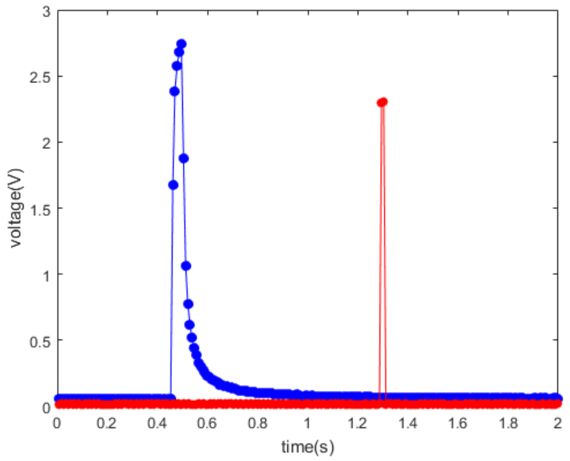

Fig. 4. Zoomed version of the response of the optical sensors connected to a LED on a static meter when loaded with 850 W resistor, dots indicate the data points. For optical sensors: TSL261RD in red and LDR in blue.

exceed a certain threshold voltage. These threshold voltages are determined experimental for each individual optical sensor.

The microcontroller reads all of the 10 optical sensors continuously and compares these voltages to the threshold level. Since two situations are possible, either a pulse or no pulse, this is programmed as a state machine with two states. In $\mathrm{curState} = 0$ there is no pulse and in $\mathrm{curState} = 1$ there is a pulse. It goes from state 0 to 1 if the voltage rises the threshold and from 1 to 0 if the voltage falls under this threshold. The pulse counter is incremented at the moment that the state changes from 0 to 1. A state diagram is shown in Fig. 6. This procedure is performed for every optical sensor, such that the output data is an array of elements containing the amount of measured pulses for each individual static meter.

After a certain time interval, this data is written to the serial

Fig. 5. Optical sensors as attached to a static meter

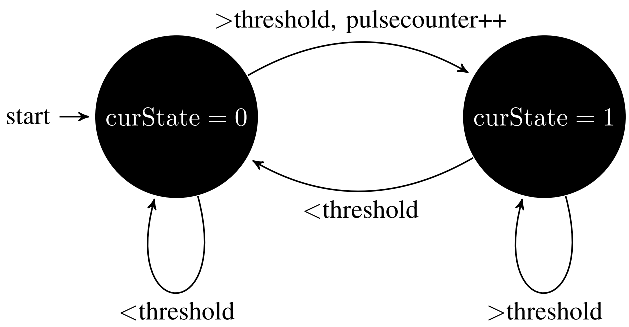

Fig. 6. State diagram of the microcontroller

monitor of the microcontroller, which is attached to a computer running MATLAB to process the data. The interval in which the data is updated to the serial monitor can change dependent on the measurements, normally around 30 to 60 seconds. This data consists of the number of pulses for each static meter and a timer indicating the total length of the measurements.

Using the number of pulses and the elapsed time, the frequency at which the pulses occur can be determined. The frequency at which the pulses occur is the energy per amount of time, which is the real power transferred in the circuit, eq. 1. Where P is the real power transfered, E is the energy consumed and t is the time. This real power can be calculated over the whole measurement period or over the data from the last update of the microcontroller only.

$$\mathrm{P}\,[\mathrm{W}] = \frac{\mathrm{E}\,[\mathrm{Wh}]}{\mathrm{t}\,[\mathrm{h}]} \tag{1}$$

For this setup, it is of great benefit that it can be seen directly if a possible source of interference interferes with the test setup. This can be achieved by calculating the real power transferred over the last update of the microcontroller. The data obtained from the microcontroller is the total time and total number of pulses. The number of pulses counted is translated to energy consumed, by using the LED pulse speed of the static meter, which is the number of pulses the LED has per kWh consumed, as can be seen in eq. 2. The data of the last update is also stored in MATLAB and compared to the new data to get the real power over the last update, as can be seen in eq. 3.

$$\mathrm{energy_i}\,[\mathrm{Wh}] = \mathrm{pulses_i} \cdot \mathrm{LEDpulseSpeed_i} \tag{2}$$

$$\begin{aligned} \Delta\,\mathrm{energy}\,[\mathrm{Wh}] &= \mathrm{energy_{upd}}\,[\mathrm{Wh}] - \mathrm{energy_{old}}\,[\mathrm{Wh}] \\ \Delta\,\mathrm{time}\,[\mathrm{s}] &= \mathrm{time_{upd}}\,[\mathrm{s}] - \mathrm{time_{old}}\,[\mathrm{s}] \\ \mathrm{real\,power}\,[\mathrm{W}] &= \frac{\Delta\,\mathrm{energy}\,[\mathrm{Wh}]}{\Delta\,\mathrm{time}\,[\mathrm{s}]} \cdot 3600 \end{aligned} \tag{3}$$

Using this procedure, every time there is new data present at the serial monitor, the real power transferred over this interval as measured by the static meters is calculated.

V. Verification Setup

This section shows a verification of the test setup that is built as described in the previous chapters.

A. LED pulse counting

To verify if this setup can monitor the static meters correctly, a resistive load of 1900 W is connected to the setup and the energy consumption monitored by our setup to the energy consumption as indicated on the screens of the static meters is compared. The measurement took around 21 hours and seven meters where monitored during this period. Table I shows the results of this verification, which shows that the difference between the LED pulse counting and the values as indicated on the screens of the static meters is within 3%. Most of the static meters indicate the energy consumed in kWh on their screen (this is true for: SM2, SM3, SM4, SM6 and SM7), while the pulse counter measures in the order of Wh consumed. This causes differences above 1%, for the rest of the static meters the difference is much closer. So it can be said that the setup is able to count the LED pulses correctly, with a small measurement error.

TABLE I
Comparison between energy consumption measured and indicated on the screens of the static meters.

SM	Measured [Wh]	Screen SM [Wh]	Difference [%]
SM1	40085	40300	-0.53
SM2	40014	41000	-2.40
SM3	39988	40000	-0.03
SM4	39946	41000	-2.57
SM5	39731	39970	-0.60
SM6	39335	40000	-1.66
SM7	39780	40000	-0.55

B. Power measurement

A simple test has been done to show that the measurement setup can detect changes in power transferred in the circuit fast, as would be the case when an interfering source is turned on or off. For this test a static meter is loaded with a resistor of 1900 W. When the measurements start, the resistor is turned off and consumes no energy, and it is turned on and off again after some time. It is expected that these two situations are clearly visible in a short time period.

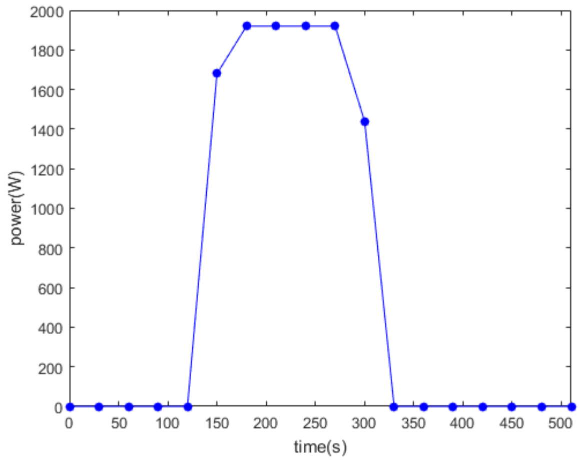

Fig. 7. Power response of a static meter, when a resistive load is turned on and off.

Fig. 7 shows the result of this test, the data is obtained from the microcontroller every 30 seconds. When the resistive load is turned on, then within a minute the setup shows that the static meter is loaded with approximately 1900 W. Only one static meter is shown in the figure, because all other meters tested show the same behavior.

VI. Disturbance in EMI Experiments

EMI experiments are performed on the injection of radio frequency (RF) signals, between 10 and 110 MHz, to the circuit using a current injection clamp. These experiments are performed in a Faraday cage to make sure that the setup is not disturbed by the surrounding and vice versa. The injection of current is done using the MIL-STD-461F CS114 test setup [7].

When performing these experiments, it was found that the injected signal was also coupled into the wires between the sensor and the microcontroller. This interference was reduced using a couple of ferrite clamp-on cores, which are wrapped around the wires one or more times. Fig. 8 shows these ferrite clamp-on cores as attached to the wires between the sensor and microcontroller. Using the ferrite cores the interference on the wires was attenuated, such that a decent measurement result was obtained.

VII. Conclusion

To perform research on the actual causes of errors on static energy meters due to interfering sources, a setup is made, which can be used to monitor a couple of static meters very fast. The setup is capable of showing the real power transferred in a circuit over a short time interval of around 30 seconds. This will allow to pinpoint possible sources of electromagnetic interference.

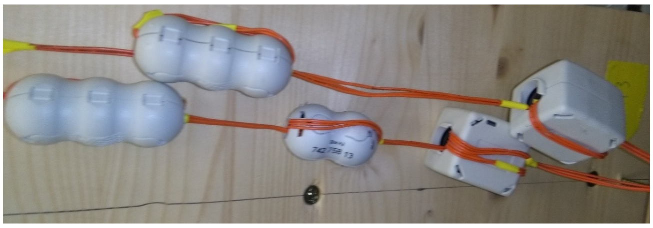

Fig. 8. Ferrite clamp-on cores wrapped around the wires between the sensor and microcontroller.

References

[1] F. Leferink, "Conducted interference, challenges and interference cases," *IEEE Electromagnetic Compatibility Magazine*, vol. 4, no. 1, pp. 78–85, 2015.

[2] J. Kirchhof and G. Klein, "EMV - grenzwertlücke - wechselrichter stört zähler," *24. Symposium Photovoltaische Solarenergie, Bad Staffelstein, 2009*.

[3] J. Kirchhof, "Grenzwertlücke - wechselrichter stört elektrizitätszähler," *EMV 2010, Dsseldorf*.

[4] F. Leferink, C. Keyer, and A. Melentjev, "Runaway energy meters due to conducted electromagnetic interference," in *IEEE International Symposium on Electromagnetic Compatibility*, vol. 2016-November, 2016, pp. 172–175.

[5] ——, "Static energy meter errors caused by conducted electromagnetic interference," *IEEE Electromagnetic Compatibility Magazine*, vol. 5, no. 4, pp. 49–55, 2016.

[6] C. Keyer and F. Leferink, "Conducted interference on smart meters," in *IEEE International Symposium on Electromagnetic Compatibility*, 2017, pp. 608–611.

[7] MIL-STD-461F, "Department of defense interface standard, requirements for the control of electromagnetic interference characteristics of subsystems and equipment," 10 December 2007.