How to Earn Money with an EMI Problem: Static Energy Meters Running Backwards

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***Abstract*—The increased use of non-linear appliances in households has resulted in several conducted electromagnetic interference issues, such as misreadings of static energy meters used for billing purposes of the households' energy consumption. In this paper a case is presented where a static energy meter indicates a power generation, while power is actually being consumed. A perceived power generation of more than 430 W is measured by a static energy meter installed in a household when a television with a commercial off the shelf remote controlled switch with dimming functionalities consumed 21 W. The same situation is reproduced in a controlled lab environment, to eliminate possible influences of other appliances in the grid, which confirmed the on-site results. The current waveforms causing this supposed generation of power are investigated and it is observed that the phase firing angle of the current pulse drawn by the load in combination with the commercial off the shelf remote controlled switch affects the metering errors and determines whether the errors indicate a false generation, a too high consumption of power, or no error at all. A combination of the household equipment and a basic unloaded switched mode power supply in conjunction with two remote controlled switches resulted in a perceived power generation of more than 600 W. Having these loads connected for the entire day would counteract the total consumption of an average household and could even "generate" energy, and thus generate money for the consumer.**

***Index Terms*—Static energy meter, conducted electromagnetic interference, non-linear, dimming, phase firing angle.**

I. Introduction

Nowadays a lot of conducted electromagnetic interference (EMI) is created by the cyclic switching of non-linear electronic devices [1]. The increased use of this non-linear equipment in households in comparison to traditional resistive equipment has resulted in several EMI cases [2], [3]. One important issue is the immunity of static energy meters resulting in misreadings, which has a large impact as consumers might be over or under billed. Examples of non-linear equipment resulting in misreadings are dimmed lighting equipment of compact fluorescent lamp (CFL) and light-emmiting diode (LED) technology [4], [5], and a speed controlled water pump [6], [7]. These experimental studies show maximum errors that exceeded 2000% due to the fast rising of pulsed currents being drawn [8]. The existence of similar equipment resulting in static energy meter errors is shown in [9].

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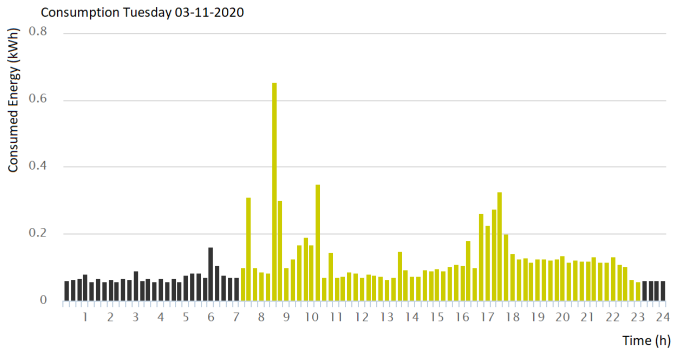
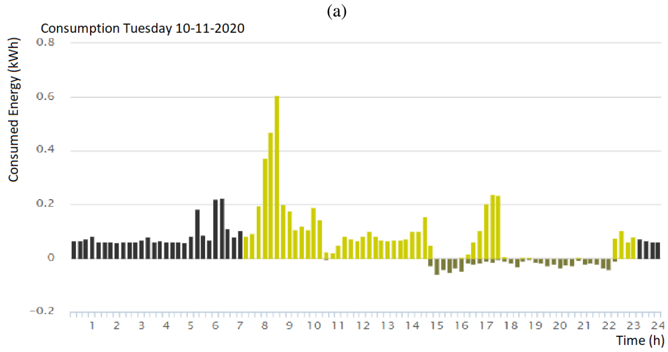
Hereafter, several possible interference cases have been reported by consumers. Some show an unexpected energy consumption, but not explicitly due to misreadings of static energy meters. With the introduction of applications, such as the Dutch Slimmemeterportal [10], consumers can monitor their energy consumption and get a much better insight. This helps with explaining the unexpected energy consumption. A consumer in the Netherlands observed an inconsistent energy consumption which appeared after installing a commercial of the shelf (COTS) remote control for switching household equipment on and off, see Fig. 1. The remote control switch also included a dimming functionality, but the salesperson told the consumer it could also be used solely for turning equipment on and off.

Fig. 1. COTS switch with dimming functionalities initially bought with the idea of using it as an on and off switch

The initial energy consumption is visible in Fig. 2(a), where the black data corresponds to off peak hours and the yellow data to peak hours. It shows a constant consumption of around 250 W which is present 24/7 due to water pumps in a pond, but no other out of the ordinary energy consumption is visible. After connecting the COTS switch however, something peculiar happened. The energy consumption dropped significantly when the equipment was turned on and even reached negative values, as can be seen clearly in Fig. 2(b). Clear gaps can be seen here around 15:00 and between 18:00 and 22:00. At these moments the installed static energy meter's instantaneous power reported a power generation, which has been seen to go up to 430 W, see Fig. 3. The household has no power



(a)



(b)

Fig. 2. (a) Initial energy consumption of a household in the Netherlands (b) Inconsistent lower energy consumption in the same household as Fig. 2(a), when connecting a COTS on and off switch with dimming functionalities to household equipment

generating equipment such as solar panels. The installed static energy meter was manufactured in 2017, and is thus compliant with the updated test standard IEC 61000-4-19 in 2014 [11].

In this paper the current waveforms causing this supposed generation of power are investigated.The static energy meter is approached as a black box, while recreating and testing the on-site found inconsistent energy consumption/generation situation in a controlled lab environment. This is done in order to test the influence of the remote controlled switch in combination with the equipment on static energy meters, without introducing additional complexity of the complete household situation. The remote controlled switch in combination with the equipment is tested as a load for a set of static energy meters, which also includes a specimen of the static energy meter installed in the household situation. The setup is powered by two different approaches, first using an ideal power supply such that the measurements are not disturbed by the non-linearities of the power supply and secondly using the mains supply from the building, resembling a real on-site scenario.

The paper is structured as follows. The measurement setup used to capture the waveforms and to monitor the static energy meter readings in case of the inconsistent energy consumption is described in Section II. After this, in Section III, several waveforms are shown that have different effects on the static energy meters, of which some result in a false indication of a power generation by the static energy meter. In Section IV the conclusion will be given.

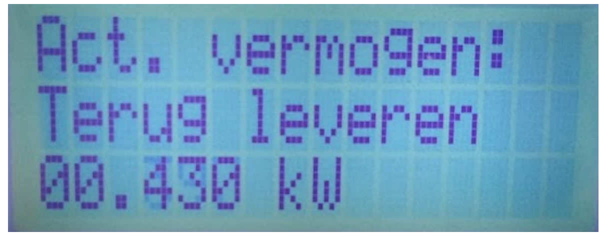


Fig. 3. Observed instantaneous power (Act. vermogen) from a static energy meter showing power being generated (Terug leveren) in a household without power generating equipment

II. Measurement Setup

In this section the setup is described first, which is used to read out the static energy meters and to capture the waveforms causing potential misreadings. Secondly, the used load and corresponding test signals are described.

A. Static Energy Meter Setup

First, the measurements are performed using a four-quadrant Pacific Power Smart Source 140-TMX AC creating an ideal grid at 50 Hz, 230 V RMS, such that the non-linearities of the power supply do not influence the measurements. Secondly, the mains supply of the building is used to resemble the real on-site scenario. The power from the source is supplied to a set of 24 static energy meters, representing the installed base of static energy meters throughout the Netherlands, which can be seen in Fig. 4. Only the readings from the static energy meters that show erroneous results are shown in Section III, where four erroneous static energy meters are found. The naming convention of SM1 (static energy meter) until SM4 is uncorrelated with the order they appear in the setup of Fig. 4. The same version of the static energy meter which resulted in the observed inconsistent energy generation in the household, but built in 2019, is also included in the setup, referred to as SM3. The internal consumption of the static energy meters has been accounted for and individual static energy meters can be tested by switching on and off (groups of) static energy meters. As a reference the Yokogawa WT500 power analyzer is used, which is placed between the static energy meters and the load. The voltage and current waveforms are captured using a Pico Technology TA043 differential voltage probe with a frequency range up to 100 MHz and a Keysight N2779A current probe with a 100 MHz analog bandwidth. A PS4824 PicoScope is used as a digitizer, which has a sampling rate of 1 MHz and 1 s of the waveforms are recorded, thus capturing 50 cycles at mains frequency.

B. Tested Loads

The COTS remote controlled switch in combination with the household equipment, which consists of a switch mode power supply (SMPS), resulting in the observed inconsistent energy generation was used as a load in the lab. In the lab it

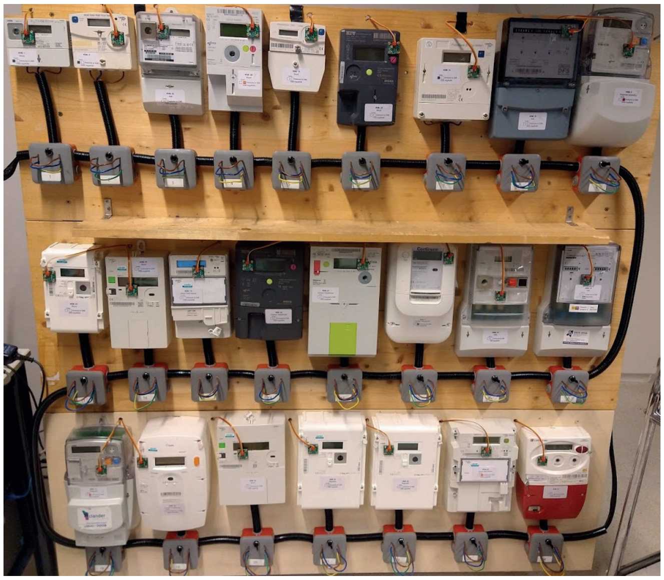


Fig. 4. Picture of the 24 static energy meters used in the setup

was observed that the remote controlled switch always initiates a dimming function when turning on equipment, thus not solely functioning as a switch, as was the consumer's intended usage. The dimming function concentrates the energy of the equipment into a small time interval reducing its consumption by creating a pulsed current. The dimming function then phase shifts this current pulse with respect to the voltage waveform. The possible firing angle (FA) ranges from 45° up to 135°, where a FA of 45° caused the perceived power generation in the household. Three possible situations will be tested with a FA of 45° (maximum dimming found in the household situation), 90° (minimal dimming), and 135° (being a mirrored version of the found maximum dimming). The different waveforms can be seen in Fig. 5. These situations draw 21 W, 22 W and 20 W, for the left, middle and right pulse respectively. The measurement are repeated using a different basic SMPS as it was observed that the SMPS inside the household equipment was causing the high currents being drawn.

III. Results

The results obtained with the previously mentioned measurement setup are displayed and analyzed in this section. This section is divided in three subsections, first the COTS remote controlled switch with dimming functionalities, referred to from now on as dimmer, is used in conjunction with the same equipment as was used in the household situation, to reproduce the results in a controlled lab environment. This situation is referred to as load 1, drawing around 21 W when the pulse has a FA of 90°. Secondly the same dimmer is used in combination with a basic unloaded SMPS, referred to as load 2, drawing around 4 W when the pulse has a FA of 90°. Lastly both measurements are combined in one new measurement, drawing around 25 W. For every loading condition, the measurements are performed with an ideal grid and the building's mains.

The four static energy meters can be subdivided into two groups, the first having errors in the same style as mentioned in [6], containing SM1 and SM2. Furthermore, the second group, introducing a new type of error, containing the same static energy meter as found in the household, referred to as SM3 and SM4.

A. COTS dimmer with household equipment

First the COTS dimmer is connected to the household equipment that showed an inconsistent energy generation as mentioned in the introduction, to reproduce this situation in the lab.

1) Ideal Grid: The three waveforms drawn by load 1 when an ideal grid is used can be seen in Fig. 5, where a pulse is set at the FA of 45°, 90° and 135°, respectively.

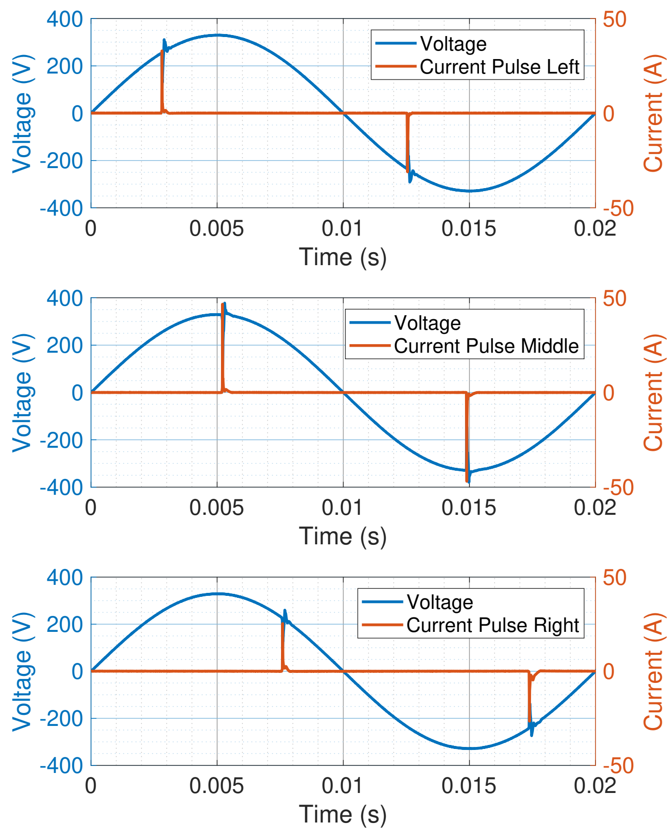


Fig. 5. Household equipment with a COTS dimmer supplied by an ideal grid, waveform 1, 2 and 3

The resulting measured powers by the static energy meters and the reference power analyzer are summarized in Table I, as waveforms 1, 2 and 3. When looking at the pulse with a FA of 45°, waveform 1, it is seen that the static energy meters measure a power generation, i.e. a negative consumption, while the reference indicates that the power is consumed from the grid! Thus, the situation found in the household is properly reproduced. When considering the pulse with a FA of 90°, waveform 2, no significant error is found. When phase shifting the current pulse to 135° a peculiar result is found, compared to a FA of 45°. In this case the static energy meters showed a much higher energy consumption compared to the reference. For SM3, which is also installed in the household, the absolute measured power is in the same order of magnitude for a FA of 45° and 135°, with the major change being the polarity of the error. The differences in the time-domain characteristics of the waveform, that are obtained using the waveform model in [12], can be seen in Table II, showing the charge, crest factor, peak value, pulse width and slope of the waveforms. From this it is evidenced that there are no major significant differences between the parameters of the waveforms, other than the obvious and intended phase shift. This shows that the FA of similar pulses determines whether the tested static energy meters report a false generation of power for a FA at 45°, no significant error for a FA at 90° or a higher consumption of power for a FA at 135° for some static energy meters, even ones that are compliant with the updated test standard of 2014 [11].

TABLE I. Static energy meter (SM) readings for waveforms 1 to 6

#	WT500 (W)	SM1 (W)	SM2 (W)	SM3 (W)	SM4 (W)
1	21 W	-297 W	-286 W	-350 W	-56 W
2	22 W	35 W	32 W	42 W	37 W
3	20 W	485 W	462 W	314 W	159 W
4	21 W	-398 W	-452 W	-365 W	-30 W
5	22 W	20 W	22 W	29 W	30 W
6	21 W	635 W	661 W	324 W	158 W

TABLE II. Time-domain parameters of the test signals

Test signal	Charge (mC)	Crest factor	Peak value (A)	Pulse width (ms)	Slope (A/µs)
Waveform 1	1.4	41	34	0.23	3.5
Waveform 2	1.0	42	48	0.11	6.4
Waveform 3	1.5	28	26	0.39	2.4
Waveform 4	1.4	35	28	0.22	2.6
Waveform 5	1.0	40	44	0.10	5.2
Waveform 6	1.0	32	23	0.22	2.0

2) Mains: The same three current waveforms are reproduced for load 1, but now using the mains instead of an ideal 50 Hz supply, and can be seen in Fig. 6. It is observed that the drawn voltage is distorted and is minimally affected by the current pulse, while the drawn current pulses have faster slopes, but have a similar shape compared to the ideal grid, Table II. The resulting readings from the static energy meters can be seen in Table I, where waveforms 4, 5 and 6 represent FAs of 45°, 90° and 135°, respectively. Two groups can be distinguished in the static energy meter readings for the difference in errors. For the static energy meters SM1 and SM2 the absolute errors are larger compared to the ideal grid due to the capacitive nature of the mains of the large building compared to the ideal power supply, causing larger slopes for the currents, which has been shown previously to correlate with the metering errors [8]. Furthermore, for static energy meters SM3 and SM4 the errors are in the same order of magnitude for the mains compared to the ideal grid, suggesting that the FA has the largest influence.

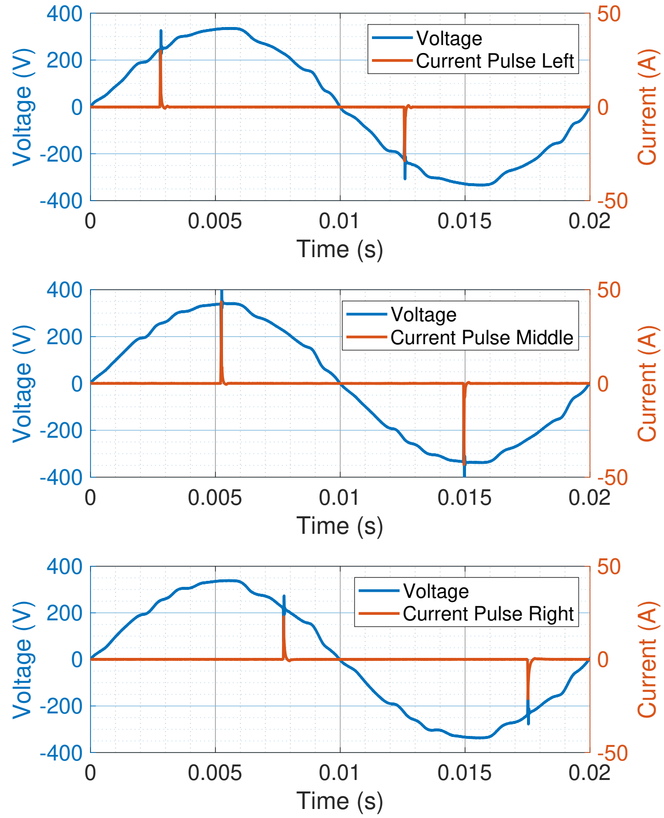


Fig. 6. Household equipment with a COTS dimmer supplied by the mains, waveform 4, 5 and 6

B. Dimmer with unloaded SMPS

Next the measurements are repeated with load 2 that consist of a basic unloaded SMPS. This is done to remove the effects that the other parts of the appliance in load 1 can have on the measurement. These measurements are subdivided in the same format as the previous measurements.

1) Ideal Grid: The waveforms drawn by load 2 can be seen in Fig. 7, where the current is being drawn due to the combination with the dimmer. The static energy meter readings resulting from these waveforms can be seen in Table III, considering waveform 7 and 8 with FAs of 45° and 135°, respectively. This measurement shows that a SMPS in combination with the dimmer, that only consumes 4 W, causes a large impulsive current resulting in static energy meter errors. This means that this type of static energy meters are easily fooled into perceiving power generation when in reality only little power is being consumed, with a relatively simple configuration of the COTS dimmer in combination with a SMPS.

2) Mains: When changing the supply from the ideal grid to the mains of the building the same type of current waveforms are found as shown in Fig. 8, however with more ringing in the current. The errors are presented in Table III for waveform 9 and 10 with FAs of 45° and 135°, respectively. When looking at SM1 and SM2 it seems that the ringing could be the cause of the lower errors.

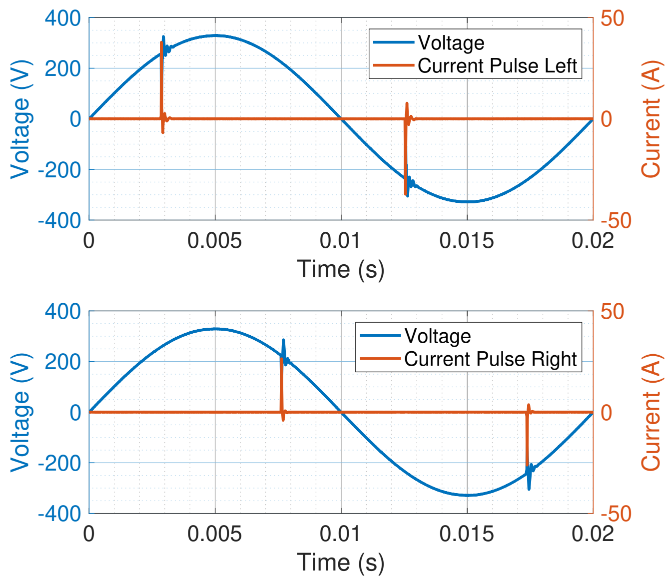


Fig. 7. A dimmed unloaded SMPS supplied by an ideal grid, waveform 7 and 8

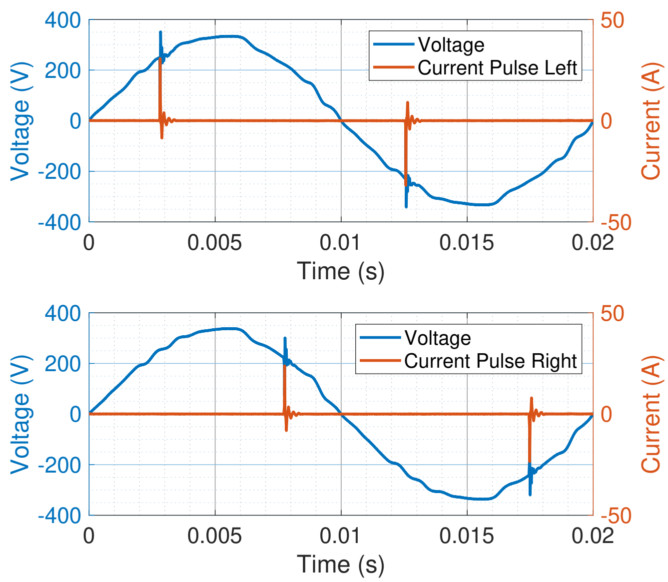


Fig. 8. A dimmed unloaded SMPS supplied by the mains, waveform 9 and 10

C. *Two dimmers with two loads*

To look further into the effects of the pulses the two previously shown measurements are combined, by using two identical dimmers connected to load 1 and 2 respectively.

1) Ideal Grid: The waveform that resulted from the combination of the two loads is shown in Fig. 9, where two pulses can be clearly distinguished. The results of the static energy meter readings are shown in Table IV, where waveforms 11 and 12 with FAs around 45° and 135°, respectively, represent the ideal grid situation.

For the same static energy meter as found in the household, SM3, it was found that the severity of the error increases when

TABLE III. Static energy meter readings for waveforms 7, 8, 9 and 10

#	WT500 (W)	SM1 (W)	SM2 (W)	SM3 (W)	SM4 (W)
7	4 W	-37 W	-24 W	-291 W	-57 W
8	3 W	216 W	104 W	246 W	117 W
9	4 W	-8 W	-32 W	-228 W	-104 W
10	3 W	39 W	36 W	203 W	107 W

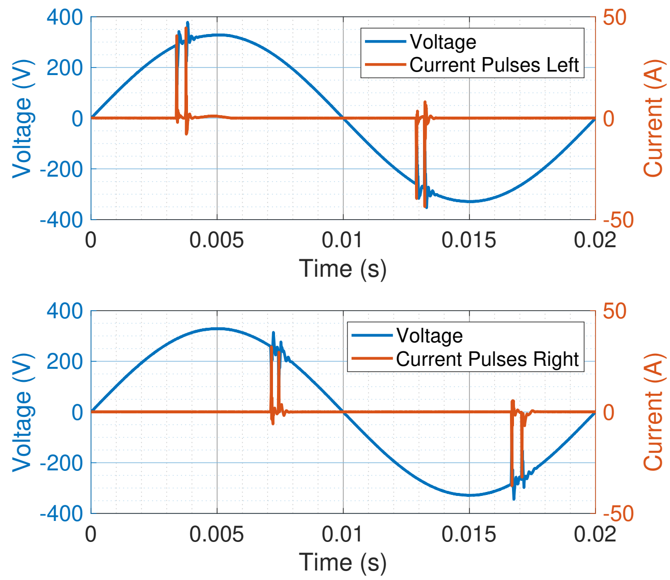


Fig. 9. Two dimmed loads supplied by an ideal grid, waveform 11 and 12

adding additional pulses! While for the other, mostly older, static energy meters the errors are reduced, or remain the same compared to the uncombined load measurements. This result shows that the extend of the problem can be even further amplified by the combination of several dimmers that are loaded with SMPS equipment, and adding the corresponding pulses with different FAs with respect to each other within the voltage.

2) Mains: For the mains, errors in the same order of magnitude are found. The waveforms of this measurement are shown in Fig. 10, while the results are presented in Table IV, as waveforms 13 and 14 with FAs of 45° and 135°, respectively.

TABLE IV. Static energy meter readings for waveforms 11, 12, 13 and 14

#	WT500 (W)	SM1 (W)	SM2 (W)	SM3 (W)	SM4 (W)
11	25 W	-178 W	-203 W	-613 W	-247 W
12	24 W	472 W	372 W	661 W	102 W
13	26 W	-375 W	-451 W	-573 W	-197 W
14	24 W	567 W	652 W	550 W	78 W

The observation from the consumer that his installed static energy meter reported a power generation while energy is being consumed, is confirmed by the lab experiments. The consumer's installed static energy meter was manufactured in 2017 and the specimen in the lab is from 2019. This shows that static energy meters that have to fulfill the IEC 61000-4-19 [11] immunity standard can still be sensitive to EMI problems. Meaning that interference signals found in

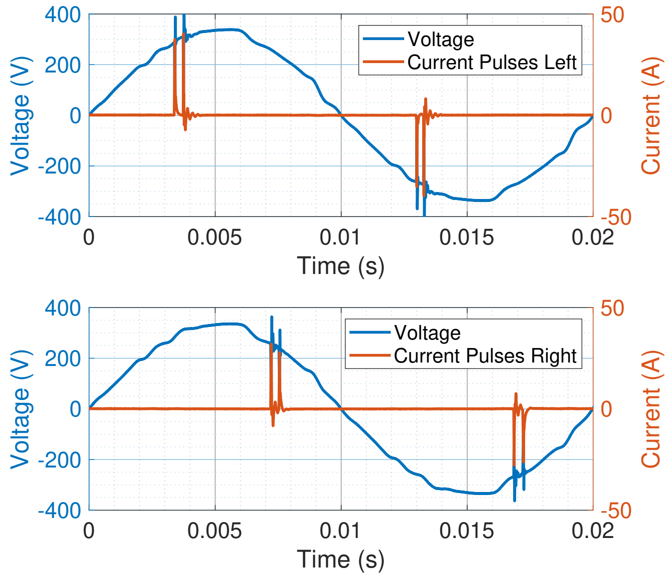


Fig. 10. Two dimmed loads supplied by the mains, waveform 13 and 14

household situations are beyond the immunity standard, as well as the static energy metering requirements in [13].

IV. Conclusion

A peculiar situation in a household in the Netherlands is identified where a static energy meter, from 2017, shows a generation of power with no power generating equipment such as solar panels installed. This situation occurs when using a COTS remote controlled switch with dimming functionalities combined with household equipment. The remote controlled switch and equipment are tested in the lab, such that the measurements are performed without the possible interference from other appliances present in the household situation. It is observed that the remote controlled switch always initiates a dimming function when turning on equipment, thus not solely functioning as a remote controlled switch, as was the consumer's intended usage. In the lab the same type of static energy meter is installed together with 23 other static energy meters representing the installed base of static energy meters throughout the Netherlands. In this setup the same results are obtained for four static energy meters, including the same type of static energy meter found in the household. These lab results show a generation of 365 W while 21 W is actually being consumed by a current pulse with a FA of 45° with respect to the voltage. The exact opposite result is found when phase shifting this pulse to 135°, causing a perceived power consumption of 314 W while 20 W is being consumed. Drawing a current pulse at a FA of 90° results in no significant errors for all static energy meters. This shows that the FA affects/amplifies the errors and determines whether the errors indicate a perceived generation or a higher consumption of power. The same result for power generation are reproduced by connecting a basic unloaded SMPS to the remote controlled switch. A maximum power generation of 613 W is found with a combination of two loads consisting of SMPSs, actually consuming around 25 W, showing that the errors add up when introducing more loads with dimmers. Having such a setup running 24/7 counteracts the average household consumption, and would even generate a positive income of money. The fact that it happened with a static energy meter from 2017 (household) and with a static energy meter of the same type in the lab, from 2019, shows that static energy meters with these errors are still being installed throughout the Netherlands, since they fulfil the updated IEC 61000-4-19 test standard of 2014.

V. Acknowledgement

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References

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

[2] CLC/TR 50627, "Study Report on Electromagnetic Interference between Electrical Equipment/Systems in the Frequency Range Below 150 kHz," *Ed. 2*, 2014.

[3] K. Murakawa, N. Hirasawa, H. Ito, and Y. Ogura, "Electromagnetic interference examples of telecommunications system in the frequency range from 2kHz to 150kHz," *2014 International Symposium on Electromagnetic Compatibility, Tokyo*, pp. 581–584, 2014.

[4] F. Leferink, C. Keyer, and A. Melentjev, "Static energy meter errors caused by conducted electromagnetic interference," *IEEE Electromagnetic Compatibility Magazine*, vol. 5, no. 4, pp. 49–55, 2016.

[5] Z. Marais, H. Van den Brom, G. Rietveld, R. Van Leeuwen, D. Hoogenboom, and J. Rens, "Sensitivity of static energy meter reading errors to changes in non-sinusoidal load conditions," *2019 International Symposium on Electromagnetic Compatibility (EMC Europe 2019)*, pp. 202–207, Barcelona, Spain, 2019.

[6] B. ten 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," *Renewable Energy and Power Quality Journal (RE&PQJ)*, pp. 15–19, Santa Cruz de Tenerife, Spain, 2019.

[7] B. ten Have, T. Hartman, N. Moonen, and F. Leferink, "Misreadings of Static Energy Meters due to Conducted EMI caused by Fast Changing Current," *2019 Joint International Symposium on Electromagnetic Compatibility and Asia-Pacific International Symposium on Electromagnetic Compatibility*, pp. 445–448, Sapporo, Japan, 2019.

[8] B. ten Have, T. Hartman, N. Moonen, and F. Leferink, "Inclination of Fast Changing Currents Effect the Readings of Static Energy Meters," *2019 International Symposium on Electromagnetic Compatibility (EMC Europe 2019)*, pp. 208–213, Barcelona, Spain, 2019.

[9] R. V. Leeuwen, H. van den Brom, D. Hoogenboom, G. Kok, and G. Rietveld, "Current waveforms of household appliances for advanced meter testing," *2019 IEEE 10th International Workshop on Applied Measurements for Power Systems (AMPS)*, Aachen, Germany, 2019.

[10] EnergyAlert. Slimmemeterportal. (2021, Jan 7). [Online]. Available: https://www.slimmemeterportal.nl/

[11] "Electromagnetic Compatibility (EMC) - Part 4-19: Testing and measurement techniques - Test for immunity to conducted, differential mode disturbances and signalling in the frequency range from 2 kHz to 150 kHz, at a.c. power port," *IEC 61000-4-19:2014*, 2014.

[12] B. ten Have, M. A. Azpúrua, T. Hartman, M. Pous, N. Moonen, F. Silva, and F. Leferink, "Waveform Model to Characterize Time-Domain Pulses Resulting in EMI on Static Energy Meters," *IEEE Transactions on Electromagnetic Compatibility (Early Access)*, pp. 1–8, 2021.

[13] "EN 50470-3:2006 Electricity metering equipment (a.c.) – Part 3: Particular requirements - Static meters for active energy (class indexes A, B and C)," 2006.