From Susceptible Static Energy Meters to Electromagnetic Compatible Energy Measurements

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de Nederlandse EMC-ESD Vereniging
EMC-ESD Event 2023
Hotel van der Valk Vianen
Dinsdag 21 november

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Static Energy Meter Errors Caused by Conducted Electromagnetic Interference

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Smart energy meters giving readings up to six times too high, study finds

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'Slimme meter is onbetrouwbaar'

Nieuws • 03-03-2017

UMSTRITTENE STUDIE

Warum manche Stromzähler extrem falsch messen

Finances personnelles > Informations > Actualités

Certains compteurs intelligents surestimeraient la consommation en électricité

Le Figaro le 12/03/2017 à 14:49 — 2

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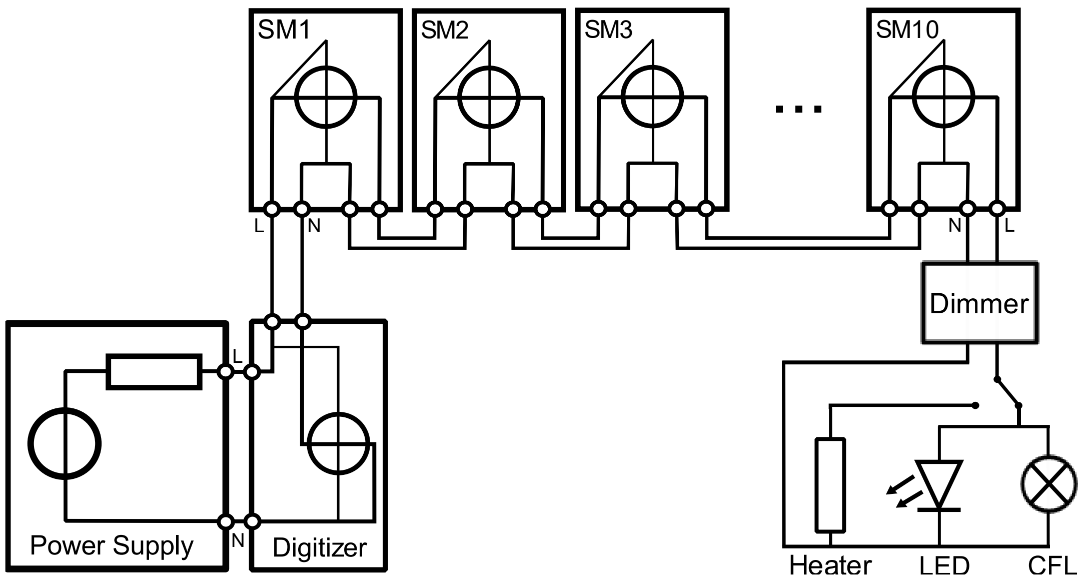
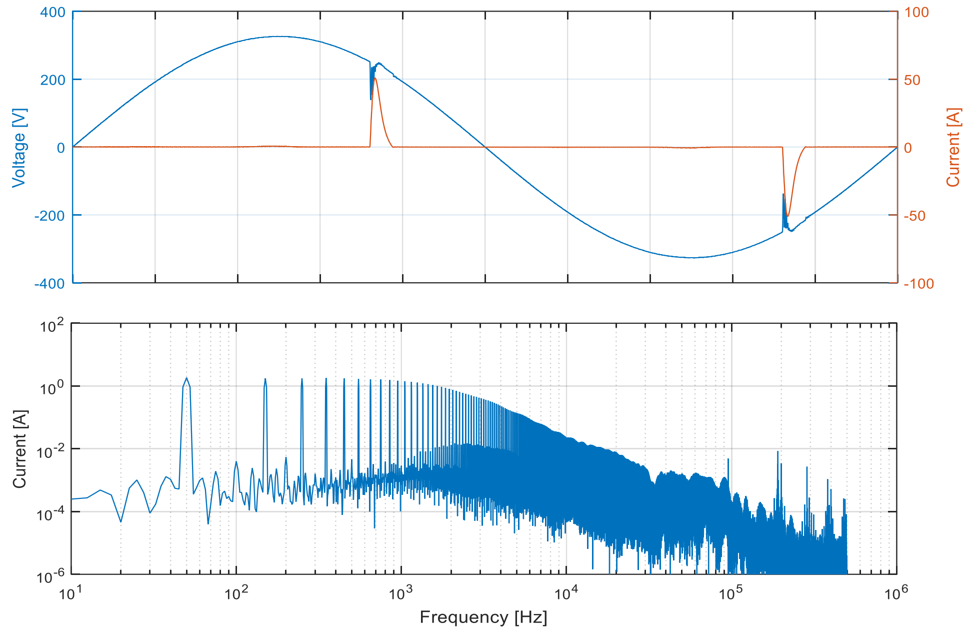
Verification at VSL





Measurements:

- Signal shape, FFT
- Energy of all meters

Traceable to international reference standards

⇒ Confirmation of UT findings

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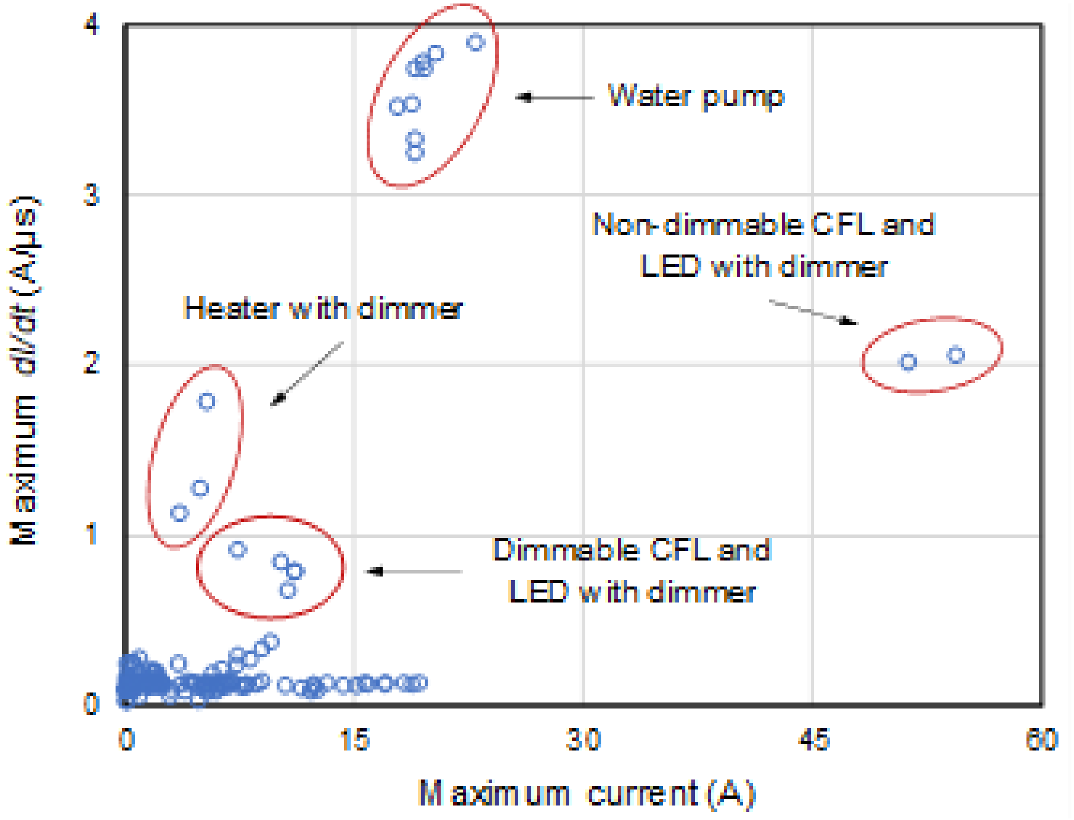
Household equipment

- 2015-2018: LED and CFL lamps and heater with dimmers
- 2018-2019: laptop, PC + monitor, smart-TV, refrigerator + freezer, microwave, USB chargers, DVD players, induction cookers, blenders, vacuum cleaners, drilling machines, patio heaters, coffee machines, water pump
- Most important parameters: I_{max} and *dI/dt*



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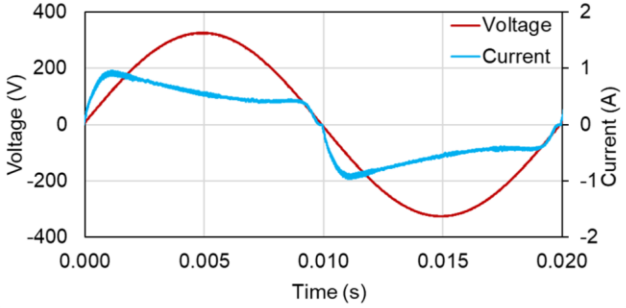
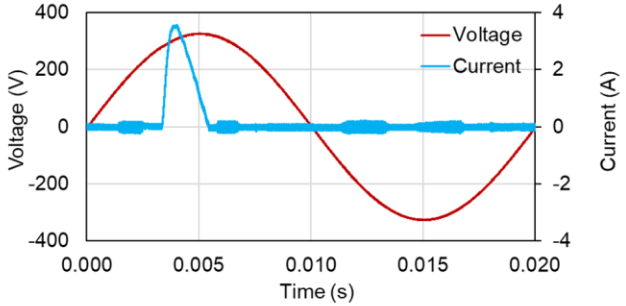
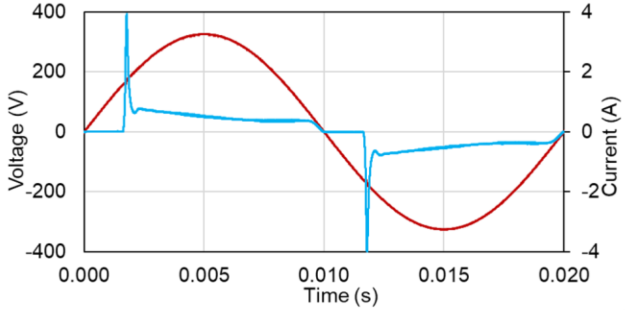
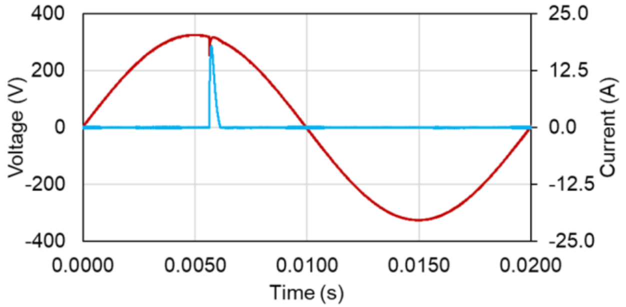
The main problem: dimming



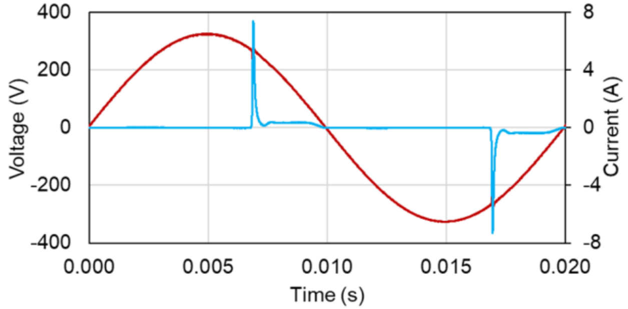


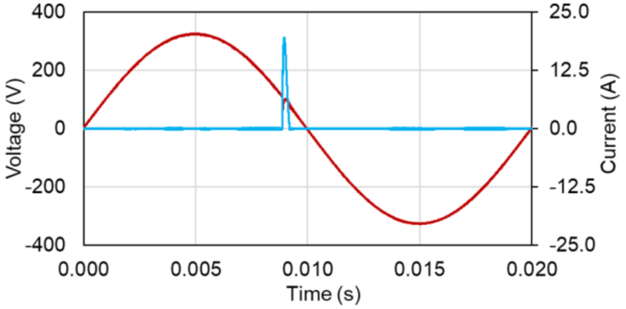
Phase firing dimmer





Phase shifting dimmer





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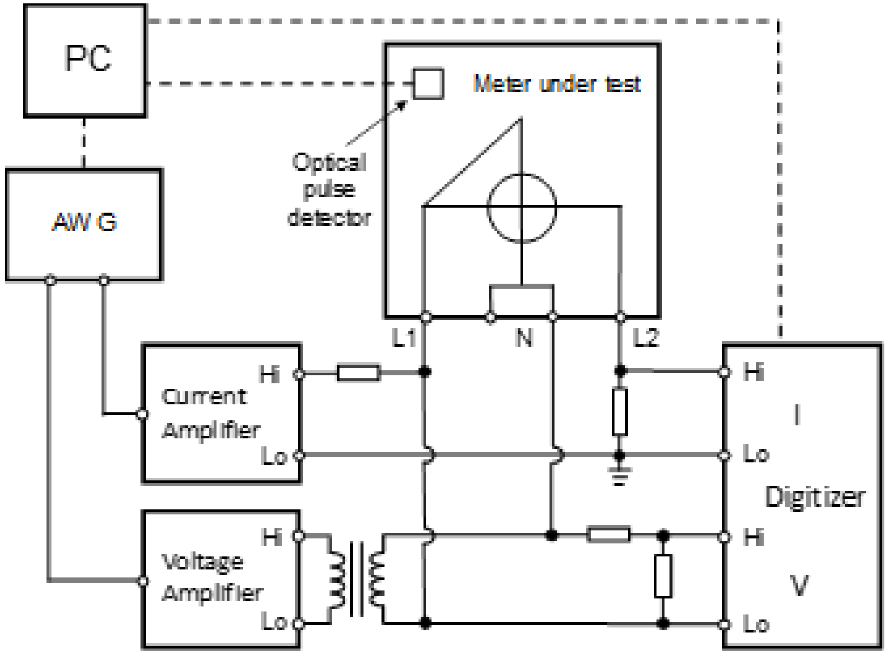
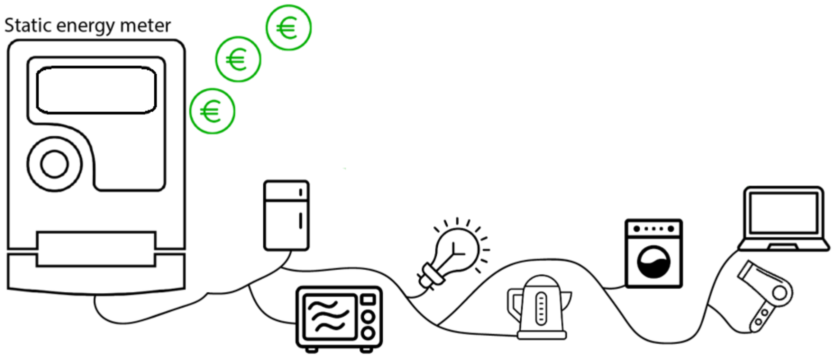
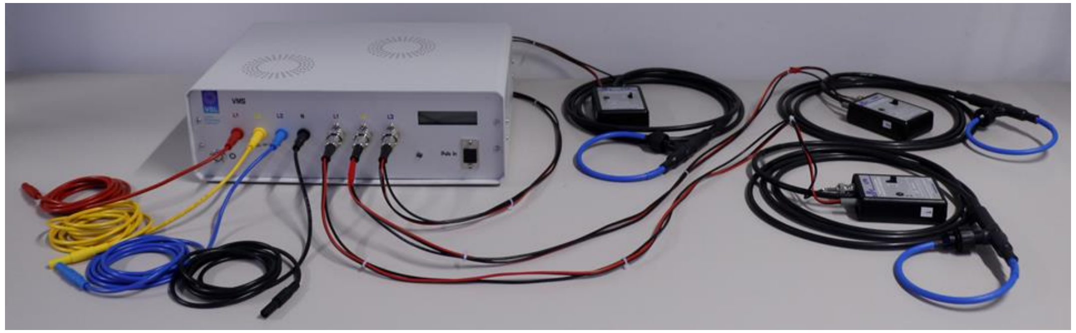
Verification studies



- Accuracy and reliability of the measurements
- Individual household appliances vs. real-world waveforms





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MeterEMI project

- 3-year research project, completed 2021
- EU funds through EMPIR
- 7 partners:
  - 5 National Metrology Institutes (NPL, VSL, CMI, METAS, JV)
  - 2 Universities (Utwente and UPC)
- Chief Stakeholder: Netbeheer Nederland
- > 25 supporting stakeholders

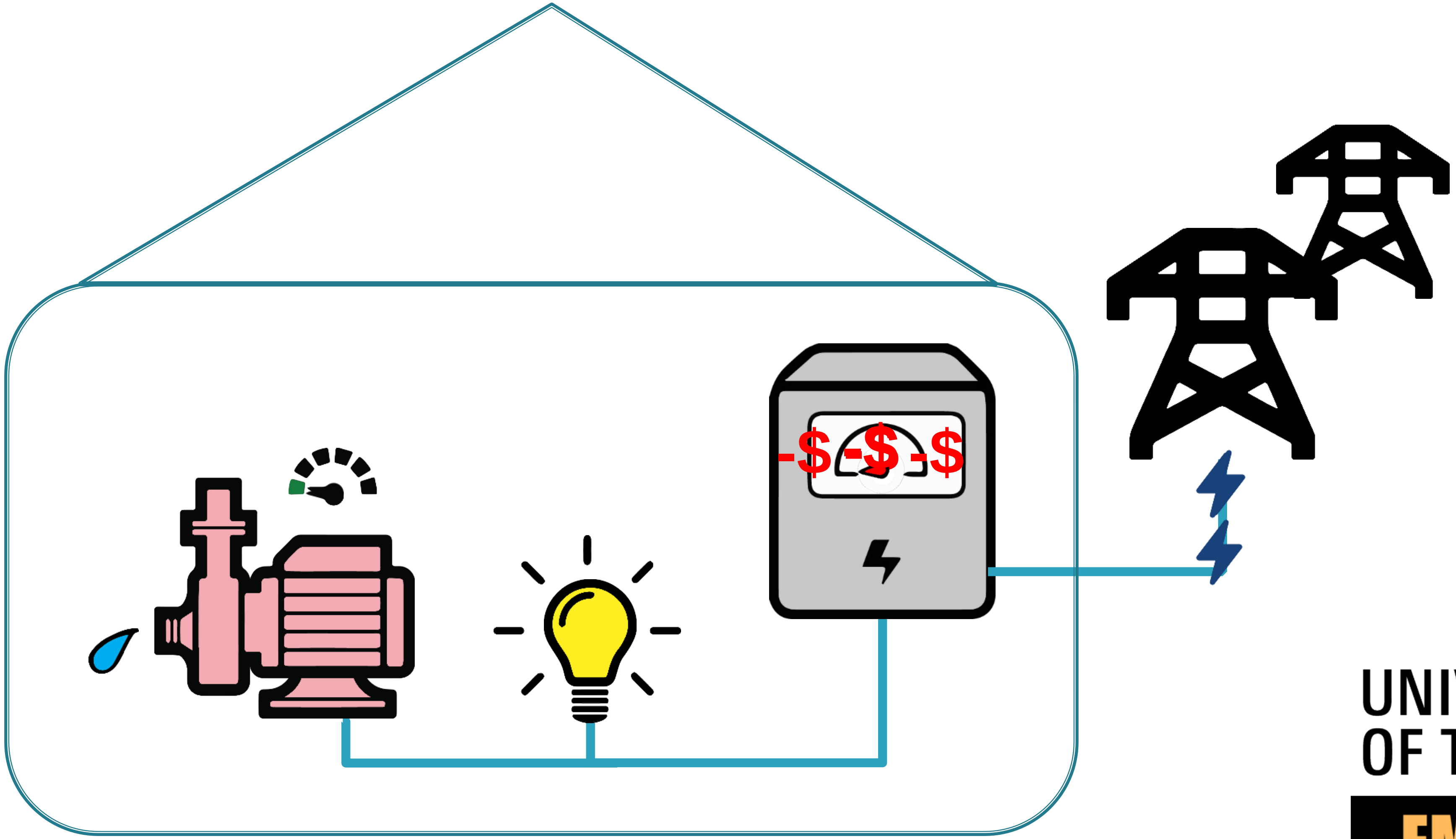
The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

Test results: appliances vs on-site signals

Signal	Sensor Year P [W]	A1 S 2019 ε [%]	A2 CT 2017 ε [%]	A3 U 2009 ε [%]	A4 U 2018 ε [%]	A5 H 2008 ε [%]	A6 CT 2017 ε [%]	A7 R 2008 ε [%]	A8 CT 2017 ε [%]	A9 S 2017 ε [%]	A10 U 2017 ε [%]	A11 CT 2017 ε [%]	A12 U 2010 ε [%]	A13 H 2015 ε [%]	A14 R 2013 ε [%]	A15 R 2019 ε [%]	A16 S 2017 ε [%]
R0	793	0	0,1	0,0	-2,8	-0,2	0,0	0,1	0,0	0,0	0,0	-0,1	-0,1	-0,1	0,1	-0,3	0,0
R50	430	0,1	0,1	0,9	-2,9	-0,3	0,0	-4,6	0,1	0,0	-0,1	-0,1	-1,3	0,3	-0,9	-1,3	0,0
R75	242	0,2	0,3	-0,6	-3,1	-0,6	0,0	191,4	0,2	1,4	-0,1	-0,1	26,8	-1,2	106,6	-2,7	0,3
CL50	329	1,3	1,0	-27,0	-1,4	-0,2	0,3	-70,9	1,3	1,9	6,0	0,5	-6,4	-16,8	-76,7	3,1	-37,5
CL75	293	1,9	1,7	-39,5	-0,8	-1,4	0,5	117,0	1,7	2,9	7,3	0,7	123,8	173,1	101,8	3,1	-45,3
RCL0	1367	0,1	0,1	0,0	-2,8	-0,1	0,0	0,3	0,0	0,0	0,0	-0,1	-0,1	0,2	0,2	-0,1	-0,1
WP1	19	1,9	3,9	-38,1	-2,0	-7,2	2,2	2711,8	4,5	1,6	5,8	0,1	1119,0	4,2	2648,6	-3,1	-1,9
WP4	34	1,0	2,2	-52,1	-2,3	-3,5	1,3	1368,7	2,6	0,9	3,3	0,0	543,4	3,1	1258,2	-1,6	1,1
WP9	68	0,4	0,6	-56,2	-2,5	-1,7	0,2	200,2	0,6	0,4	1,1	-0,1	31,2	1,9	136,3	-0,5	2,3
WP10	67	0,2	-0,3	-0,3	-2,8	-1,7	-0,4	-1,7	-0,4	0,0	-0,2	-0,2	-0,6	0,4	-0,7	-0,5	0,1

Signal	Sensor Year P [W]	A1 S 2019 ε [%]	A2 CT 2017 ε [%]	A3 U 2009 ε [%]	A4 U 2018 ε [%]	A5 H 2008 ε [%]	A6 CT 2017 ε [%]	A7 R 2008 ε [%]	A8 CT 2017 ε [%]	A9 S 2017 ε [%]	A10 U 2017 ε [%]	A11 CT 2017 ε [%]	A12 U 2010 ε [%]	A13 H 2015 ε [%]	A14 R 2013 ε [%]	A15 R 2019 ε [%]	A16 S 2017 ε [%]
UPC2.1	1848	0,1	0,1	0,0	-2,8	-0,1	0,0	0,2	0,1	0,0	0,0	-0,1	-0,1	0,0	0,2	-0,4	-0,1
UPC2.2	-131	0,0	-0,1	0,2	2,9	TO	0,0	TO	0,0	0,0	0,0	0,1	-0,4	-0,5	3,1	0,9	0,0
UPC2.3	694	0,1	0,0	0,0	-2,8	-0,2	0,0	0,1	0,0	0,0	0,0	-0,1	-0,6	0,3	0,1	0,0	0,0
UT1.1	719	0,1	0,1	0,3	-2,8	-0,2	0,0	8,9	0,0	0,0	0,0	-0,1	0,0	-0,1	10,1	-0,3	-0,1
UT1.2	237	0,2	0,8	-0,3	-2,9	-0,6	0,9	-2,1	1,0	0,0	-0,1	-0,1	0,0	0,4	-0,9	-0,9	-0,2
UT1.2a	180	0	-3,0	-0,4	-2,6	-0,6	-3,6	-58,2	-3,9	0,0	0,0	-0,1	5,2	1,9	-59,0	1,1	-3,9
UT1.2b	179	0	3,0	-0,3	-3,0	-0,8	3,7	25,5	3,6	-0,1	-0,3	-0,1	-0,9	-0,3	28,6	-2,1	-6,7
VSL1	2233	0,1	1,3	0,8	-2,9	-0,1	1,1	0,7	1,3	0,0	0,1	-0,1	2,2	0,1	0,3	-0,8	0,0
VSL2	31	0,3	-0,5	-1,5	-2,4	-3,4	-0,3	640,2	-0,5	-0,2	-0,4	-0,3	5,0	-0,1	333,7	1,7	-4,5
VSL3	69	0,3	0,1	0,3	-2,6	-1,6	0,0	-5,1	0,1	0,0	0,0	-0,1	0,1	1,3	-0,9	0,9	-0,1
VSL4	32	0,1	-0,1	TO	-2,8	-3,4	-0,2	818,0	-0,2	-0,5	-0,5	-0,4	-30,3	2,8	796,5	0,2	-0,7
VSL5	1392	0,1	0,2	0,4	-2,8	-0,1	0,0	31,4	0,1	0,0	0,1	-0,1	1,7	0,1	28,7	-0,4	-0,1

Static Energy Meter Errors



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Measurement Setup

- 140-TMX AC Power Supply
- Ideal grid at 50 Hz, 230 V RMS
- Mains supply of the building
- 24 static energy meters
  - representing the installed base of static energy meters throughout the Netherlands
- The internal consumption of the static energy meters has been compensated
- Reference: Yokogawa WT500
- Voltage and Current waveforms

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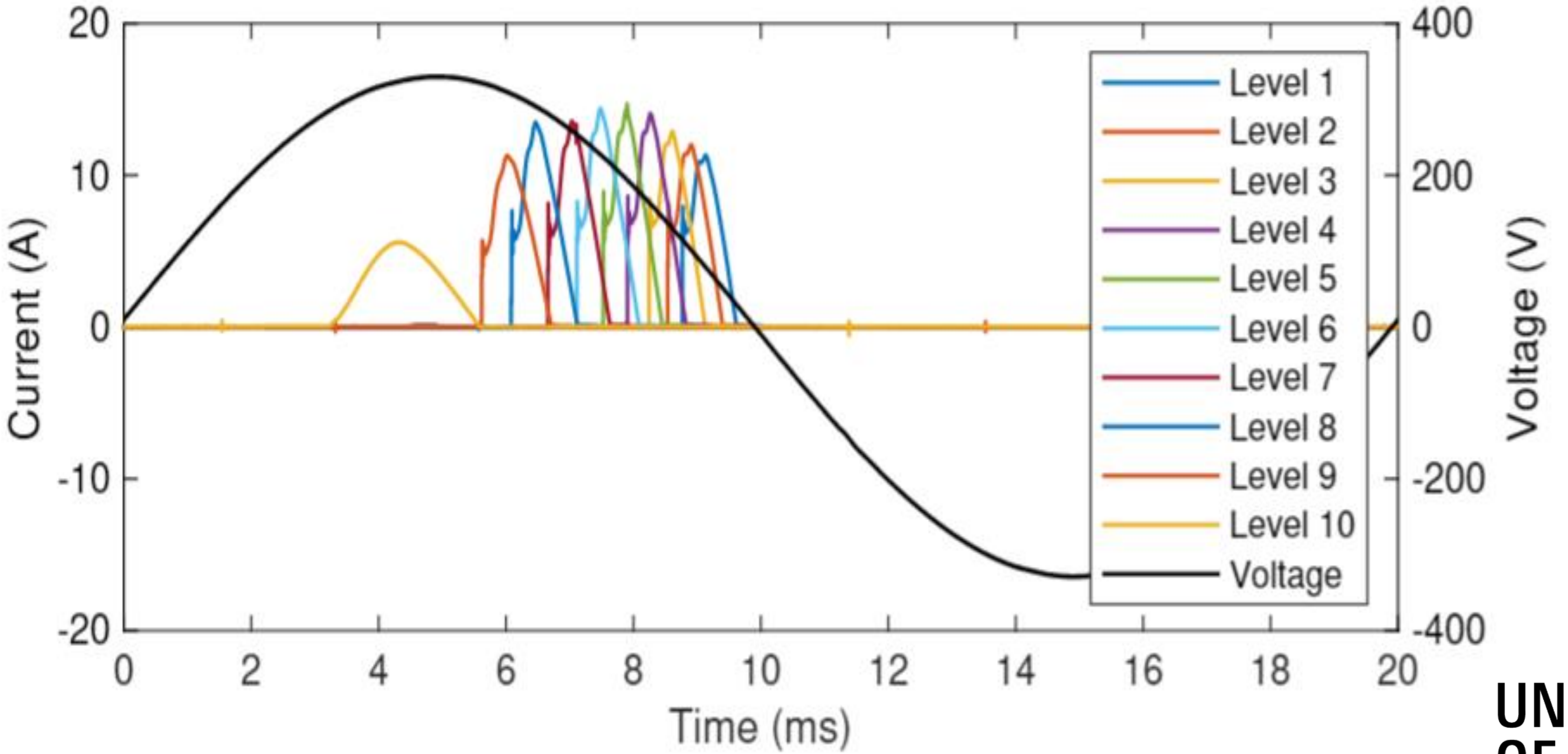
Waterpump



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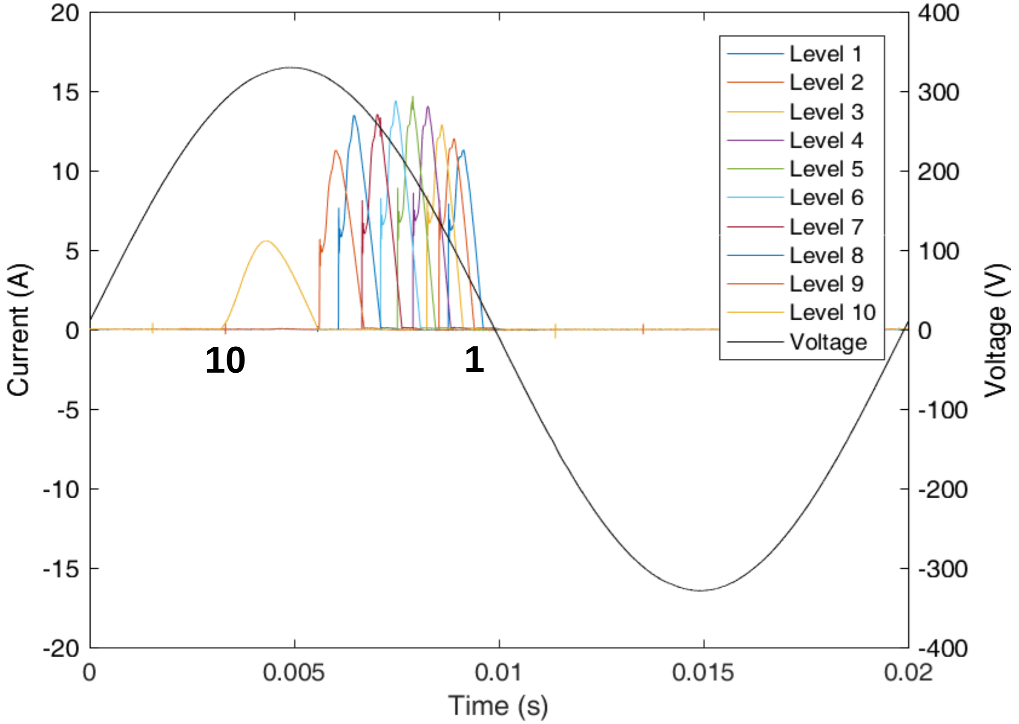
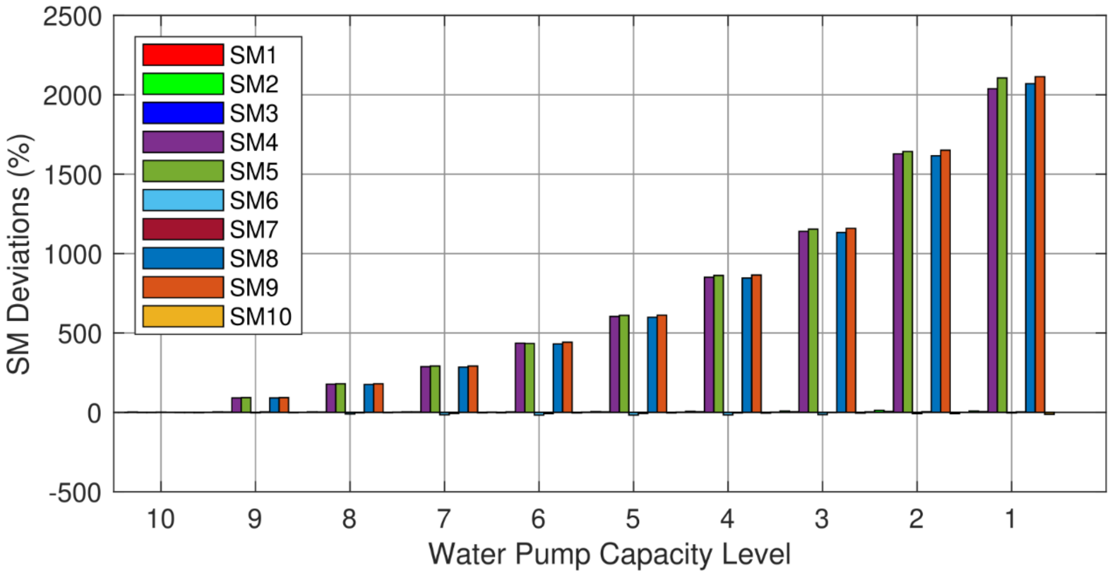
Waterpump

- Lower waterpump capacity
  - Bigger error
- Faster rising edge
- Closer to the zero crossing

B. Have, T. Hartman, N. Moonen, C. Keyer, and F. Leferink, "Faulty Readings of Static Energy Meters Caused by Conducted Electromagnetic Interference from a Water Pump," *Submitted to Renewable Energy and Power Quality Journal (RE&PQJ)*, 2019.





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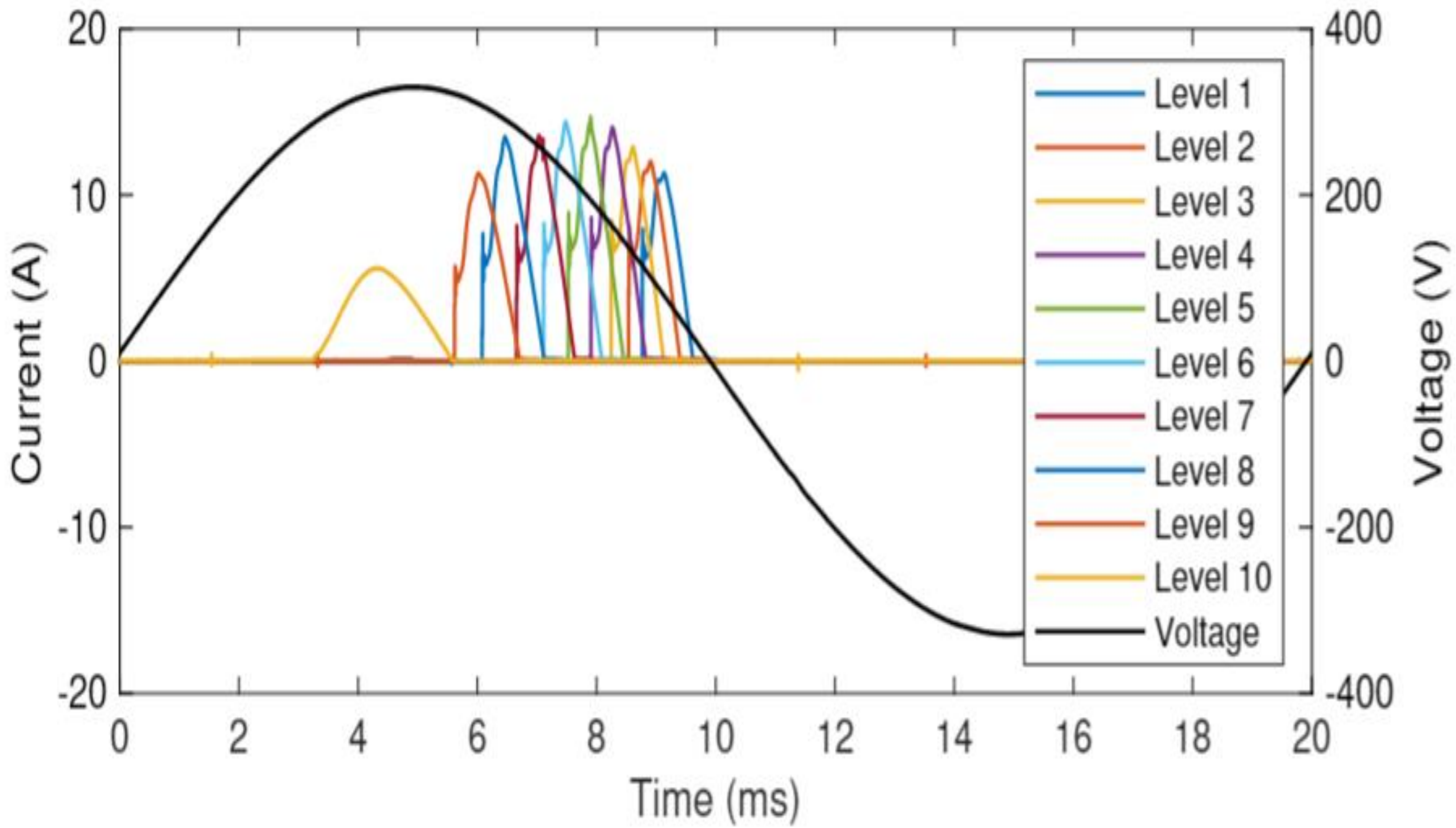
Waveforms

- Parameters
  - **Current slope (di/dt)**
  - **Phase firing angle**
  - Rise time
  - Fall time
  - Crest factor
  - Power factor
  - Peak current
  - Total harmonic distortion
  - Energy (pulse width)



How to Earn Money With an EMI Problem

- Monitor their energy consumption

- Inconsistent energy consumption
  - After installing a remote-control on and off switch

Consumption Tuesday 03-11-2020

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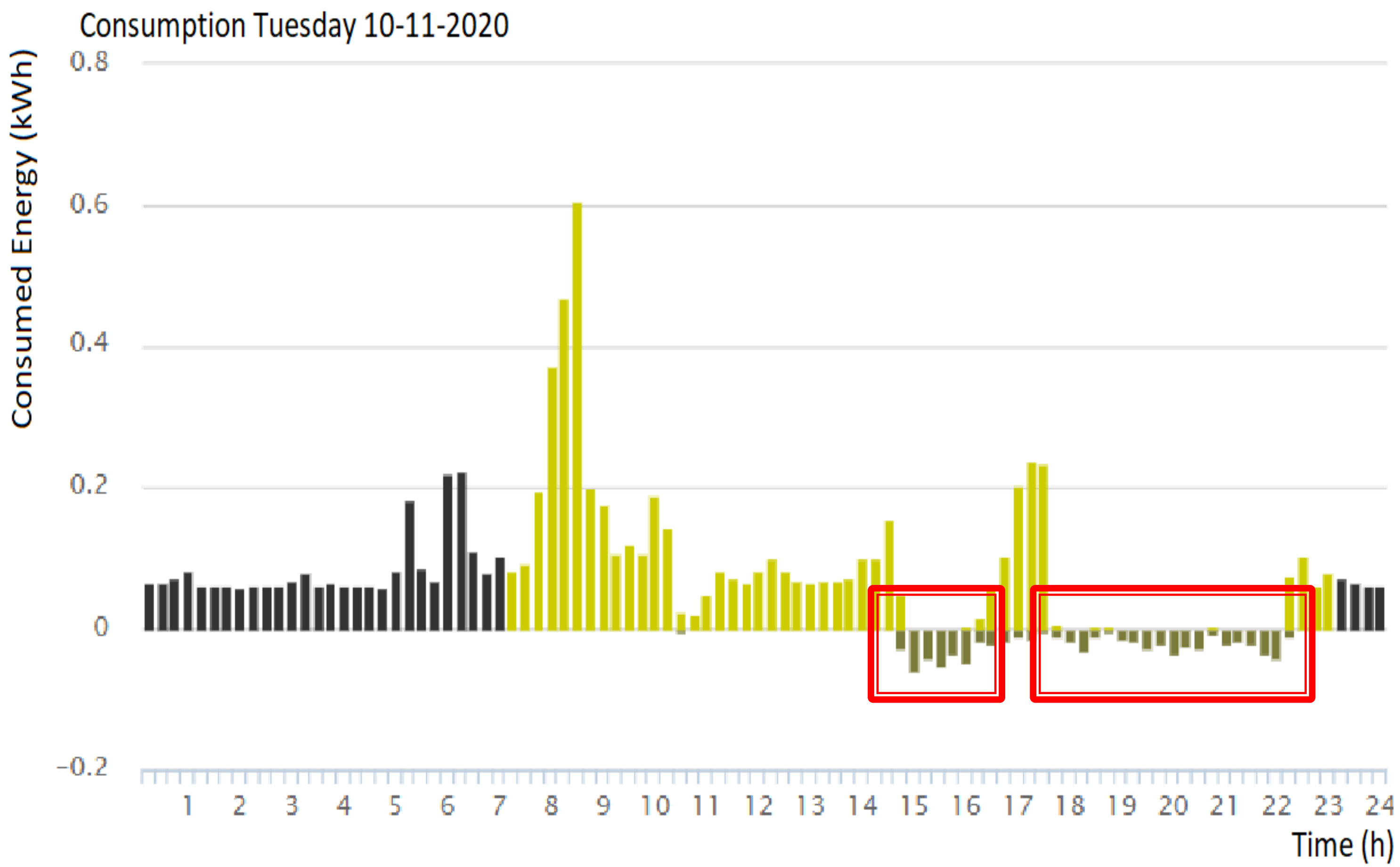
How to Earn Money With an EMI Problem

- A constant consumption of around 250 W
- After connecting the COTS switch
- Energy consumption dropped significantly
  - Reaching negative values!
- No power generating equipment



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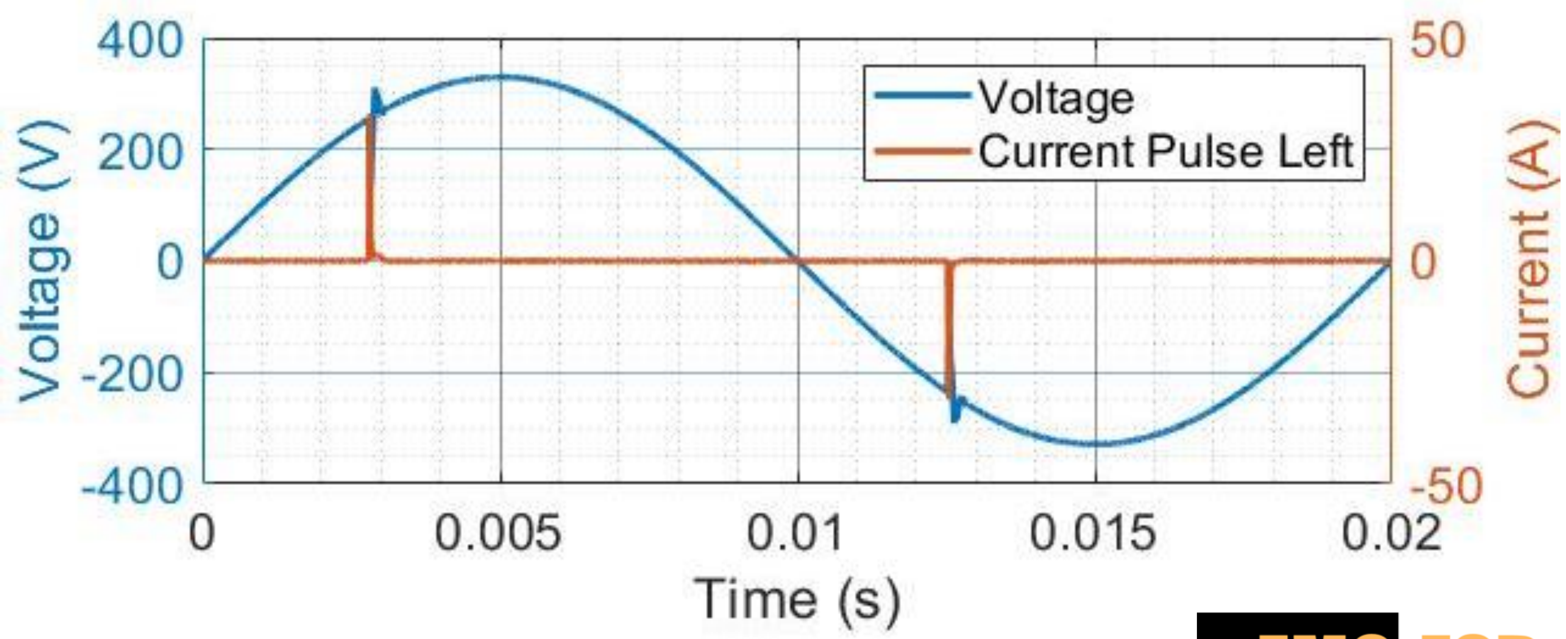
How to Earn Money With an EMI Problem

- Remote-control on and off switch
  - Including dimming functionalities
- Household equipment
  - Switched mode power supply
- The switch always initiates a dimming function
  - Phase shift (FA 45°)



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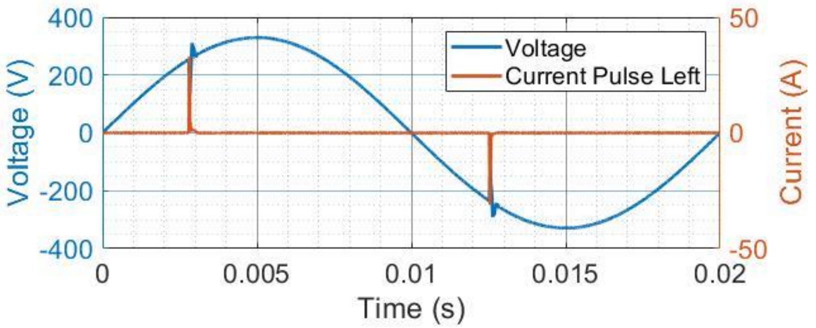
Results - Household Equipment

- Fast rising edges



#	WT500 (W)	SM1 (W)	SM2 (W)	SM3 (W)	SM4 (W)
1	21 W	-297 W	-286 W	-350 W	-56 W

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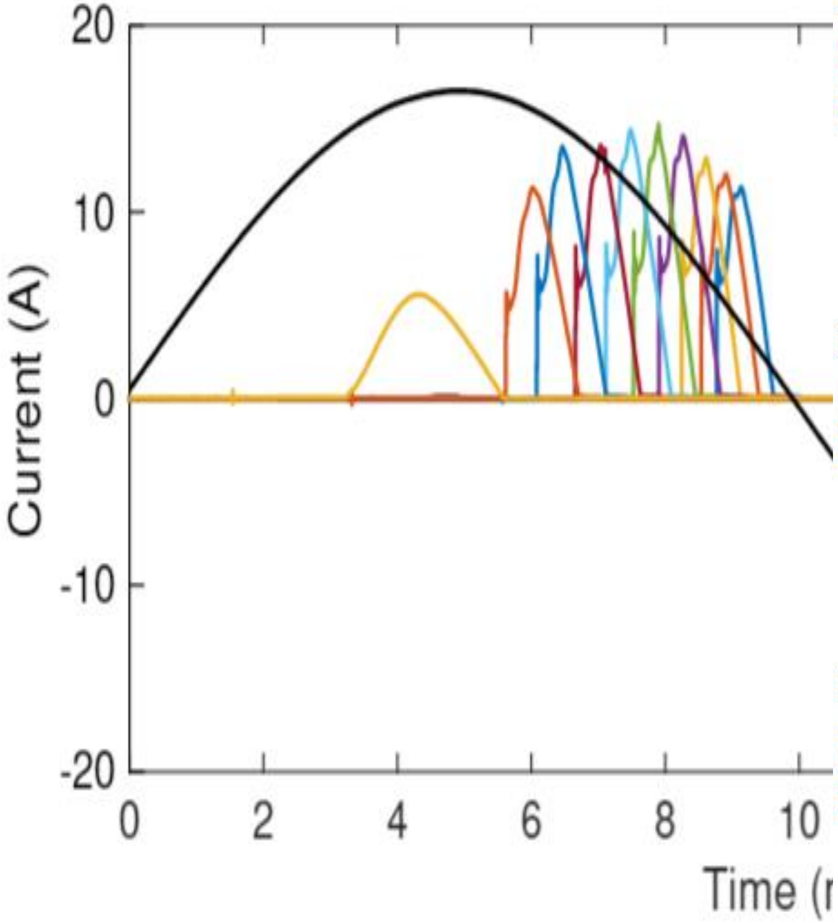
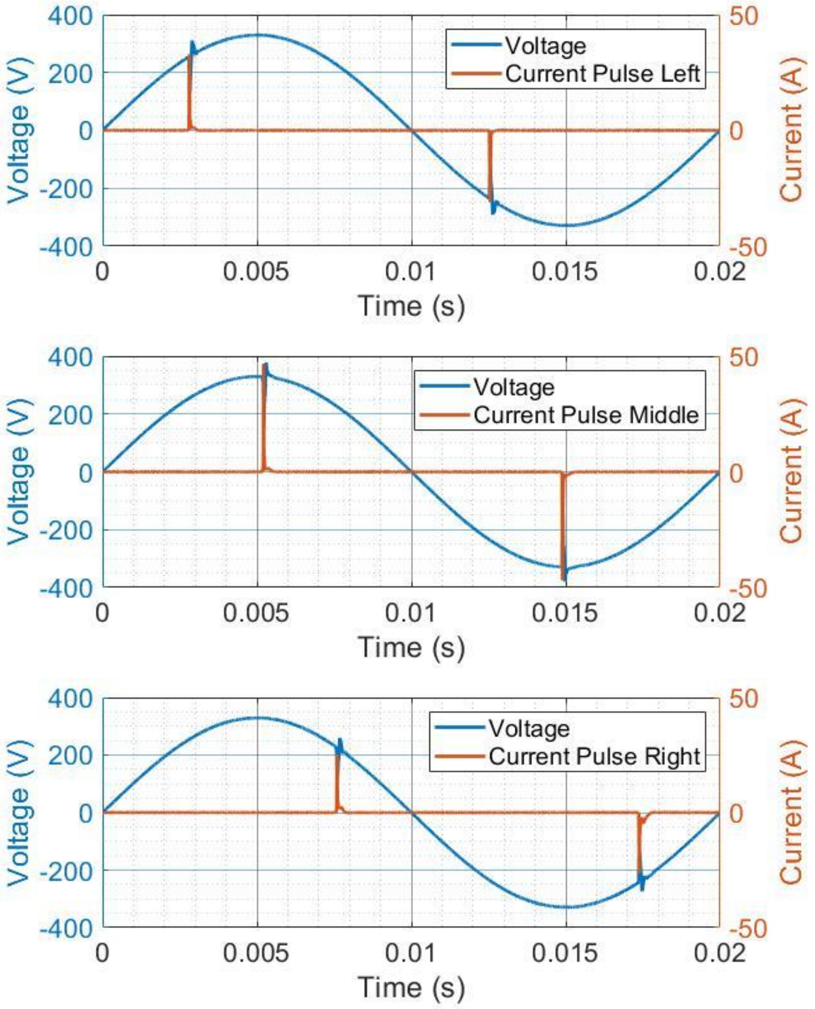
Waveforms

- Parameters
  - **Current slope (di/dt)**
  - **Phase firing angle**
  - Rise time
  - Fall time
  - Crest factor
  - Power factor
  - Peak current
  - Total harmonic distortion
  - Energy (pulse width)





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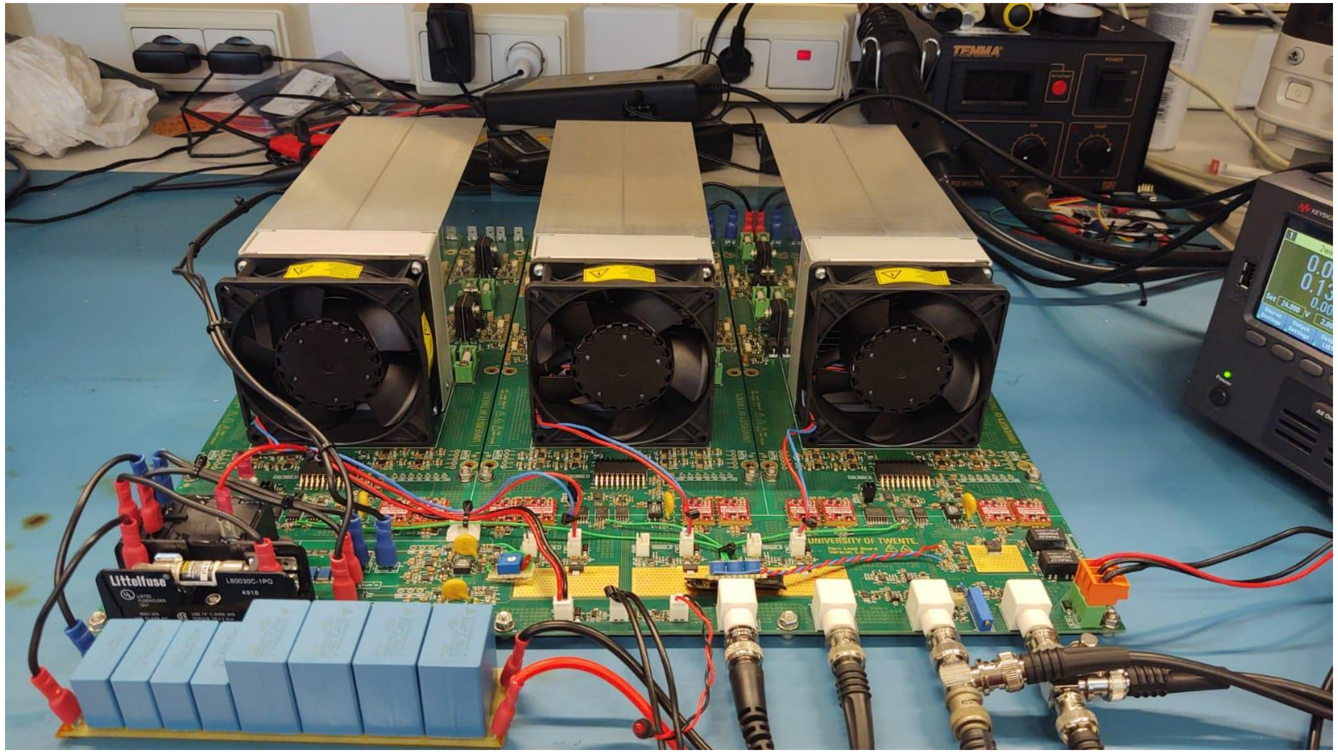
Controlled-Current Load

- Controlled-current load has been designed and built
  - Quantifiably determine the relation between waveform parameters and meter errors



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LINE
NEUTRAL
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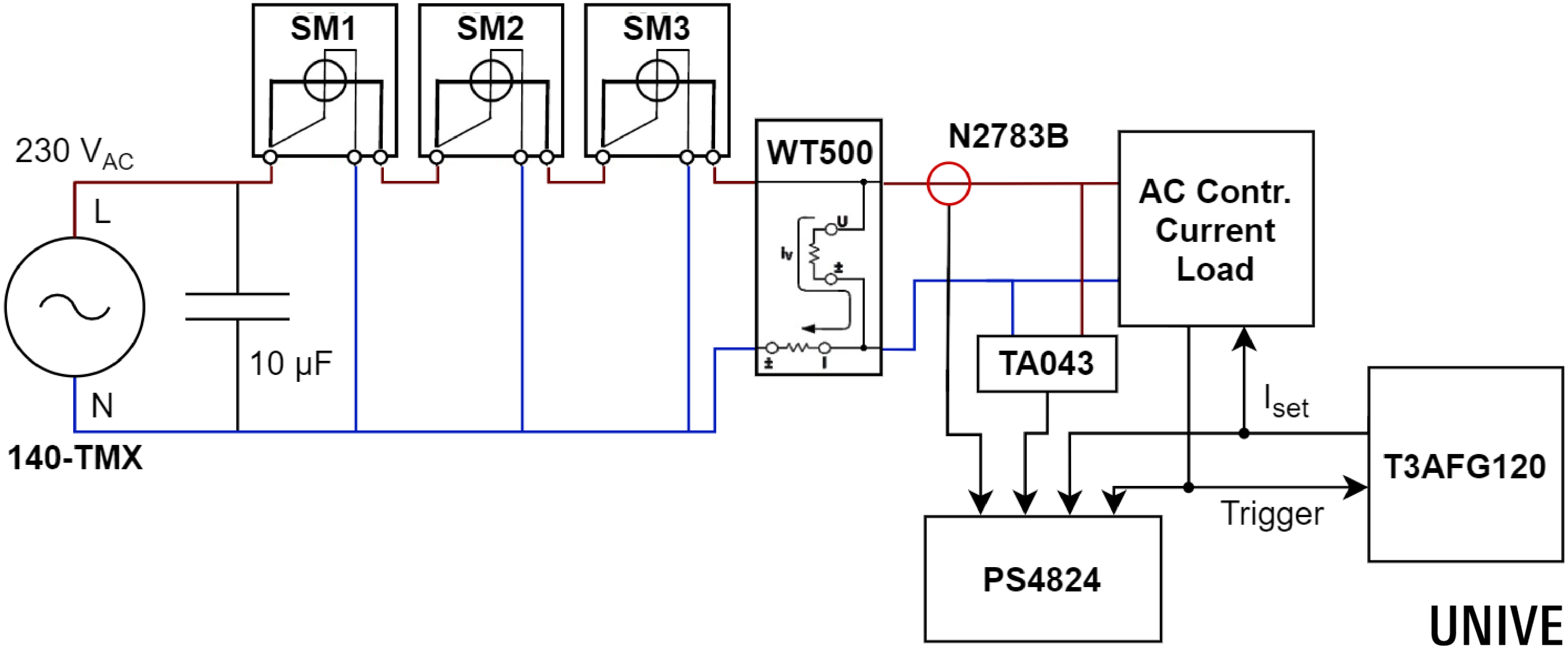
AC Controlled-Current Load
LOAD ON
ERROR



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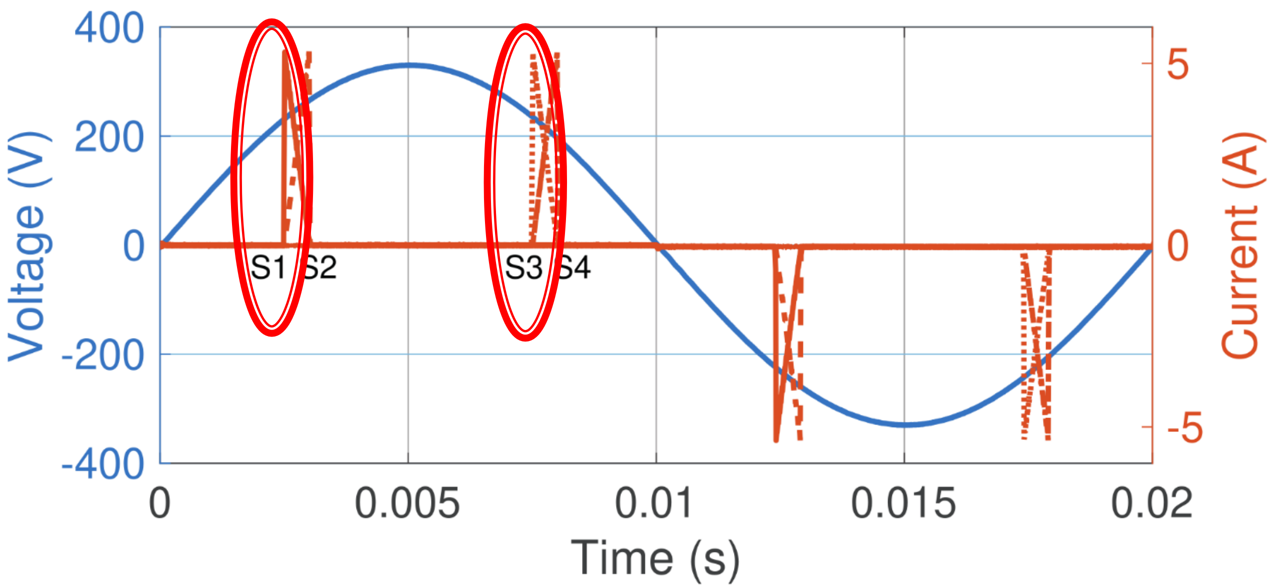
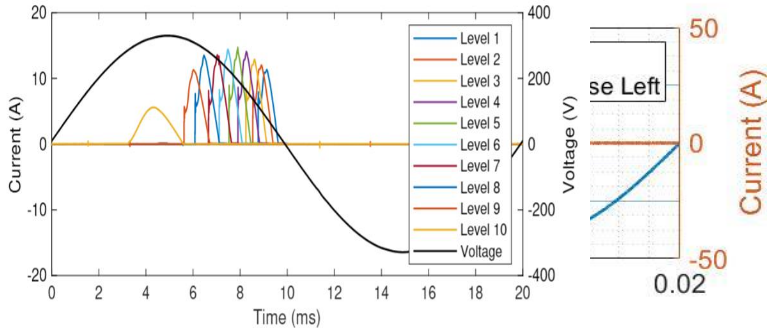
Rising Edge Versus Falling Edge

	Reference	ΔSM2
S1	35 W	-63 W
S2	37 W	+43 W
S3	33 W	+58 W
S4	32 W	54 W



	Edge	Phase FA	Δ Error
S1	Fast Rising [↑]	Below 90°	- Error [W]
S2	Fast Falling [↓]	Below 90°	+ Error [W]
S3	Fast Rising [↑]	Above 90°	+ Error [W]
S4	Fast Falling [↓]	Above 90°	- Error [W]

	t_r	t_f	Peak	Rising SR	Falling SR	FA
S1	10 µs	500 µs	5 A	0.5 A/µs	-0.01 A/µs	45 °
S2	500 µs	10 µs	5 A	0.01 A/µs	-0.5 A/µs	45 °
S3	10 µs	500 µs	5 A	0.5 A/µs	-0.01 A/µs	135 °
S4	500 µs	10 µs	5 A	0.01 A/µs	-0.5 A/µs	135 °



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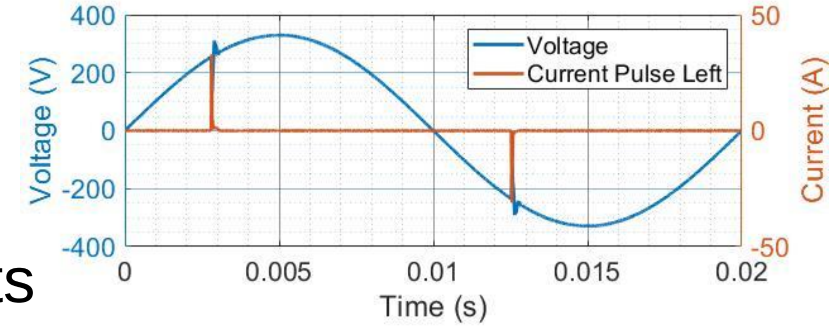
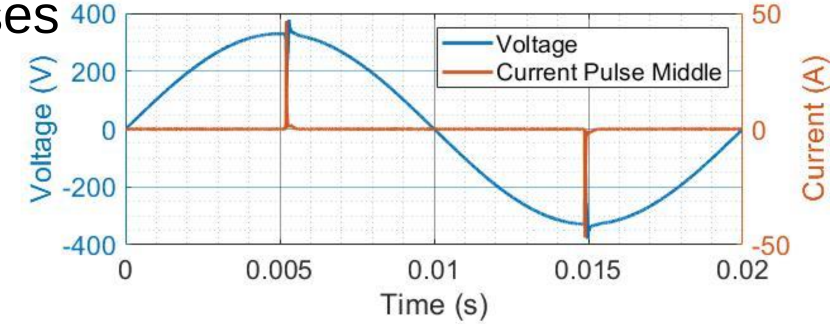
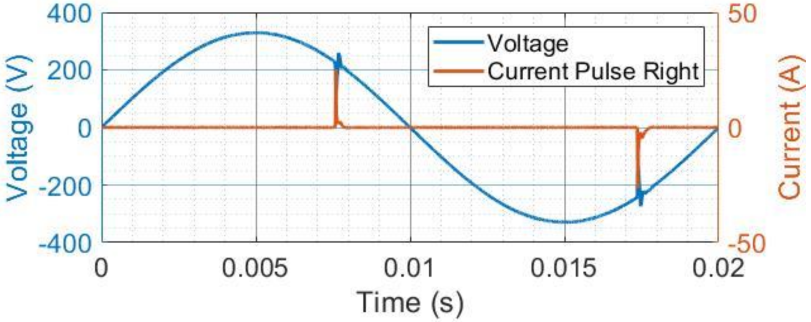
Phase

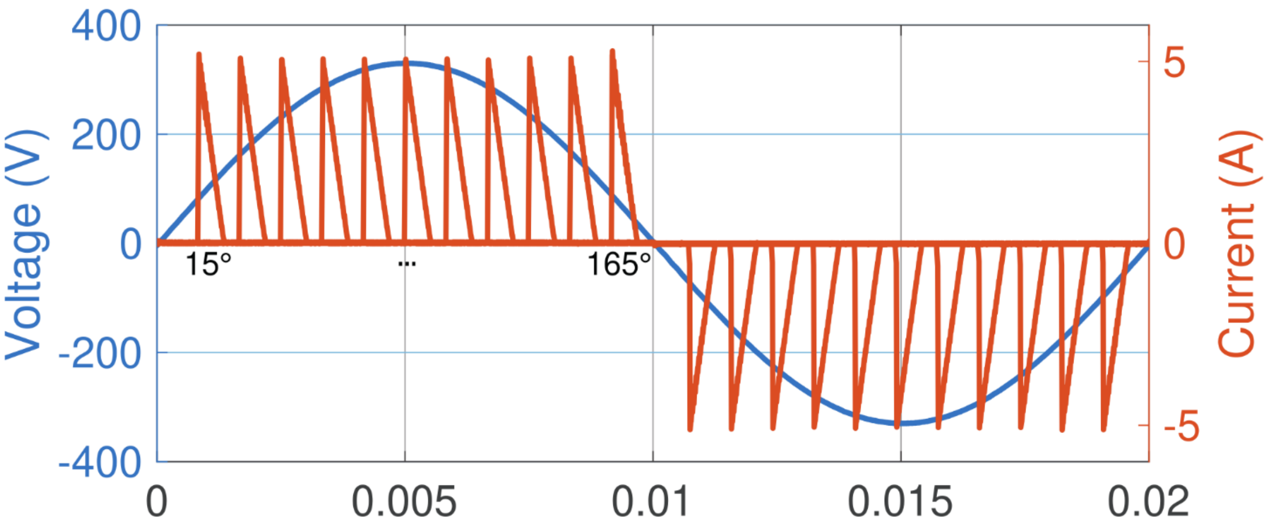
- Separate measurements
  - Different Phases

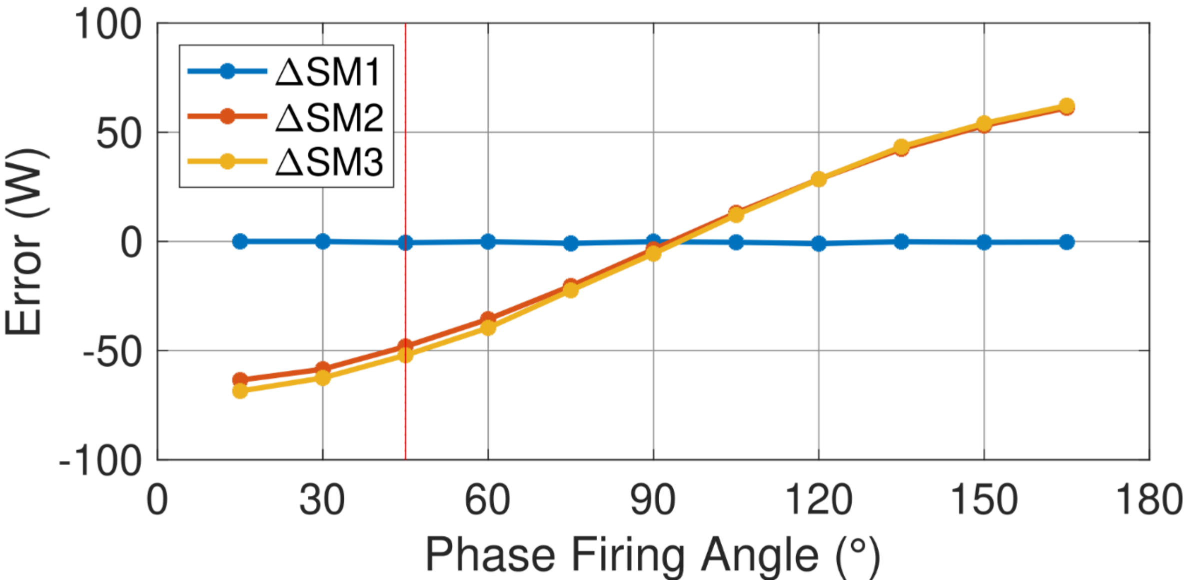






#	WT500 (W)	SM1 (W)
1	21 W	-297 W
2	22 W	35 W
3	20 W	485 W





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Current Measurement Chain

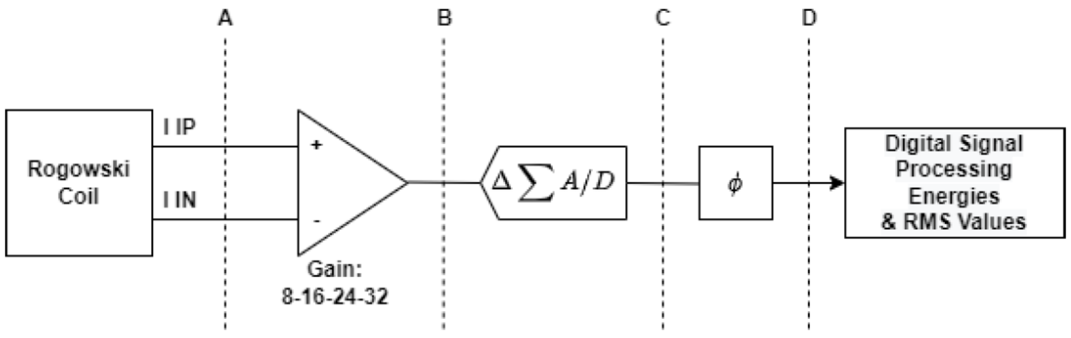
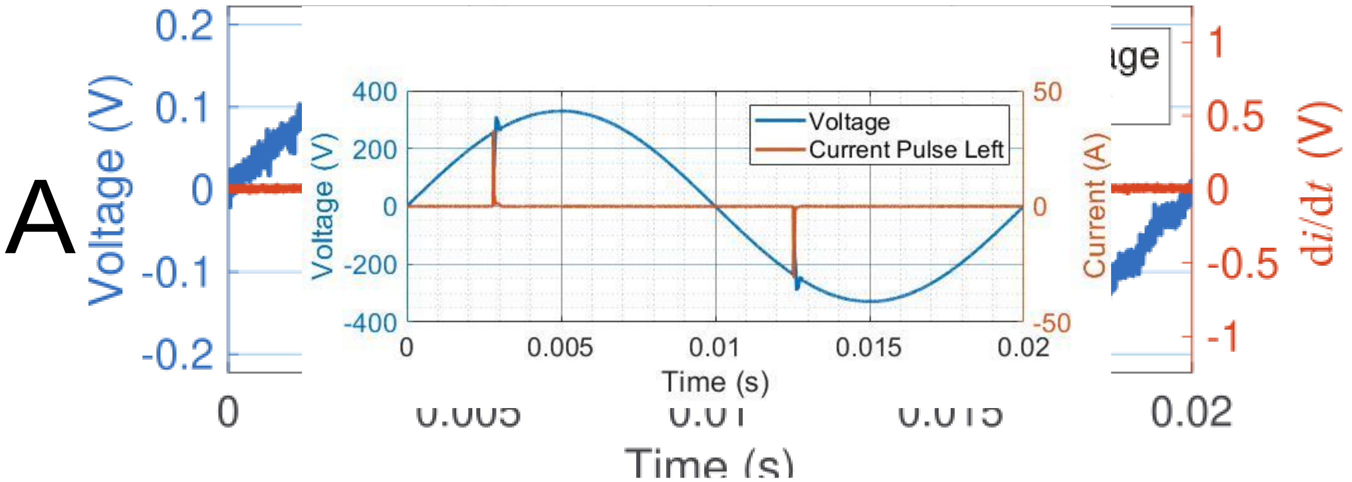


Figure 5.2. Block diagram of the current measurement chain inside the STPM01 chip that is used in SMs

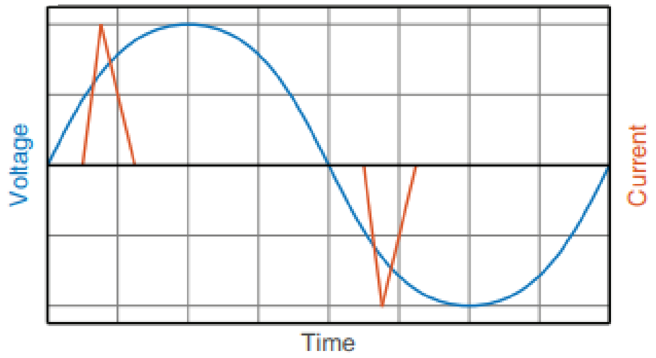


Current channels	
Gain	**Max input voltage (V)**
8X	±0.15
16X	±0.075
24X	±0.05
32X	±0.035

STMicroelectronics, “Programmable single phase energy metering IC with tamper detection,” STPM01 datasheet, Jun. 2011, Doc ID 10853 Rev 8.

Susceptibility of Static Energy Meters

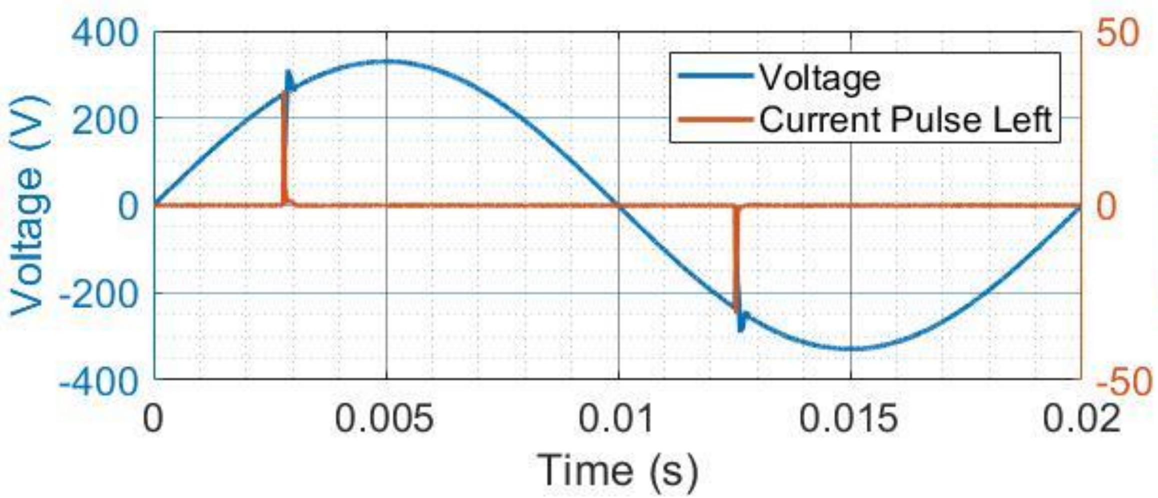
- Simplified Pulse
- Differentiated
- Clipped
- Distorted current waveform after integration



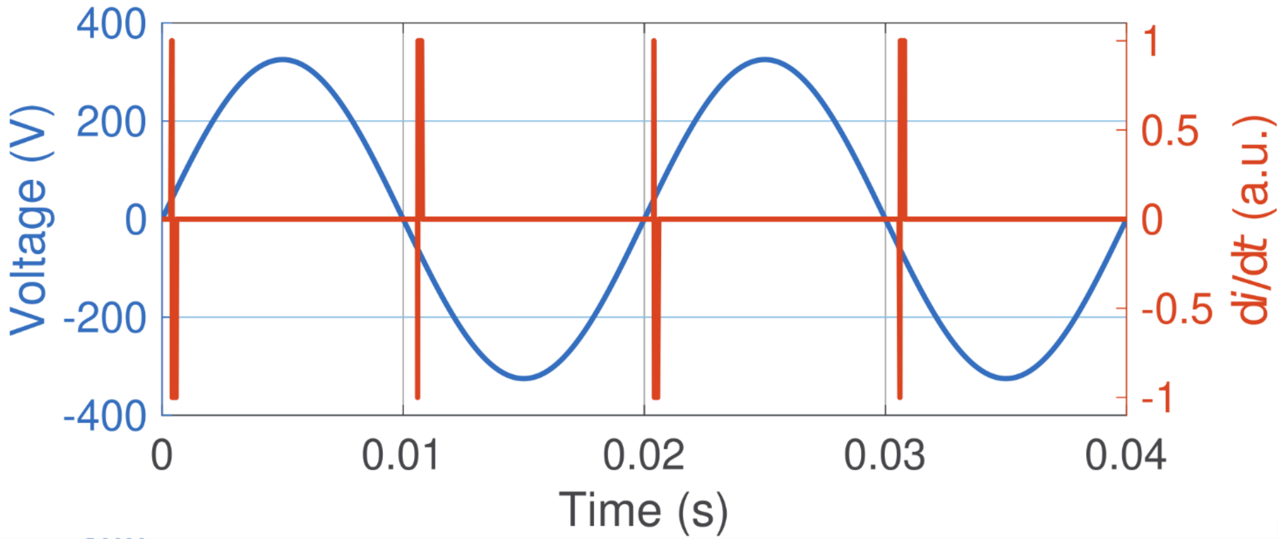
(a) Pulse with a fast rising edge

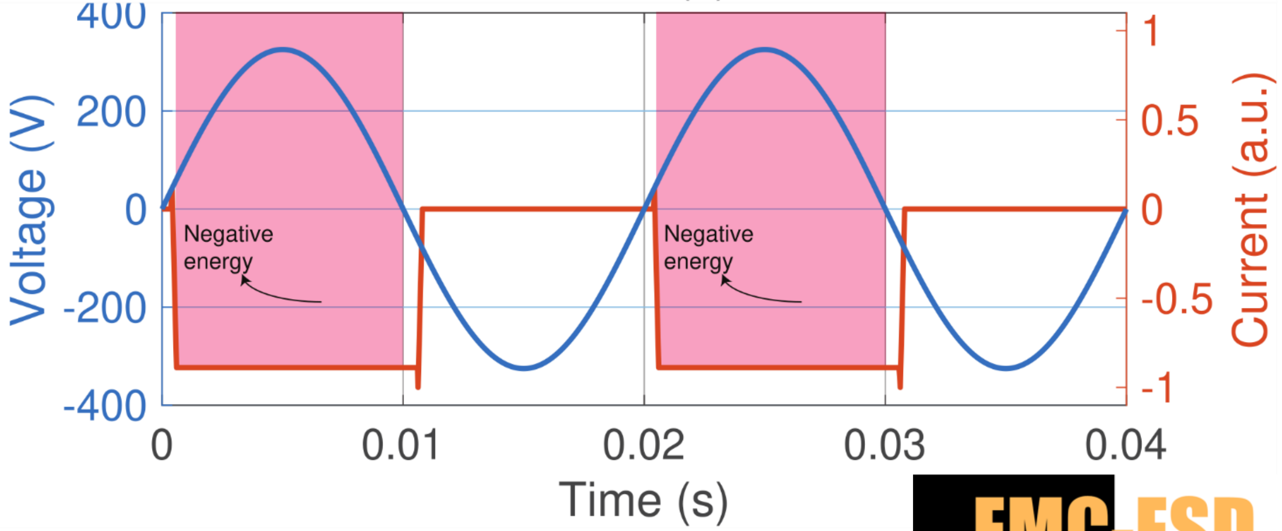
Fig. 4. Schematic overview of the clipping of the differentiated current

Susceptibility of Static Energy Meters

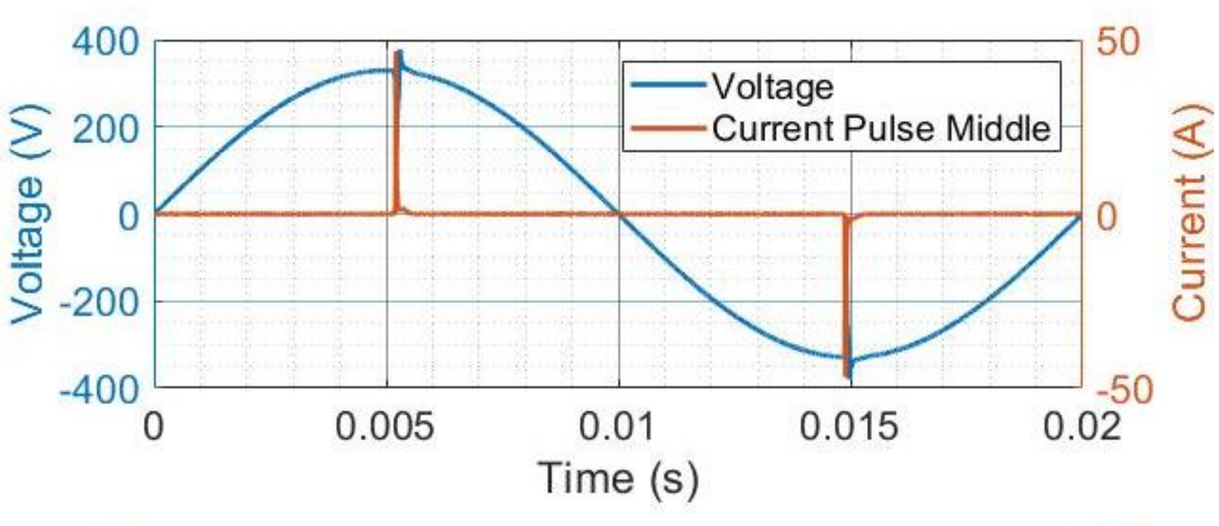


WT500 (W)	SM1 (W)
21 W	-297 W

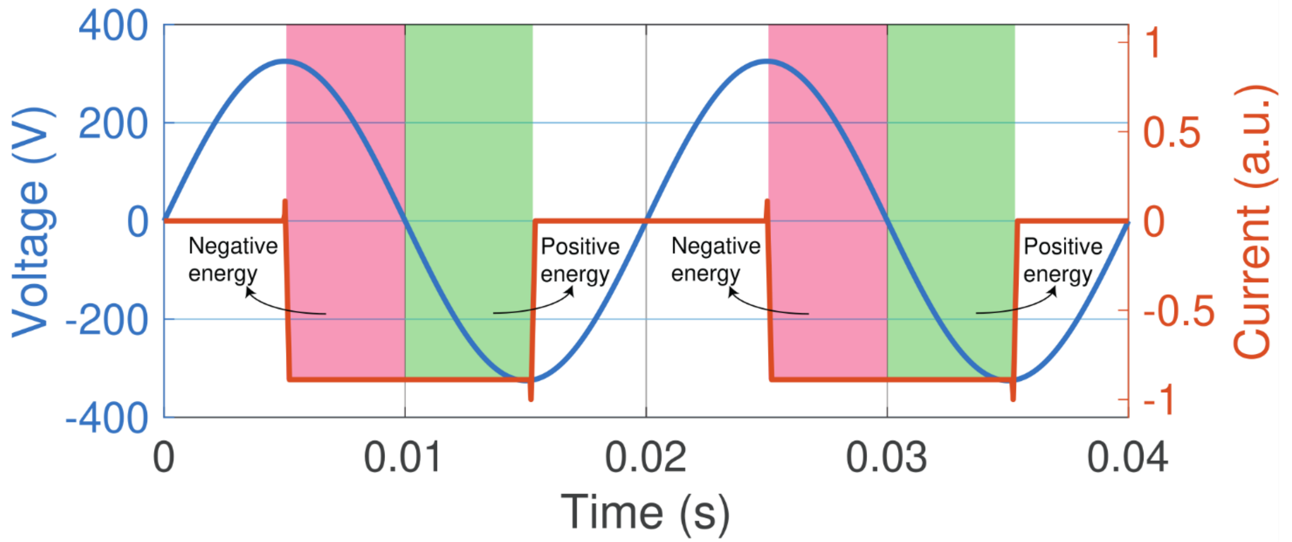




Susceptibility of Static Energy Meters



WT500 (W)	SM1 (W)
21 W	-297 W
22 W	35 W



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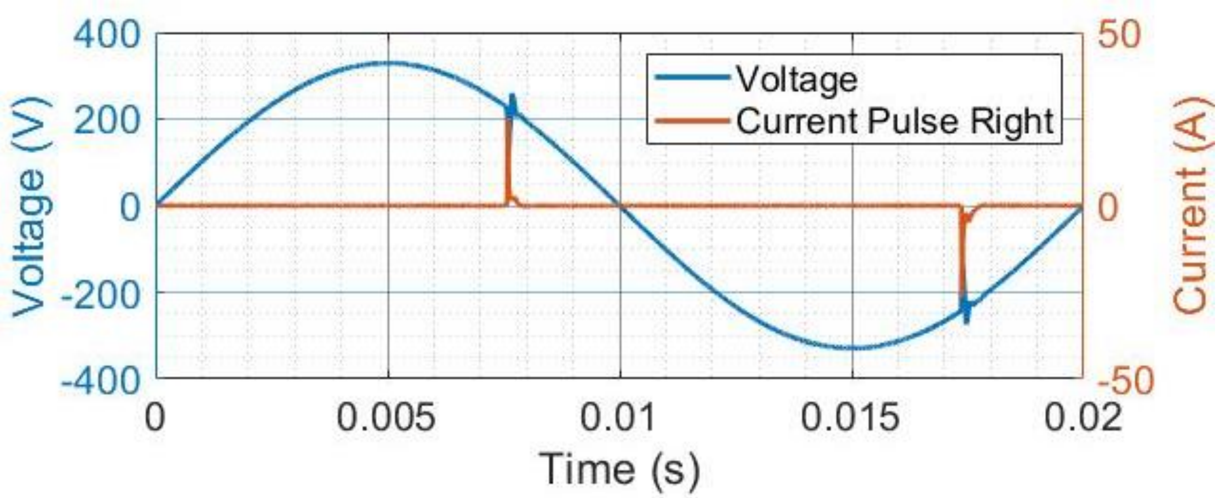
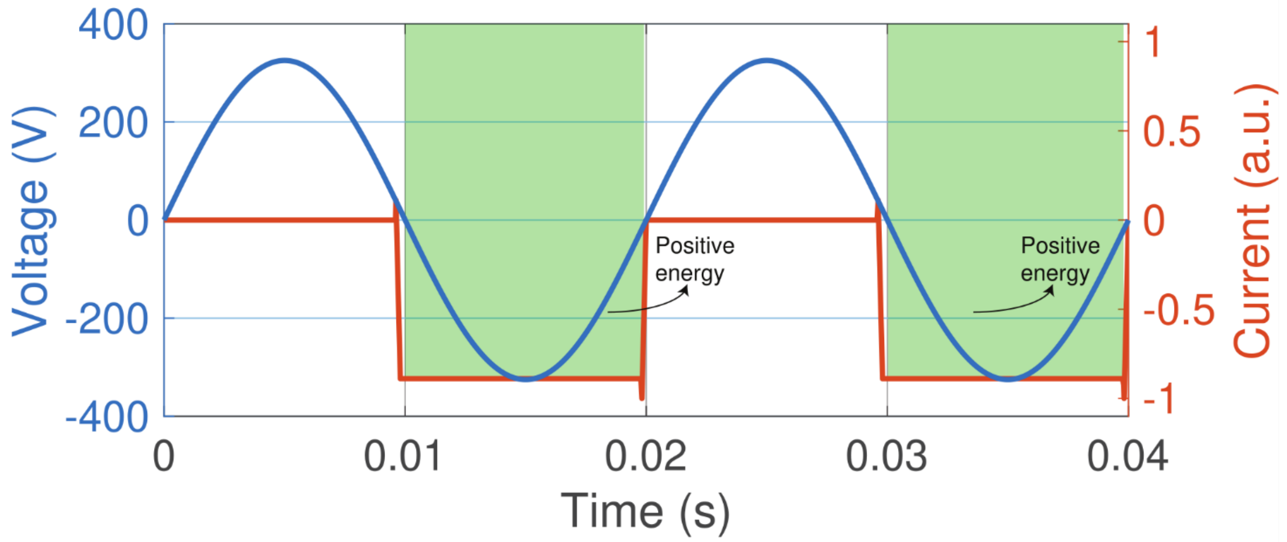
Susceptibility of Static Energy Meters

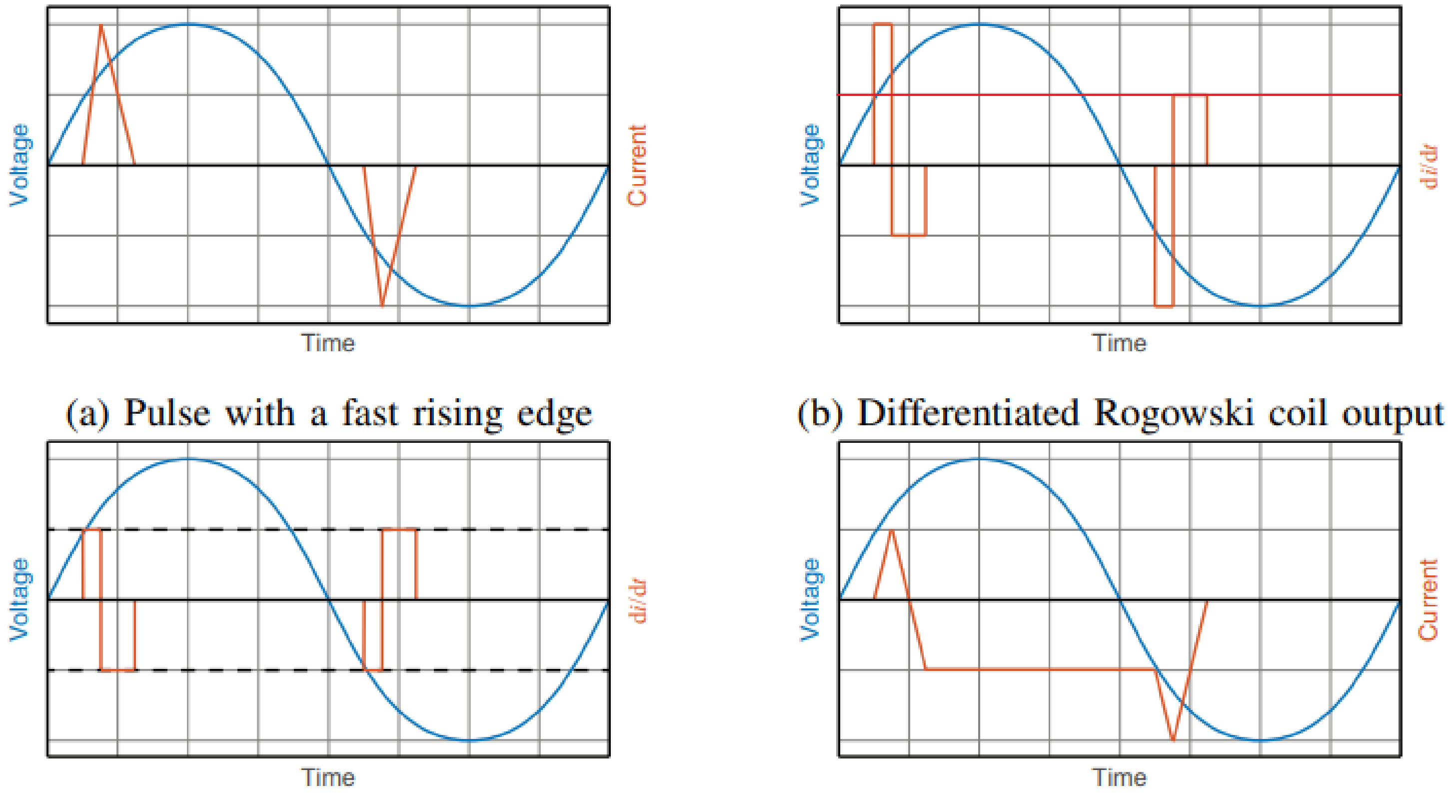




WT500 (W)	SM1 (W)
21 W	-297 W
22 W	35 W
20 W	485 W

Susceptibility of Static Energy Meters

	Edge	Phase FA	Δ Error
S1	Fast Rising [↑]	Below 90°	- Error [W]
S2	Fast Falling [↓]	Below 90°	+ Error [W]
S3	Fast Rising [↑]	Above 90°	+ Error [W]
S4	Fast Falling [↓]	Above 90°	- Error [W]



(a) Pulse with a fast rising edge
(b) Differentiated Rogowski coil output
(c) Clipped amplifier output
(d) Distorted current after integration

Fig. 4. Schematic overview of the clipping of the differentiated current

Intentional EMI

	Edge	Phase FA	Δ Error
S1	Fast Rising [↑]	Below 90°	- Error [W]
S4	Fast Falling [↓]	Above 90°	- Error [W]

- How to protect?
- Why could this happen in the first place?
  - We have standards, right?
  - CE + CE ≠ CE

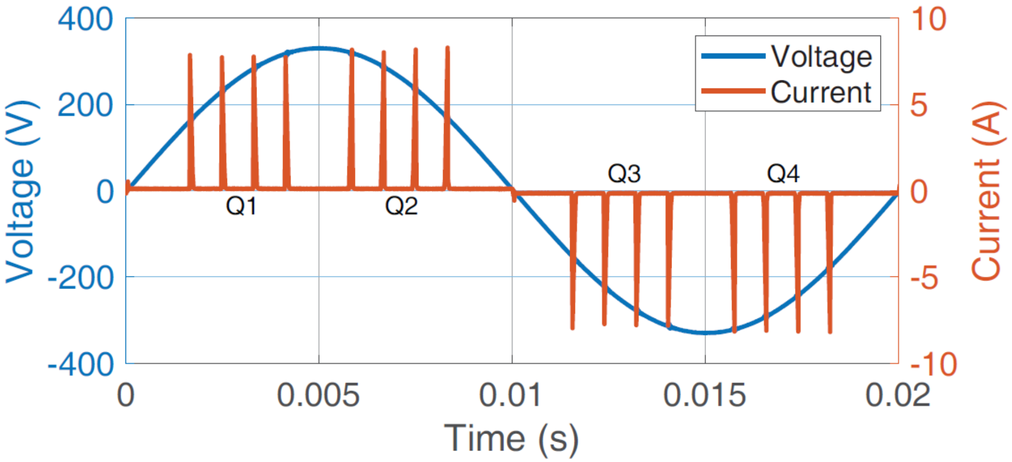


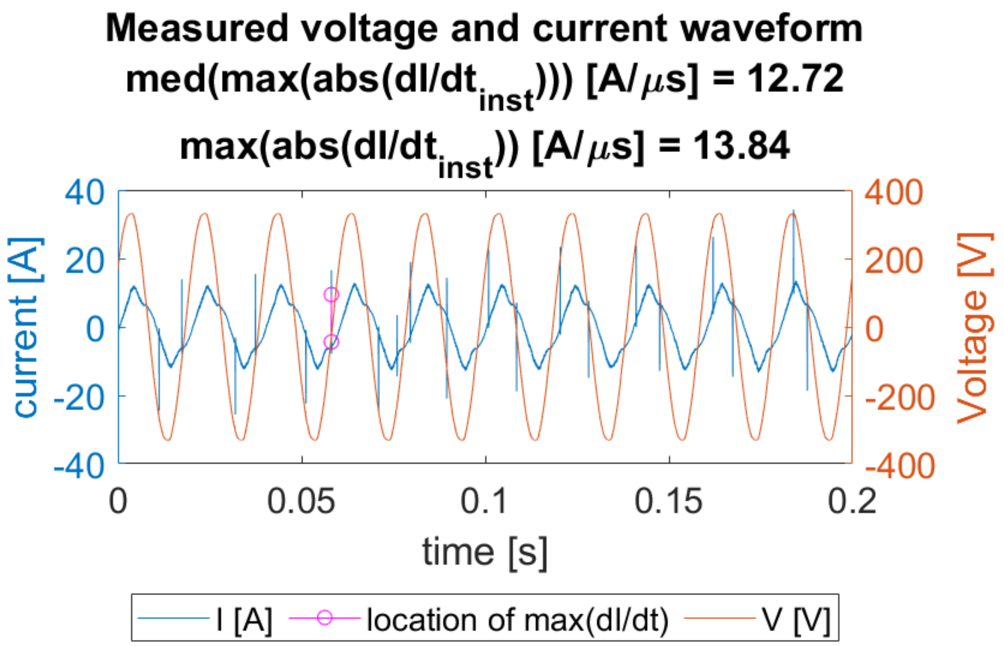
Table 5.4: Worst case waveform characteristics

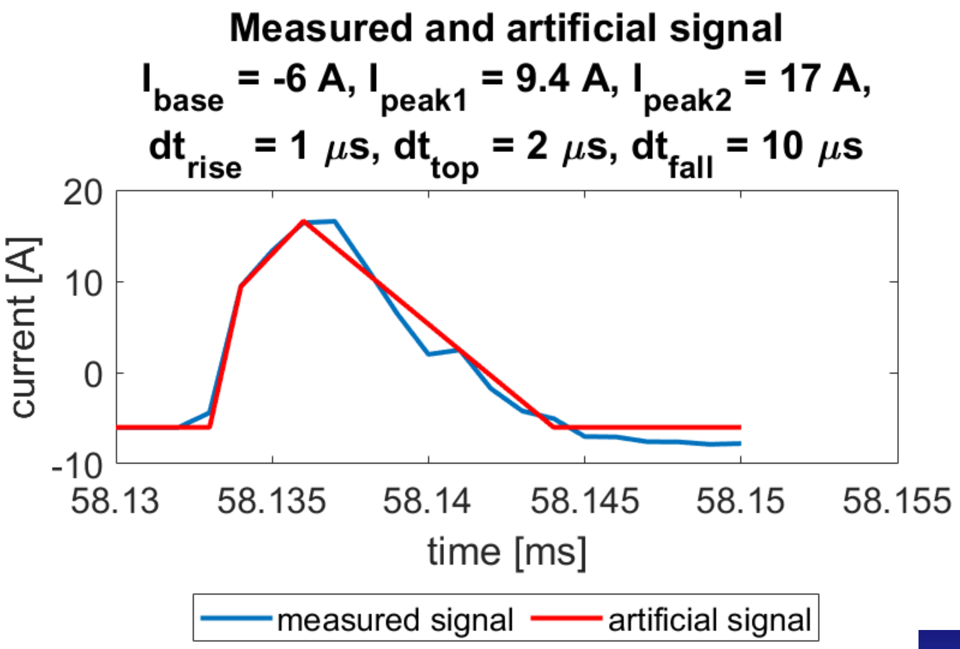
Quarter	t_r	t_f	Peak	Rising SR	Falling SR
1st & 3rd	8 µs	80 µs	8 A	1 A/µs	-0.1 A/µs
2nd & 4th	80 µs	8 µs	8 A	0.1 A/µs	-1 A/µs

Table 5.5: Worst case waveform errors

SM1	SM2	SM3	Reference	ΔSM2	ΔSM3
95 W	-989 W	-1036 W	95.9 W	-1085 W	-1132 W

Proposal to CENELEC TC13 WG01





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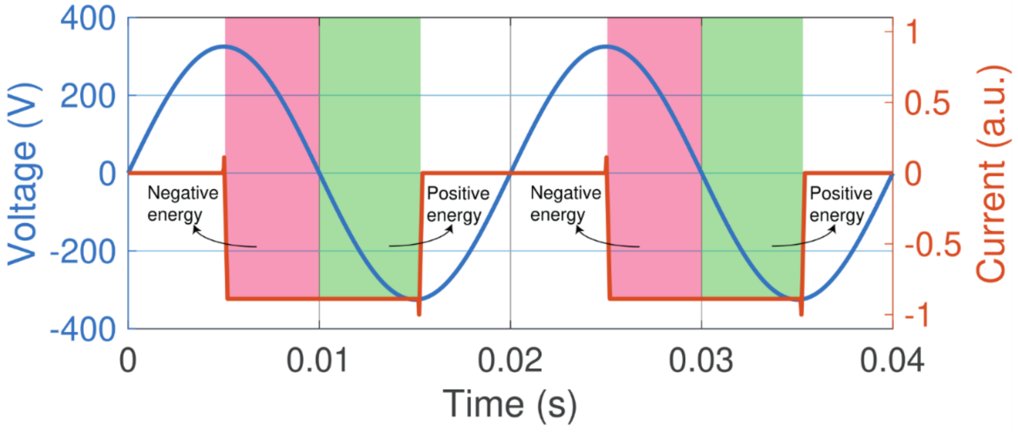
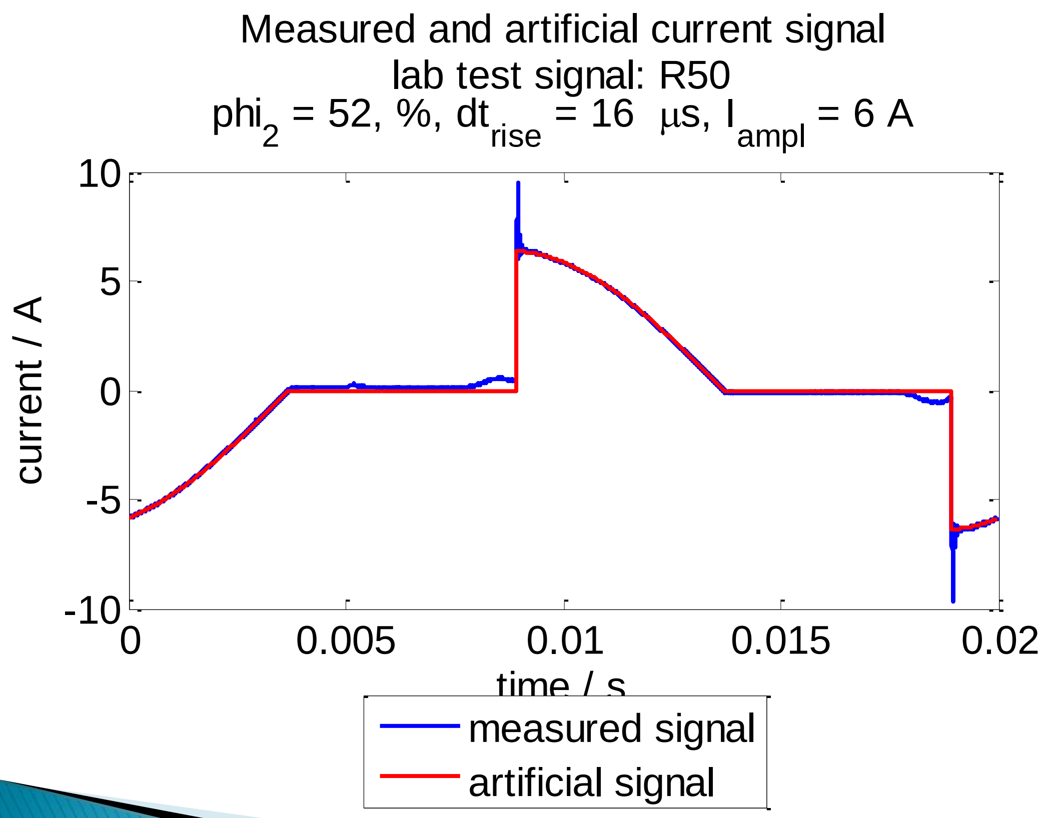
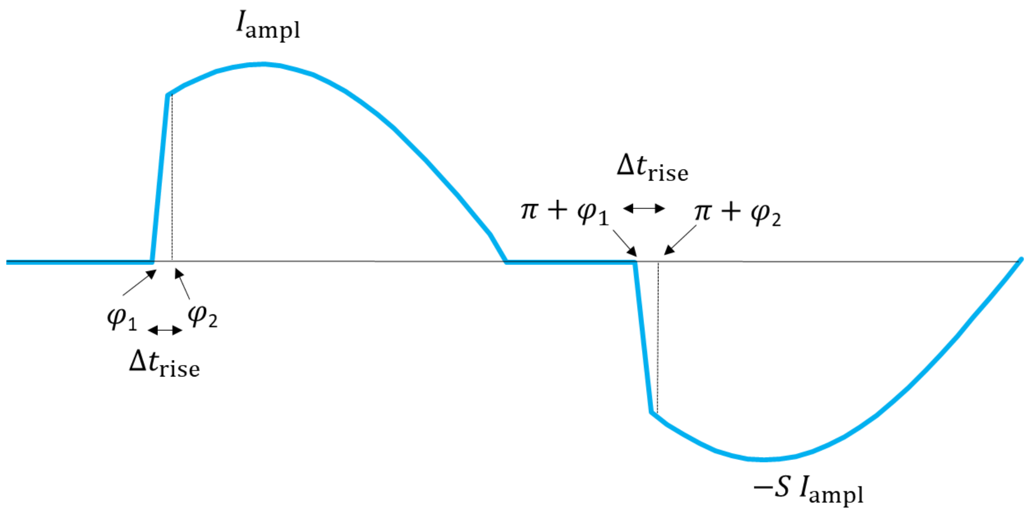
Phase-fired waveform







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Whose liability?

- Static meter manufacturers?
  - → Standardization (IEC TC13 WG11, CLC TC13 WG01, …)
- Household electronics manufacturers?
  - → CE mark
- Customers?
  - → Common sense
- Utilities, metering companies?
  - → “It is *their* energy bill”
- Government?
  - → Regulations (OIML, Welmec)
- What about the potential effects on other equipment?
  - → Do present emission and immunity tests cover these waveforms?

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Present status and future

- In-situ cases were found with COTS equipment
- The root-cause for Rogowski coil meter errors was found
  - Phase and di/dt
- Investigated and tested > 70 meters
- Impact study in the Netherlands based on statistics
- Dutch rules for new meters

  Meters should operate correctly for all test waveforms
- Cenelec TC 13 WG 01 task force MeterEMI

  Selection of proper test waveforms in addendum of EN 50470
- Influence of voltage distortion?

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Extra

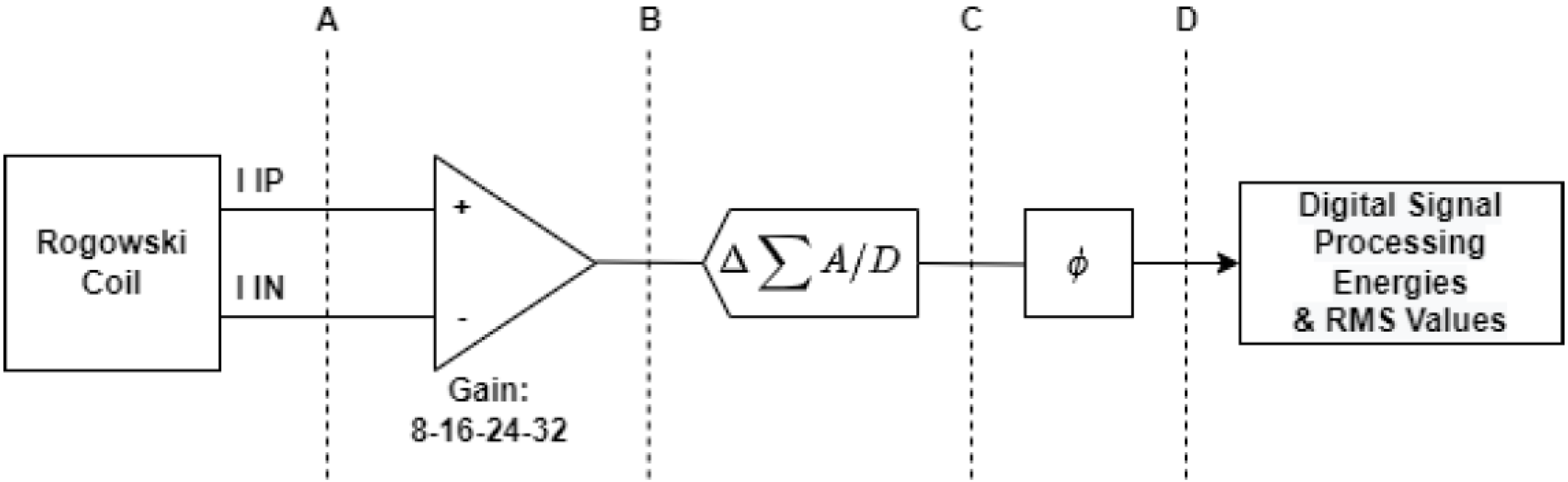

Figure 5.2. Block diagram of the current measurement chain inside the STPM01 chip that is used in SMs [98]

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