Electromagnetic Interference on Static Meters When Combining Linear and Non-Linear Loads

Kasper Müller   Bas ten Have   Tom Hartman

***Abstract*—Non-linear devices such as switch-mode power supplies and dimmers are used on an ever increasing basis. Previous studies show that there is electromagnetic interference between these non-linear loads and some commercial static energy meters, resulting in large errors when measuring energy consumption. These studies mostly focused on the impact of an isolated non-linear load. In a real household we find both linear and non-linear loads. By studying what happens to the interference when both non-linear and linear loads are present this paper better establishes the impact of the problem in an on-site situation. In a setup with 24 static meters of different types, previously found interfering non-linear loads are put in parallel with linear loads. For some meters, based on shunt and current transformer methods, absolute errors tend to zero when a linear load is present. It is also shown that the addition of a linear load has a minor impact on the error of around $10\,\%$ per kW for some Rogowski coil based meters. The interference is not effected by current sensing type alone as most tested meters show no errors at all. Most importantly the study shows that the Rogowski coil meters that have shown most significant interference in previous studies, still give errors over $450\,\mathrm{W}$ and $-220\,\mathrm{W}$ with a linear load above $1800\,\mathrm{W}$ present. This means that some meters indeed pose a very real problem, not just in the lab with isolated loads, but for everyday consumers.**

***Index Terms*—combination effect, error, linear, measurement, non-linear, static meter**

I. Introduction

Every household has an energy meter. This device measures your electricity consumption so the energy company knows how much to bill you for. In recent years the energy companies have been pushing for so-called smart meters. These meters offer features such as not having to manually report your consumption. Importantly these (often newer) meters no longer use mechanical components and the Ferraris principle to measure consumption, but rely solely on electrical components. We call these energy meters, static meters, because they no longer rely on moving parts. It has however been shown that these static energy meters can deviate in measurements from the real power when it comes to non-linear loads. For instance dimmed compact fluorescent light bulbs have been shown to cause up to $583\,\%$ deviation in a certain static meter compared to a reference mechanical meter [1].

We speak of a non-linear load when the current waveform drawn by the load is not linearly related to the voltage input. In other words the current does not follow the source voltage. This is illustrated in Fig. 1. Examples of non-linear loads include compact fluorescent and light emitting diode based lamps, switch-mode power supplies and dimmers.

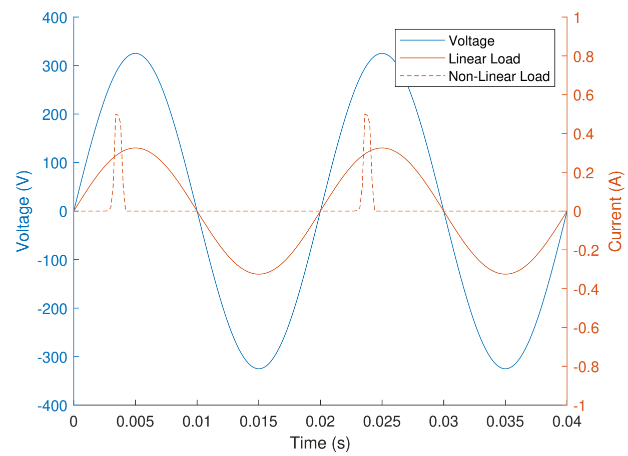

Fig. 1. Waveforms of current-draw from linear and non-linear loads

More recent research shows specific waveforms and devices causing even higher interference. In [2] waveforms are analysed showing errors upto $2114\,\%$. This is also shown when compared with an accurate power spectrum meter in an isolated setup, meaning that the reported consumption is wrong. Although the errors shown in these studies vary heavily based on the meter and waveform itself it can be concluded that there is in fact an electromagnetic compatibility (EMC) problem between the non-linear loads and some static meters.

To get a better grasp of when meter interference occurs, [3] develops a parametric waveform model for non-linear currents, classifying which properties of the waveform produce meter errors. In general it is found that problematic waveforms are narrow, fast-rising and pulsed. Making the waveforms more narrow, fast-rising (see Fig. 2) or of higher amplitude will cause more meter interference [3].

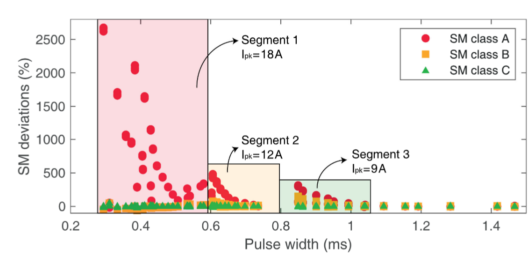

Fig. 2. Pulsewidth and its correlation with meter errors [3].

Knowing that non-linear devices can cause EMC problems in the static meters with their current-draw patterns presents a striking realisation: this could be a problem of large societal impact, especially since these waveforms can be found in the field. This is shown for instance shown in [4] that finds 379 on-site examples of loads conforming to the waveform model; estimating errors up to $935\,\%$. As fairly pointed out by [5] a real household does not feature non-linear devices exclusively. In a typical household we see linear devices in combination with non-linear devices. To understand the real impact, for instance for the customer, the absolute error of these combinations needs to be found.

In this paper we take steps in this direction: problematic waveforms found in previous studies are put into a lab environment together with linear loads to resemble the on-site situation and see the combined effects on meter interference. By testing multiple different loads on a set of 24 static meters it is found that most tested meters show no signs of interference at all. Furthermore, adding a linear load to an interfering non-linear load seems to have a small but different effect based on the current sensing principle utilized by the meter. Most importantly, putting linear loads on the meters with previously reported high interference leads only to a minor reduction in absolute error. This means there are currently meters in use that will lead to significant wrong readings even in real household scenarios.

The paper is structured as follows. First Section II explains the general setup and the selection process of the loads. Section III shows the errors in meters. After identifying two trends encountered with just linear loads the section proposes a method of normalisation to isolate the effects the linear load has on the errors of the interfering non-linear load. The section then shows normalized results for the two chosen waveforms from Section II. In section IV the results are discussed and put into perspective. Lastly Section V compiles the results.

II. Method

This section describes how the combined effect of linear and interfering non-linear loads on static meters were tested. Section II-A explains the general setup and the way of measuring errors. Section II-B shows how the results will be processed. Section II-C tells which loads were used and why.

A. Measurement Setup

To measure the effects on many meters a similar setup to that used in [2] and is used. This setup will now be described along Fig. 3 moving from left to right. The normal building grid is used as a supply. This is done to more closely match the real world scenario. The supply is fed through a line of 24 static meters. These meters are all connected in series and can be bypassed with a switch. The meters are read out by counting light impulses of their calibration LED, which blinks a set amount of times for every kilowatt the meter measures. The blinks are detected with light sensors connected to an Arduino. At the end of the meters the Yokogawa WT5000 is connected as reference meter. After this a Keysight N2783B current clamp along with a Picotech TA043 differential voltage probe are also connected to a Picoscope 4000. Behind the reference meter resides the socket. All the non-linear and linear loads are plugged into there and can be individually turned on or off. All of the components are connected to a central PC running a Matlab script that can both control the setup, read out the sensors and analyse the obtained results.

B. Processing

When measuring, the Picoscope is set to capture a $1\,\mathrm{second}$ signal, sampled at $1\,\mathrm{MHz}$, of the voltage and current waveform. This is done for every minute in the total measurement run. All the cycles in these waveforms are stacked and averaged for visualisation and characterisation of the waveform itself. The Yokogawa provides the real power reference which is used to calculate the absolute errors.

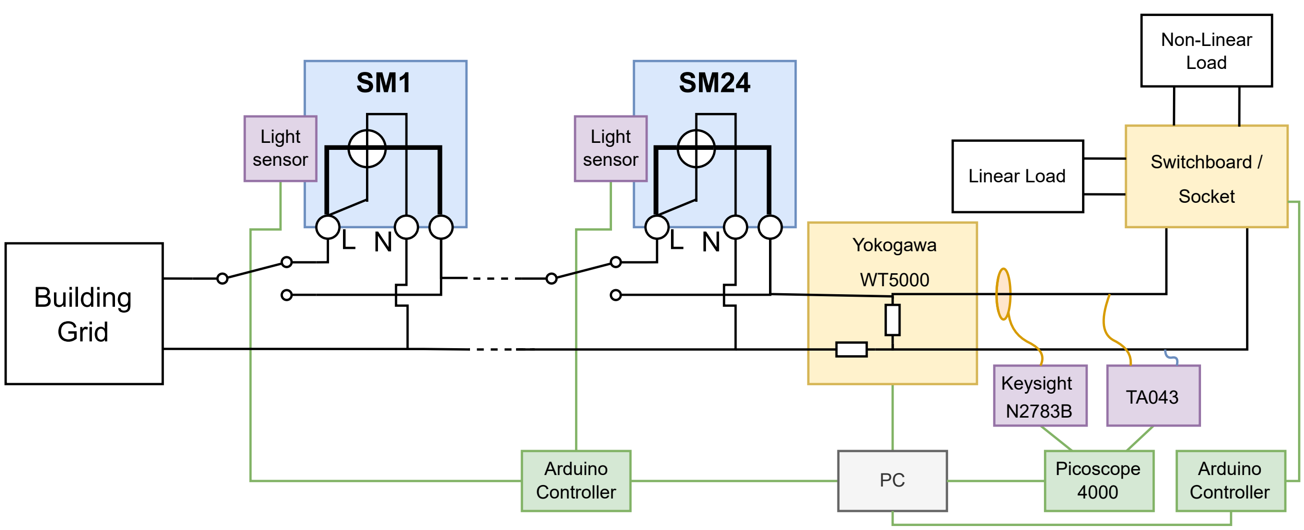

Fig. 3. Measurement setup

In previous research the relative error in percentages is usually given. In this paper the absolute power difference is considered. This is done because percentages of power error become less meaningful when high linear loads are present, especially if the non-linear draws much less power compared to the linear load. This is because the linear loads themselves do not contribute to the interference of the meter.

C. Loads

By introducing a commercial heater that has fixed wattage values of 190 W, 300 W, 500 W, 800 W, 1300 W or 1800 W a setup is achieved that can introduce a linear factor while remaining easy to test with the same values. Along with the heater, a box is constructed containing two $1\,\mathrm{k}\Omega$ resistors. Giving a smaller linear wattage of around 26 W, 53 W or 106 W. This can be used to add finer steps of linear power. More importantly this allows to have linear power draw that is close to the wattage of the non-linear loads. In this study the two linear loads are combined to form the (measured) steps 28 W, 55 W, 109 W, 213 W, 337 W, 443 W, 538 W, 637 W, 841 W, 938 W, 1324 W, 1421 W, 1771 W and 1839 W which are used for all experiments.

The first non-linear load is a waterpump. Identified in [6] the commercial pump was found and analysed giving meter errors as low as $-61\,\%$ and high as $2675\,\%$. Using the pump has a two reasons. We can verify the previous results and because of the fixed mode the setup is repeatable. Pump-mode 1 has been used because in previous papers this load resulted in the highest errors. The waveform of the pump is shown in Fig. 4.

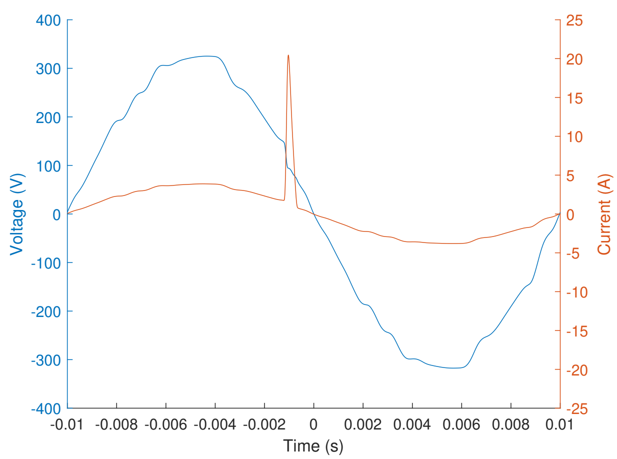

Fig. 4. Waveform of the waterpump with a 640 W linear load.

The second non-linear load is that of a dimmed switch-mode power supply. Identified in [7]. According to the study some static meters give errors of over -430 W. With no other load the meter detects power generation when in reality power was being drawed from the grid. If you have a certain static meter in your house this could essentially mean lower energy bills when plugging such a device in the socket. The waveform of the dimmed power supply is shown in Fig. 5.

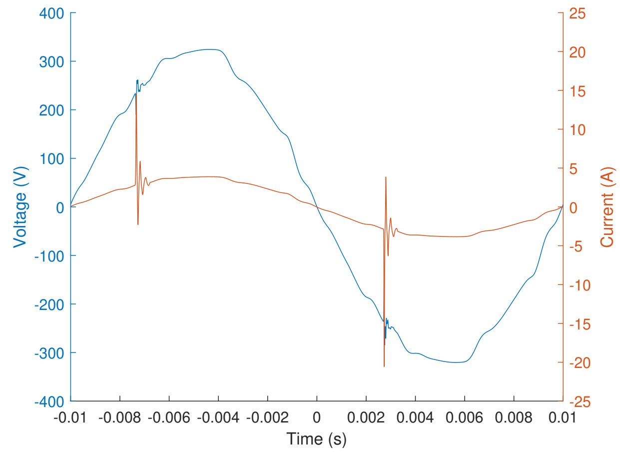

Fig. 5. Waveform of the dimmed switch-mode power-supply. Combined with a 640 W linear load.

III. Results

This section describes the results found in this study. First solely linear loads are tested, providing a baseline for possible errors already present in a setup with only non-interfering linear loads. After found effects a normalisation of the setup is proposed that allows to focus on how the interference of a non-linear load changes. After this the linear and non-linear loads are combined as described in Section II-C. The effects and problematic meters of the waterpump are shown first and the effects of dimmed power supply are described hereafter.

A. Linear load

For linear behaviour meter standards have been well established [8]. In [1] it can clearly be seen that less dimming and more resistive-based loads lead to smaller meter interference. To test the measurement setup and verify this result only the resistive loads were connected. This results in the error-graph shown Fig. 6. Each line represents a different static meter. The black dotted line shows the allowed $2.5\,\%$ error margin.

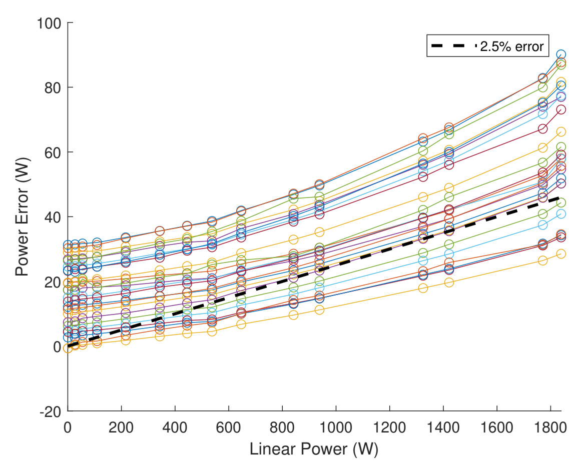

Fig. 6. Meter errors on linear loads.

From Fig. 6 we can see two striking effects. First of all the meters with a higher index have a lower absolute errors. Looking back at Fig. 3 this makes sense as the lower-index meters also detect the energy usage from the subsequent meters. On average every meter uses about 1.68 W. The other effect is the upwards inclination of the graph. More linear draw causes the absolute errors to increase exponentially but slow. This is not necessarily surprising and these meters still comply to the standard [8] that describes a maximum error of 2.5 %. When removing the consumption of the subsequent meters, no errors above 2.5 % are observed.

B. Normalising Further Results

As previously mentioned, in this study it is not useful to look at relative errors. As found by the previous results it is also not useful to look at just the absolute errors on their own. This is because the allowed error margin on static meters is 2.5 % and we also see a higher amount of absolute error when the total power increases. Since we are primarily concerned what happens to the effect of the interfering non-linear loads when a linear load is added, it makes sense to filter this effect out. So the results shown in Fig. 6 are used to create an extensive profile. This profile should be able to compensate both for the meters being in series and the errors caused by the increasing linear power draw. When subtracting this profile from further results what remains is the relation between the power of the linear load and the change in absolute error caused by the a non-linear load. This is precisely what we we are interested in.

C. Waterpump

When introducing the waterpump from [6] put on mode 1, it draws around 25 W. The average power indication of the 24 meters in our setup was taken and normalised with the errors from purely linear loads (see Section III-B). This gives the resulting absolute measurement errors for the 24 static meters or SMs for short, plotted in Fig. 7.

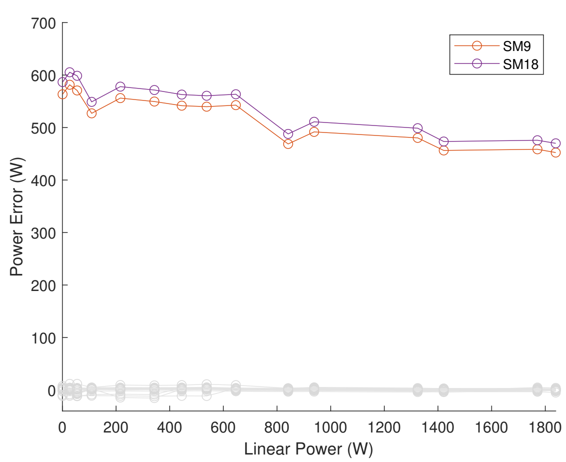

Fig. 7. Normalised meter errors with the introduction of the commercial waterpump from [6] on mode 1.

We can clearly see two meters with errors rising high above the rest. These are meters 9 and 18 which are both Rogowski coil meters. The interference with 0 W linear load present concurs with the results found in [6]. We can see that both of these meters follow the same error pattern with a difference of 19 W. The interference follows a downward trend when the linear power increases. In total the error in the measured range goes down 22 % for both meters. It is important to note that on the highest linear power draw the combination of loads still gives over 450 W of error which equates to 24 % offset from the power reported by the reference meter.

The effect of the other meters can be seen in Fig. 8. Here all meters with an absolute error of over 10 W are highlighted. You can see that meters except 4, 5, 12 and 21 stay under 8 W of error which quickly drops into below the 2.5 % margin. Interestingly SM 21 follows a waveform pattern similar to SM 9 and SM 18 although there is a much smaller offset. SM 21 indeed also is a Rogowski coil meter which might be the explanation for this. SM 4, 5 and 12 follow a pattern where the error suddenly disappears and stays away after a certain amount of linear load is added. In addition for SM4 the error also suddenly appears. SM 4 and SM 5 both work on a shunt principle and SM 12 uses a current transformer to measure the current.

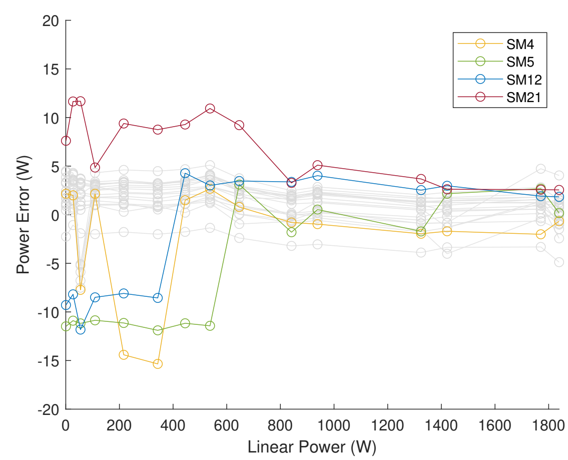

Fig. 8. Errors with commercial waterpump from [6] on mode 1, zoomed-in.

D. Dimmed power supply

The experiment was repeated with a power supply connected to a dimmer. In total this power supply draws 4 W with a highly non-linear waveform. After normalising, the errors are plotted in Fig. 9. This time SM 18 and SM 21, both Rogowski coil meters, are most notable. Especially SM 21 has high errors. SM 18 starts with 402 W of power error but instantly drops to 0 W and stays there as soon as a linear load is added. SM21 starts at -293 W of error and slowly drops to -227 W. Meaning a decrease of around 23 % over the measured range.

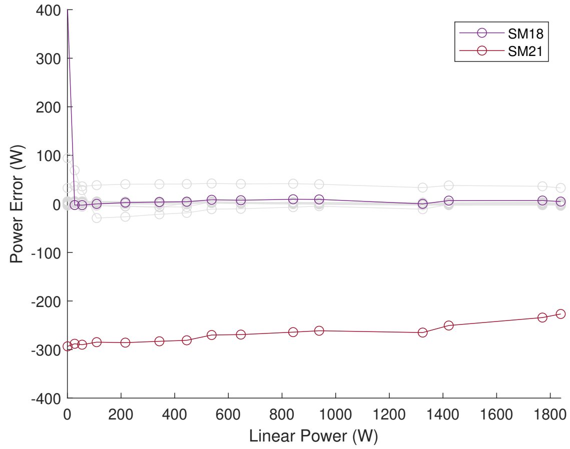

Fig. 9. Errors with a switch-mode power supply connected to a dimmer simulating [7].

Now again we zoom in (shown in Fig. 10). Both meters giving high errors and the meters from Section III-C have been highlighted. Although SM 18 has a dip with low errors and SM 23 starts with a lot of error, the rest of the meters show a relatively stable amount of errors with higher linear loads present, with SM 9 giving the most significant errors; always around 40 W. When we look back at the erroneous meters from before (highlighted in Fig. 10 also) we can see similar patterns for SM 4, 5 and 12. They suddenly drop to a lower amount of error and stay there. SM 9 and 18 show different patterns this time: SM 9 staying very stable around 40 W and SM 18 showing very high errors first before going down to around 5 W of error. SM 23 was not identified before and here now follows a trend toward less error for higher amounts of linear load. SM 21 was the meter found in [7]. Indeed this Rogowski coil gives a very big amount of error. Even with a linear power draw of 1900 W it has over −220 W of error equating to 16 % of the total consumption.

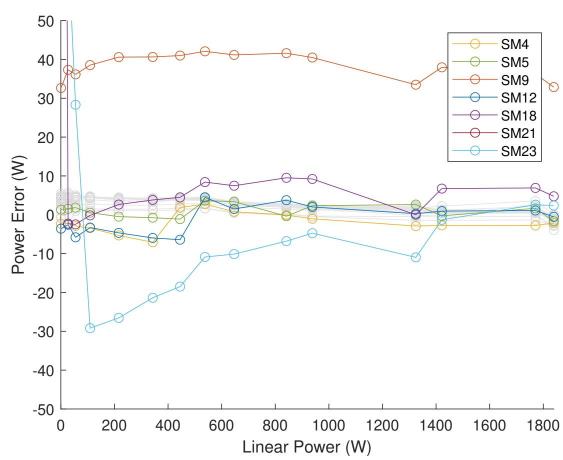

Fig. 10. Errors with a dimmed switched zoomed-in and highlighted for previou culprit meters.

IV. Discussion

In this study the societal impact of static meter interference was researched. This was done by testing a combination of linear and interfering non-linear loads as you would see in an on-site situation, created by appliances also found in a real household. In this light we can interpret the results.

It is interesting that meter interference is very dependant on both the current sensor type used in the meter and also the load itself. This can be seen by the various patterns shown in the results. Still it can be seen that the sensor type does not say everything. Of the tested meters only 7 meters show any significant interference at all. The other 17 meters contain meters of every sensor type also, so clearly the other internals of the meter also play a role.

For all meters it can be said that the power error goes down when more linear power is being drawn. This holds true for the relative errors (which are also used in the standard) and for the absolute power errors. In other words: the more power you use, the more accurate your meter becomes. For consumers the most important fact is that there are still large errors in the first place. And with the Rogowski coil meters these errors can be over 450 W and −220 W with a load of 1840 W present. Since the average power consumption of a house in the Netherlands is around 300 W [9] this would still result in significant over or under billing of a customer using this meter and combination of loads.

V. Conclusion

The study finds that three different Rogowski coil meters currently in use by consumers give significant interference, even with a large linear load present. With up to 1875 W of linear loads we found errors of over 450 W and −220 W, thus presenting between −15 % and 20 % of wrong readings. On most studied static meters there are no significant errors present for the tested non-linear loads. These are meters of all types, suggesting that the way different current-sensing methods are implemented is important as well. For a couple static meters, consisting of shunt and current transformer types, the errors in power are most striking when the total and linear power usage is low. This effect is not only due to interference errors being a larger percentage of the total power, the absolute power error also changes when more linear load is introduced. In this case the data suggests that these meters have a certain threshold of linear power after which the total absolute power error jumps to zero, although more research should be done to verify this claim. Some other static meters, all based on the Rogowski coil, show a small but significant drop of around 10 % per kW in absolute power error when the linear load is increased. Last but not least, this study grants more credibility to the previous papers. The high errors reported for the waterpump in [6] and the dimmed tv/switching power supply from [7] have been replicated in a setup with a grid power supply and 24 static meters. When it comes to the effects linear loads have on the errors from interfering non-linear loads we can see that it is very dependant on the waveforms itself and differs a lot based on the smart meters.

References

[1] 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, 10 2016.

[2] B. T. Have, T. Hartman, N. Moonen, and F. Leferink, "Inclination of Fast Changing Currents Effect the Readings of Static Energy Meters," *EMC Europe 2019 - 2019 International Symposium on Electromagnetic Compatibility*, pp. 208–213, 9 2019.

[3] B. T. Have, M. A. Azpurua, 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*, vol. 63, no. 5, pp. 1542–1549, 10 2021.

[4] B. T. Have, M. A. Azpúrua, T. Hartman, M. Pous, N. Moonen, F. Silva, and F. Leferink, "Estimation of Static Energy Meter Interference in Waveforms Obtained in On-Site Scenarios," *IEEE Transactions on Electromagnetic Compatibility*, vol. 64, no. 1, pp. 19–26, 2 2021.

[5] H. E. Van Den Brom, G. Rietveld, D. Hoogenboom, R. Van Leeuwen, Z. Marais, G. J. Kok, S. Sharma, and M. G. Van Veghel, "Towards improved standardization of electricity meter testing," *CPEM Digest (Conference on Precision Electromagnetic Measurements)*, vol. 2020-August, 8 2020.

[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 & Power Quality Journal*, vol. 17, pp. 15–19, 7 2019.

[7] T. Hartman, B. ten Have, N. Moonen, and F. Leferink, "How to Earn Money with an EMI Problem: Static Energy Meters Running Backwards," *IEEE International Joint EMC/SI/PI and EMC Europe Symposium*, pp. 788–793, 2021.

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

[9] "Energy - Figures - Economy — Trends in the Netherlands 2018 - CBS." [Online]. Available: https://longreads.cbs.nl/trends18-eng/economy/figures/energy/