Simulating The Effects Of Unipolar Current Pulses On Faulty Static Energy Meters

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***Abstract*—Electric appliances are becoming more common in everyday households. These appliances can cause errors in static energy meters. The most commonly found cause of these errors are pulsed currents. The pulsed current can exist in a bipolar and a unipolar pulsed variant. In this paper, the unipolar variant of the current pulse that causes errors is investigated. Both variants can cause a perceived power generation instead of a power consumption that has been measured by a reference power. A parameters that can cause these types of errors is the firing angle, thus in this paper different firing angles have been researched. Also the difference between bipolar current pulse and the unipolar current pulse will be looked at.**

***Keywords*—** Unipolar, Bipolar, Current pulse, Static energy meter, Simulink, Matlab, High pass filter, Simulation.

I. Introduction

Everyday, more and more new electronic appliances are being used in households. The electric technologies are made and cheaper every year. This helps with the distribution of these technologies all over the world. Electricity is a must have for these technologies, thus the number of people with electricity should increase and the number of people without electricity should therefore decrease. In 2010, there were 1.2 billion people without electricity, which contributes to 17% of the population at that time. 10 years later, in 2020, this number decreased to 733 million people without electricity, or 11% of the population [1]. With this comes the increase of the amount of power used and/or generated by the consumer. This has gone from a consumption of 1198 kWh per capita in 1971 to almost three times as much, to 3105 kWh per capita consumed in 2014 [2]. With more electrical appliances, the chance of errors occurring increases. One such error is the electromagnetic interference (EMI), mainly in the frequency range from 2 kHz to 150 kHz. This is due to the switching power circuits installed to increase the efficiency of ac/dc or dc/dc converters [3]. To know how much the consumer has to be billed for its consumption, the static energy meter is used. EMI has an effect on these static energy meters where the meters show a different resulting power than the reference power, thus not working correctly [4].

Previous research into the interference on the static energy meters was done using the time domain. The pulse that was found causes the most errors, are mostly nonlinear and have a pulsed shape with the rising edge faster than the falling edge [5]. Other parameters found to cause interference is the Charge, Crest factor and Pulse width [6]. Static energy meters are fitted with different current transducers. These transducers are the shunt resistor, Hall effect sensor, current transformer or the Rogowski coil. Meters utilizing the Rogowski coil are the cheapest of the four, and thus installed in many households. Three of the four current transducers cause significant errors inside the static energy meter. Current transformers and Hall effect sensors causes errors up to a maximum of 200%, while the shunt resistor causes no significant errors. The higher margin of error is caused by the Rogowski coil, with error up to 2675%. Current waveforms with a high rising slew rate with respect to the falling slew rate, will result in high voltages at the output of the Rogowski coil. The amplifier after the Rogowski coil will clip the output of the Rogowski coil, as the maximum input voltage of the amplifier is exceeded. After integrating this signal, a distorted current waveform including an offset is created. This process of differentation, clipping and integration is seen in figure 1 [7].

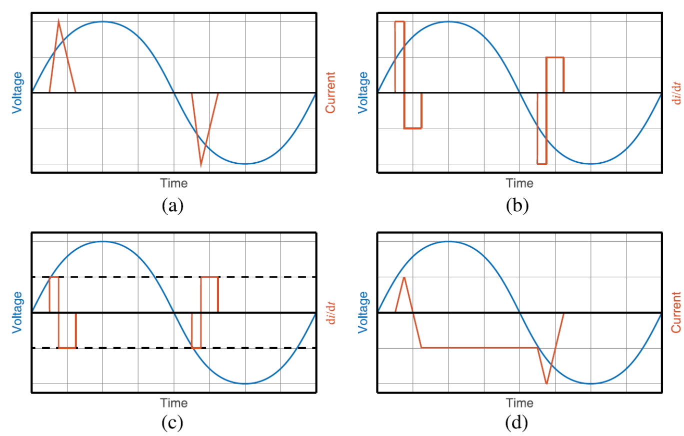


Figure 1: Bipolar current pulse through the static energy meter [7]

There are two types of pulses that causes errors, bipolar and unipolar. In this paper, the unipolar current pulse is investigated in comparison to the bipolar current pulse. The current pulse is created in a way that it can be made bipolar and unipolar. In order to understand part of the circuit inside the static energy meter, the behaviour of the high pass filter is researched. The effect of the switching of the firing angle is also looked at, as the power created should be higher for firing angles higher and lower than 90°. Then the results of the error in % of the unipolar current pulse is compared to the error in % of bipolar current pulse to see if there are any differences in the effect of the pulses. Section II show previous findings about bipolar current pulses and its parameters. The likeness between bipolar pulses and unipolar pulses is also described here. With the behaviour shown in different figures. Section III will dive deeper in the simulations of the unipolar current pulses. Different circuits have been made in order to check for errors and step by step come closer to the final circuit. These simulations are run and the results are shown in section IV. The error of the unipolar current pulse is shown before being compared to the bipolar current pulse. Finally, the paper is concluded in section V.

II. Analysis

To find the effects of unipolar current pulses on faulty static energy meters, finding the effects of the bipolar current pulse variant can help. This is easier, as there research has already been done on this subject. Expectations are set in this section using the information about the bipolar current pulses applied to the unipolar current pulse.

A. Bipolar currents

The errors found in the energy measurements, can be explained by looking at the current. The error is due to a pulsed current, caused by dimmers. Bipolar current means there are two pulses in one period of the voltage waveform, one positive pulse and one negative pulse. Parameters of the pulses are seen in figure I.

Parameter	Critical Range
Charge	$4 - 8mC$
Crest factor	> 5
Pulse width	$0.2 - 1.2ms$
Rising slope	$> 0.1A/\mu s$

Table I: Table with parameters for the pulse [6]

The pulses with these parameters in combination with the household equipment causes errors. The highest errors were encountered when a static energy meter utilizes a Rogowski coil as its current transducer [7]. The static energy meters with this coil as its current transducer can display a perceived power generation of more than 600 W, while 25 W is actually consumed. The energy metering IC used inside these static energy meters is the STPM01 chip [7].

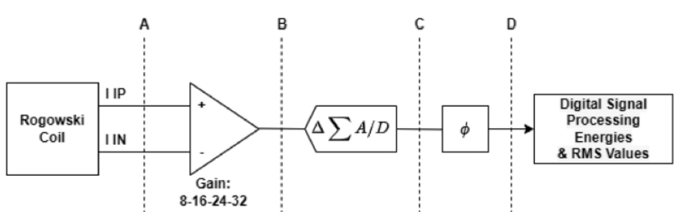


Figure 2: Inside of a static energy meter [7]

Figure 2 shows part of the datasheet of the STPM01 chip, this is the relevant part where the erroneous current will flow. First, the current pulse flows through the Rogowski coil, thus gets differentiated. The resulting pulse is a square wave (figure 1b). This pulse then flows through an amplifier inside the static energy meter, which causes clipping of the pulse (figure 1c). Because of this clipping, the surface area under the positive slope is not equal to the surface area under the negative slope. The inequality causes a distortion after integration (figure 1d), lowering part of the current before returning to zero. It is a characteristic of the bipolar pulse, as there are two identical pulses, with the second pulse multiplied by -1. The same theory plus simulations can be used for unipolar current pulses.

B. Expectation

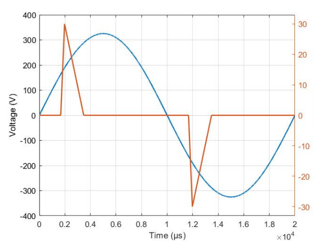
The unipolar current pulse has the should show the same behaviour as the bipolar current pulse. The only difference being that there is only one pulse in a period of the voltage, hence the name unipolar. The unipolar current pulse is differentiated by the Rogowski coil, then clipped by the amplifier before being integrated.

As the unipolar current pulse undergoes the same steps as the bipolar current pulse, some expectations about the process and the outcome can be set. The pulse that is used, has a faster rising edge than falling edge. The bipolar version is shown in figure 3a and the unipolar variant in figure 4a.

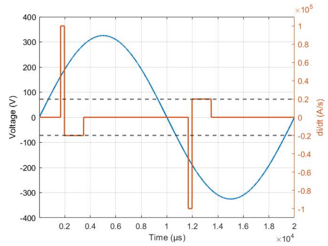
The differentiation of the unipolar current pulse by the Rogowski coil will result in the same waveform as bipolar current pulse, but only done for one pulse. This can be seen by comparing the bipolar differentiation from figure 3b with the unipolar differentiation in figure 4b.

The waveform has a higher value for the rising edge of the input and a negative lower value for the falling edge. The area under the positive and the negative slope should be equal, since there exists no offset at the input pulse. The amplifier in the static meter causes clipping of the differentiated waveform, causing the surface area from the positive slope and the negative slope to be in-equal. Because of the clipping the area under the positive slope has become smaller than the area under the negative slope. Figure 3c for the bipolar pulse clipping and figure 4c for the unipolar pulse clipping.

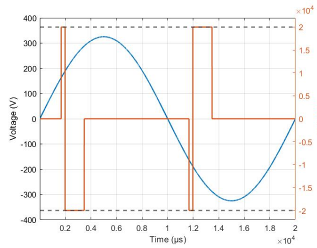
The next step for the differentiated clipped current is integration. Due to the inequality of the surface area, the positive slope runs shorter than the negative slope. This causes the integrated current to not return to zero for the unipolar pulse (figure 4d). Not returning to zero is due to the absence of the second negative pulse. Because the integrated current does not return to zero, it should approach minus infinity. The integrated bipolar current does return to zero, because the second negative pulse counteracts the first positive pulse as seen in figure 3d. Both these figure (3d and 4d) are simulated over one period. To see the effect of the integration for both the bipolar and unipolar current pulse, a figure with a longer period is needed. Figure 5a and 5b show the integrated current for the bipolar and the unipolar current pulse over 10 periods respectively.



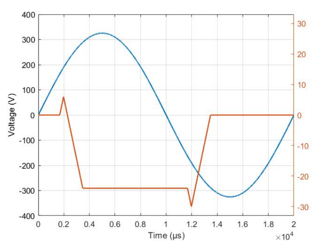
(a) Input bipolar pulse



(b) Differentiated bipolar pulse

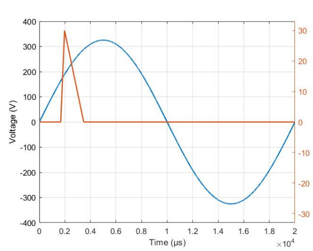


(c) Clipped bipolar pulse

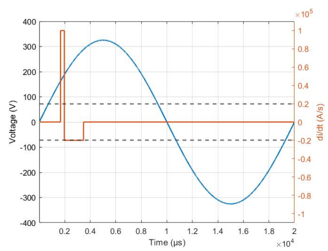


(d) Integrated bipolar pulse

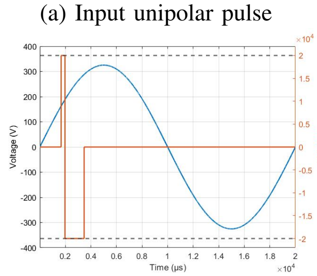
Figure 3: Bipolar current pulse variant that gets differentiated, clipped and integrated



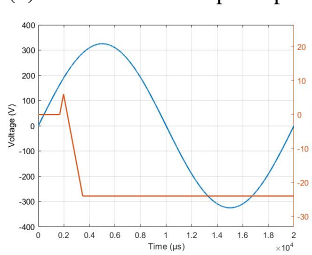
(a) Input unipolar pulse



(b) Differentiated unipolar pulse

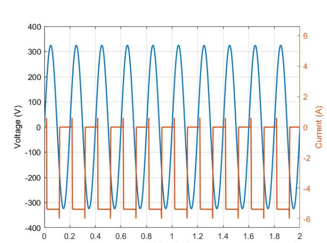


(c) Clipped unipolar pulse

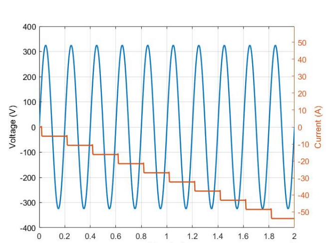


(d) Integrated unipolar pulse

Figure 4: Unipolar current pulse variant that gets differentiated, clipped and integrated



(a) Integrated bipolar pulse



(b) Integrated unipolar pulse

Figure 5: Integrated bipolar and unipolar pulse over 10 periods

With the current approaching minus infinity, the error stays the same as without the offset due to the concept of orthogonality. The theory of orthogonal power flow states that power produced by different frequency components is orthogonal to each other [8]. Basically saying that the offset does not influence the error calculation. The first assumptions has been made without the data sheet of the IC of the static energy meter (figure 6). Here it can be seen that a high pass filter is located after the amplifier and before the integrator. With the input of the circuit being the output of the Rogowski coil. A switch is located parallel to the high pass filter, to connect and disconnect the filter from the circuit. The high pass filter will filter out the DC component of the pulse, making the surface area under the positive slope equal to the surface area under the negative slope. This can be compared to shifting the whole waveform up or down. With this setup, the integrated current should not approach minus infinity.

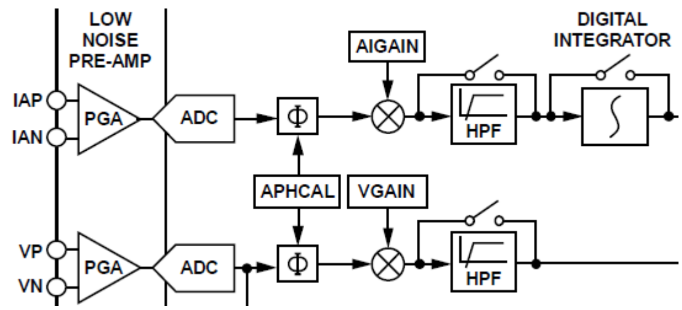


Figure 6: IC inside static meter [9]

III. Simulation

Simulating is done to find out if the previous expectations set are accurate. Different versions of the circuit inside a static energy meter utilizing a Rogowski coil were made in order to show certain parts working correctly.

A. *Verification circuit*

Section II stated that a high pass filter can be compared as subtracting the mean from a signal. The circuit used to verify this can be seen in figure 7. The pulses are generated using the repeating signal block. If necessary, the pulse can be made bipolar using a switch. The switch activates if the threshold value is higher than a chosen value (in this case > 0.5) and makes the current pulse bipolar. If this is not the case, the pulse stays unipolar. The other parameter and its initial conditions are given in section III-D.

The input bipolar/unipolar current pulse gets differentiated by the Rogowski coil. After the differentiation, the current gets amplified which will lead to clipping, represented by the saturation block. As the clipping causes the maximum peak value to clip at the absolute value of the minimum peak value. With this setup, the final current output should approach minus infinity as was explained in section II. To prevent this, the mean of the clipped current will be subtracted from itself (simulating a high pass filter). This will then be integrated by the integrator block before completing the circuit inside the static energy meter (figure 6). When all steps are completed, the final current will be multiplied by a voltage sine wave to find the output power.

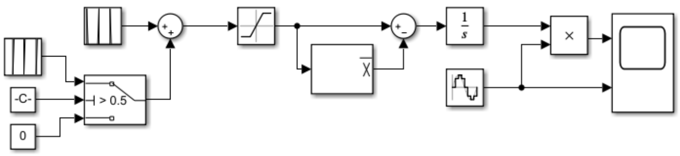


Figure 7: Circuit with mean calculation

B. High pass filter circuit

To see if the high pass filter does indeed behave the same way as using the mean of a pulse, the circuit from the previous subsection III-A has been fitted with a high pass filter. The mean calculation and subtraction of the mean has been replaced by this high pass filter. The expectation was that the high pass filter should have the same effect as subtracting the mean from the signal does. Meaning that after the integration the output current will not approach minus infinity, instead always making the current return to zero. This circuit will act as a base of the final circuit.

C. Complete circuit

Figure 8 shows the complete circuit, which will be used for further research. This circuit can also be transformed to represent two different current pulses, the unipolar variant and the bipolar variant. The current pulse can be made bipolar or unipolar using a simple switch, just like the previous circuits. The bipolar current pulse circuit can be used to verify the analysis given in section II.

The unipolar variant of the circuit will be used to measure the output power of the static energy meter. The initial triangular current pulse is generated using the repeating sequence block, simulating the pulse that gives the error in the power measurement. This current then flows through the Rogowski coil and gets differentiated. At this point, the signal gets written in the base workspace of the file with the name ”out.peak”. The value can then be used in a Matlab script to find the minimum peak of the signal. The absolute value of this minimum peak is the value where the signal gets clipped at both ends. The rest of the path inside the circuit, is already explained in the previous subsections (section III-A and III-B) using the datasheet of the ADE7953 (figure 6). The output current of the circuit together with the created voltage is written in the base workspace named ”out.current” and ”out.voltage” respectively. Now the mean of the power can be calculated by using arrays in a Matlab script to find a potential power consumption or generation.

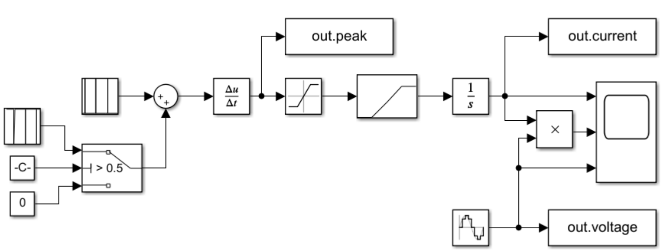


Figure 8: Final circuit simulating part of the inside of the static energy meter

D. Initial conditions

Initial conditions have to be added in order to make the circuit function correctly and to change parameters during testing to see different results. The mains voltage of most houses have a V_{rms} of $230[V]$ and a frequency of $50[Hz]$ [10]. The unipolar current pulses and the voltage sine wave therefore have to have a frequency of $50[Hz]$. The frequency of the sine wave block is measured in rad/sec instead of Hz. Thus the formula to go from Hz to rad/sec is used:

$$\omega = f \cdot 2\pi = 50 \cdot 2\pi = 100\pi[rad/sec] \quad (1)$$

giving $\omega = 100\pi[rad/sec]$ for the angular frequency. The amplitude of the pulse is shown to be between $5[A]$ and $50[A]$ [7]. So for this experiment an amplitude of $(50+5)/2 = 27,5[A]$ rounded up, $30[A]$ is chosen.

Another cause of error is the firing angle, thus this is included in the code. The firing angle can vary from 1 to 180 degrees. For complete measurements, this is divided into 5 different firing angles. Namely 30°, 60°, 90°, 120° and 150°. Given in table I is the minimum value for the slew rate (SRr) of the rising edge, which is $SRr => 0.1[A/\mu s]$. The slew rate of the falling edge (SRf) should be smaller than that of the slew rate of the rising edge, causing the falling edge to have a slower slope. In this case the SRf is chosen to be 10 times smaller. Also the SRf should have the opposite sign as the SRr, as this is the slope that should return to zero.

Coordinates of the triangular pulse are found using the firing angle, frequency, pulse amplitude and both the slew rates. The triangular pulse has three main point which will be called: P1, P2 and P3. P1 is the point on the x-axis where the rising slope starts. P2 is the peak point that has the amplitude of $Apulse = 30[A]$. After the peak value has been reached, the slope changes to the SRf value which has the opposite sign and thus will move in the opposite vertical direction. P3 is the point where this slope crosses with the x-axis.

P1 is calculated using the firing angle, the frequency and the fact a sine wave consists of 360°.

$$P1 = \frac{phi/360}{freq} \quad (2)$$

The second point P2 is calculated using P1, the amplitude of the pulse and the rising edge slew rate (SRr). The slew rate has to be scaled to the amplitude of the pulse before being added to the horizontal coordinates of P1.

$$P2 = P1 + (Apulse \cdot SRr) \quad (3)$$

P3 is calculated the same way as P2, but now with the slew rate for the falling edge.

$$P3 = P2 + (Apulse \cdot SRf) \quad (4)$$

A similar method is used to find the second pulse to make the system bipolar. The difference from unipolar calculation is that 180° has been added to the firing angle (phi) to calculate P1. Since a sine wave has 360°, shifting by 180° makes the pulse shift half a sine wave, which is exactly what is wanted.

IV. Results

Simulations has been done for the different circuits constructed in the previous section. Then the unipolar and the bipolar current pulse will be compared.

A. Simulating circuits

1) Verification circuit: As said in the previous section (section III), subtracting the mean from the signal will prevent the integrated signal from approaching minus infinity. The signal will be differentiated, clipped and the mean will be subtracted from the signal before integration. After integrating the signal, it can be seen from figure 9 that it does not approach minus infinity but does have an offset. This offset is due to the mean calculation in the first period. As the mean is not yet known in the first period it can not be subtracted from the signal, so this is only possible after the calculation is complete after the first period and starts subtracting in the second period.

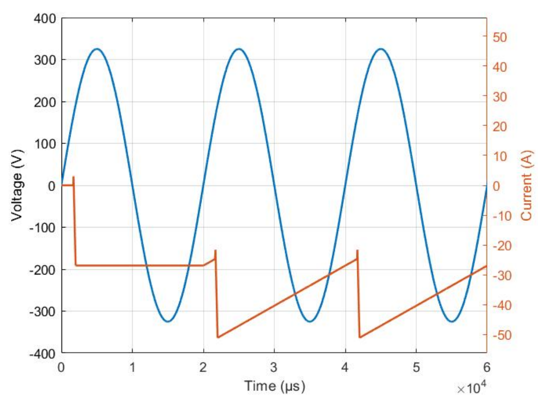


Figure 9: Circuit with the mean subtracted

A solution to this problem is to add a delay. This can be realised by adding the delay block and adding a constant to know what amount the signal needs to be delayed as seen in figure 10. To get rid of the offset, the signal has to be delayed by one period. The delay has to be one period, as the mean is calculated in the first period. Figure 11a and 11b show the delayed signal with the mean subtracted and the integrated signal with a delay added respectively. It can be noticed that the offset has been removed with this setup.

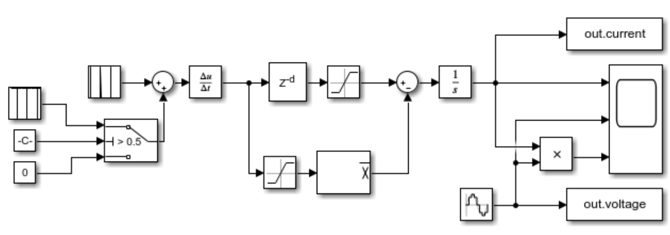
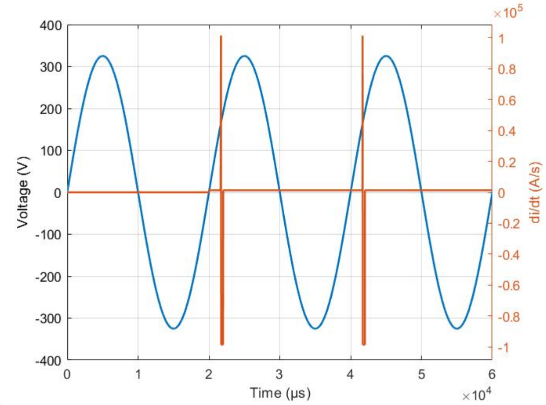
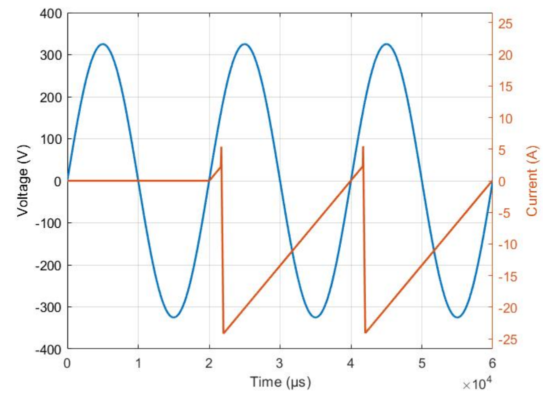


Figure 10: Circuit with the added delay



(a) Subtracted the mean and added a delay

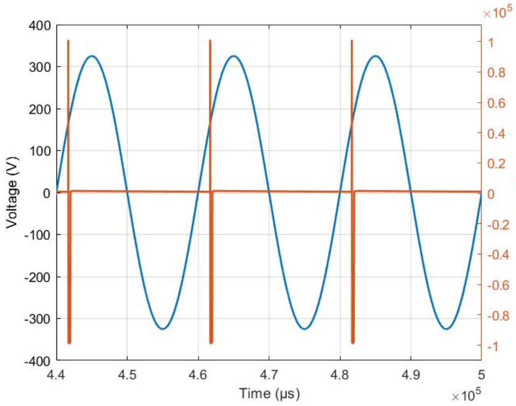


(b) Integrated current of the added delay signal

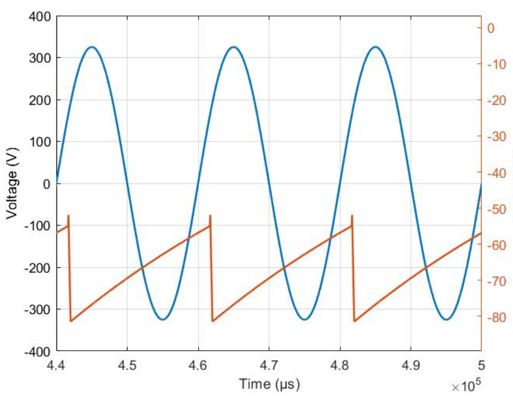
Figure 11: Current through the mean subtracting circuit

2) High pass filter: The point of this circuit is to show the similarity between subtracting the mean and using a high pass filter on the input signal. Figure 12a shows the output of the differentiated current through the high pass filter. The high pass filter filters out all DC components (0 Hz) and thus creates the desired offset as found in the previous section. Figure 12b shows the current after going through the high pass filter and being integrated. It can be seen that the high pass filter in combination with the integrator creates an offset. This is due to the value of the time constant. By changing the time constant of the high pass filter, the current waveform also changes form. By varying the time constant between 10^{-3} and 10^{3}, the best value can be found. The value chosen for the time constant is $\tau = 0.45$, as this is where the error of the output power compared to the reference power is the lowest for the firing angle of $90°$.

Comparison between the circuit with the subtracted mean calculation and show a similar behaviour. By placing figure 11b and 12b side by side, the only difference that can be spotted is the minimal offset that is created by the high pass filter. So yes, the high pass filter has the same effect as just subtracting the mean from the signal.

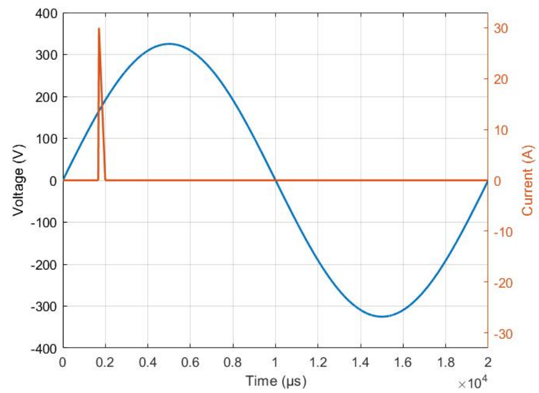


(a) Differentiated current through the high pass filter

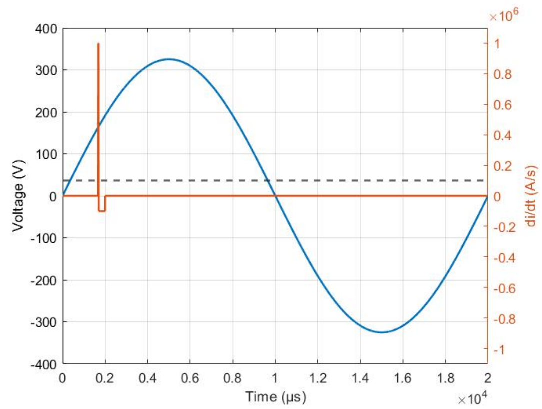


(b) Integrated current after the going through high pass filter

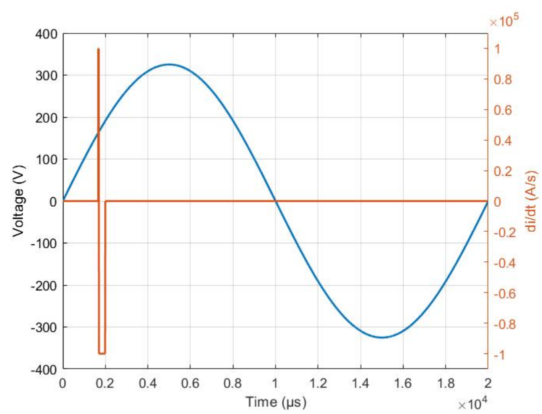
Figure 12: High pass filter circuit output



(a) Input unipolar pulse that causes errors



(b) Differentiated current pulse

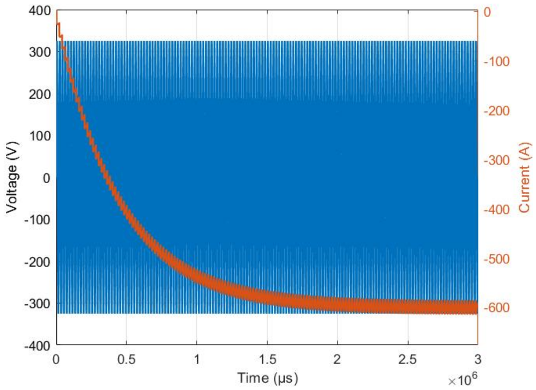


(c) Clipped current pulse

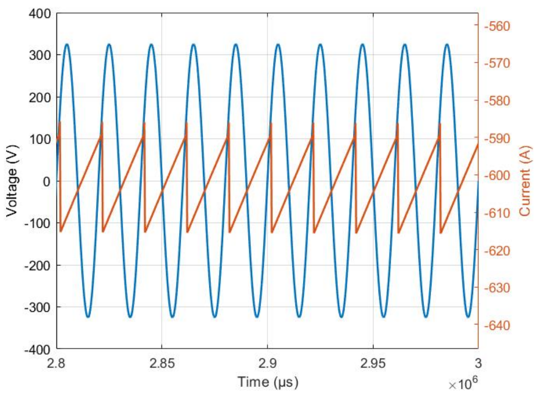
Figure 13: Output of stages of the final circuit

3) Complete circuit: The complete circuit is the full circuit inside a static energy meter. Figure 13a shows the initial pulse that causes the errors. The pulse is self made with the parameters found in the previous section. So a faster rising slope than the falling slope, and in this case a firing angle of 30°. This pulse then gets differentiated by the Rogowski coil before being clipped, figure 13b and 13c respectively. From these figures it can be seen that the maximum peak gets clipped at the absolute value of the minimum peak. This is reason the circuit causes errors, as said in previous sections. When looking at the integrated current, it can be seen that the signal does not return to zero in the first period. The signal should not be approaching minus infinity, thus for clarity the x-axis has been increased to include 150 periods (figure 14a). The integrated current signal (figure 14a) does not approach minus infinity but does have an offset. Zooming in show the behaviour of the integrated current signal (figure 14b). The integrated current does have a sawtooth wave like structure, which is the desired outcome as the integrated current should be as close to the input current pulse as possible.

With the full circuit working, the power calculation can be performed. The output integrated current (figure 14a) gets multiplied by the net voltage, resulting in the power. To know the power consumed or generated, the mean is calculated over a long enough period of time. The time period should be long enough such that integrated current has settled on a constant offset that will not change anymore. The power can be calculated even when there is such an offset, because of the orthogonality explained in section II. From the results written in table II it can be said that for firing angles between 30° and 150°, the error increases. In the instance of a firing angle of 30° and 60°, a perceived power generation is measured. The reference power and the measured output power for a firing angle of 90° have a negligible error. For firing angles of 120° and 150°, the power is slightly more than the absolute values for the power of the firing angles 60° and 30° respectively. The same can be said about the error for these firing angles.

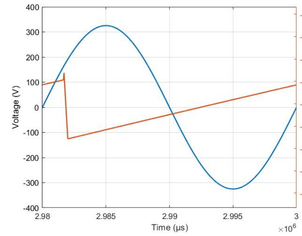


(a) Integrated current pulse over 150 periods

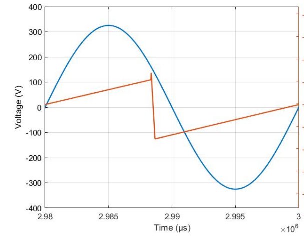


(b) Zoomed in integrated current pulse

Figure 14: 150 periods of the output integrated current and a zoomed in version



(a) Integrated current with firing angle of 30°



(b) Integrated current with firing angle of 150°

Figure 15: Integrated current for two firing angles of the unipolar current pulse together with the voltage over one period

FA	Reference Power	Output Power SM Unipolar	Error %
30°	44.35 W	-1160.13 W	-2715.85%
60°	71.65 W	-622.68 W	-969.06%
90°	80.94 W	81.03 W	0.12%
120°	68.49 W	764.80 W	1016.66%
150°	37.72 W	1242.18 W	3193.16%

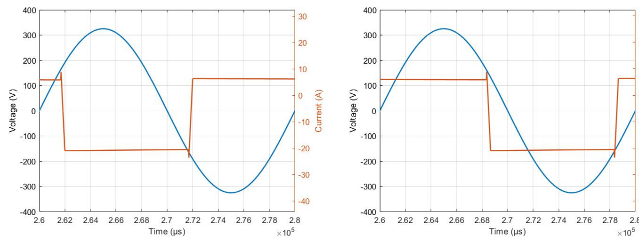
Table II: Reference power and the measured output power for the unipolar current pulse

The negative power for a firing angle of 30° and 60° can be explained when looking at figure 15a which shows the integrated current for a firing angle of 30°. This can be compared with figure 15b that shows the integrated current for a firing angle of 150°. Both figure show the integrated current together with the voltage over one period. The part of the current that has effect on the sign of the power, is the sudden drop down. In figure 15a the drop is in the first quarter of the sine wave, which means that for the second quarter, the power is calculated with a negative current value. This can be said even though there is an offset, because of the orthogonality principle [8]. With this principle the average becomes the horizontal '0' axis. So for the second quarter, the negative current value gets multiplied with the positive side of the sine wave which results in a negative power. The same can be said about the last quarter of the sine wave, where a positive current value gets multiplied by a negative sine wave value resulting in a negative power.

The current with a firing angle of 150° is seen in figure 15b together with the voltage. Here it can be seen that for the first half of the sine wave, the positive current gets multiplied by the positive sine wave. And the negative current multiplied by the negative part of the sine wave resulting in a positive power.

B. Comparison

Knowing the unipolar circuit gives the correct output, it can now be compared to the bipolar circuit with the same parameter values. The experiment is also done with the firing angles of 30°, 60°, 90°, 120° and 150°. As there are two pulses instead of one, it is expected the power will double compared to the unipolar pulse. Table III show the output powers for the bipolar circuit. This is compared to II to find differences. It can be seen that the reference power and the measured output power are approximately double the powers from the unipolar current pulse, as expected. The error percentages for the bipolar current pulse are approximately the same as the unipolar current pulse error percentages. Which would be expected as the power should double everywhere, keeping the error at the same level. Output of the bipolar pulse circuit for a firing angle of 30° and 150°can be seen in figure 16a and 16b respectively. The same can be said about the negative power measurement with the bipolar current as that from the unipolar current. As seen in figure 16a, the switch from positive to negative is at 30° thus multiplying a negative current with a positive voltage in the first half of the sine. And multiplying a positive current with a negative voltage, creating a negative power output when adding both. For the firing angle at 150° (figure 16b) the switch is at the end of the first half of the sine wave, making a positive current multiply with a positive voltage. In the second half of the sine wave, a negative current gets multiplied with a negative voltage, then creating a positive power output.



(a) Integrated current with firing angle of 30°

(b) Integrated current with firing angle of 150°

Figure 16: Integrated current for two firing angles of the bipolar current pulse together with the voltage over one period

FA	Reference Power	Output Power SM Bipolar	Error %
30°	90.99 W	-2327.17 W	-2657.61%
60°	143.33 W	-1252.32 W	-973.73%
90°	162.33 W	155.08 W	4.47%
120°	137.68 W	1522.62 W	1005.91%
150°	75.34 W	2477.55 W	3188.49%

Table III: Reference power and the measured output power for the bipolar current pulse

V. Conclusion

A possible cause of errors of the static energy meter has been investigated. The current pulses found to cause this have two variants, the bipolar current pulse and the unipolar current pulse. The errors are caused by the use of the amplifier which clips the differentiated current pulse. This clipping causes a distorted integrated current. The integrated unipolar current pulse approaches minus infinity without the use of a high pass filter. Thus there was a look in the behaviour of a high pass filter, what it does and what the effects are. It was concluded that the high pass filter has the same effect as subtracting the mean of the signal from the signal itself. The difference between the two is that the high pass filter causes an offset, that is created by the time it needs to compensate the surface area under the rising slope and the falling slope. The output of the unipolar current pulse through the static energy meter has a saw-tooth like waveform, thus returning to its maximum value and not approaching minus infinity. For firing angles 30° and 60° a negative power output is measured, which is caused by the form of the integrated current. For both the firing angles, the positive side of the sine wave gets multiplied with a higher amount of negative valued current than positive valued current, creating negative power for this half. The negative second half of sine wave is multiplied by mostly positive current, also creating a negative power. For the firing angles of 120° and 150° the exact opposite can be said. As more positive current gets multiplied by the positive values of the sine wave and more negative current gets multiplied by the negative values of the sine wave, thus creating a positive power output. Comparing the bipolar and the unipolar current pulse, it is found that the power output is almost exactly doubled. This is the case for both the reference power and the measured output power. Because this is the case, the error roughly stays the same for both the bipolar and unipolar current pulse.

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