Low Pass Filtering to Improve Robustness in Energy Measurements that Utilize Rogowski Coils

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Abstract—**A low pass filter has been designed to improve robustness in energy measurements. The first order low pass differential filter design has been based around the requirement that the phase shift at 50 Hz is easily compensated with a phase calibration register in the energy metering IC. A water pump with dimmer is used as non-linear load. Results show that the measurement error can be as high as 714 W above the actual power consumption of 23-25 W without the use of a filter. This error has been reduced to 2 W with the filter installed. Changing the current channel gain has been shown to give a significant effect on the measured power. The current wave forms at these different gains show that the measuring error likely results from clipping. The pulsed current drawn by the non-linear load change to a saw tooth shape when the gain is raised.**

Index Terms—**EMI, LPF, Energy meters, ADE7953, Rogowski coil**

I. INTRODUCTION

The issue with static energy meters was first discovered when two farmers compared the output of their PV systems. Both farmers had installed identical systems, but a 40% difference in power generation was observed. This difference was traced back to a fan controller, which created interference that was picked up by the energy meter [1]. The main cause behind the faulty readings can be generally described by conducted electromagnetic interference (EMI). This can be caused by non-linear loads/devices. Especially devices that switch rapidly or generate current pulses cause the observed issue [2].

At the University of Twente, one interference case from the usage of a water pump has been further investigated. A consumer had reported high energy reading compared to the rating of the water pump. The setup consisted of a water pump with built in dimmer, which allows the user to vary the capacity of the pump. When the dimmer is in use, small current pulses occur. The pump is connected to 10 common European static energy meters. A precision energy analyzer is used to compare with the energy meter readings [2].

This setup was then tested for the ten different dimmer levels of the water pump. The main findings from these measurements are mainly that a lower dimming level results in a larger energy deviation in the energy meters. It could be seen from current measurements, that higher deviations seem to occur at higher phase shifts created by the dimmer. In the measurements using mains power, the maximum deviations of -61% to +2675% have been found. Using the ideal power supply, a correlation between grid impedance and deviation was also found. Namely, a lower grid impedance results in a higher deviation. This can be explained by the fact that the high frequency interference is allowed to flow more freely with low impedance [2].

It has been found that there is also a correlation between the inclination of the current waveform and the resulting deviation. A higher inclination results in a higher energy meter deviation. This is observed to happen with current measuring devices that measure the derivative of the current, such as a Rogowski coil [3].

Currently there is also research into which wave form parameters influence or create this error. This is realized using an AC-controlled Current load, which has been designed at the University of Twente to allow greater flexibility in waveform parameters, such as extreme crest and power factors [4].

Another research paper [5] went more into detail on the actual frequency components of the the current signal and the impact of these frequencies on the active power. The orthogonality of power flow with Parceval's theorem are used to determine that only the 50 Hz component of the current wave form contributes to the active power, assuming a pure 50 Hz supply voltage. This means that if there is a lot of harmonic distortion in the current, the active power is fully confined to the fundamental frequency.

It has been determined that in the worst case scenario, when the current and voltage THD reach the maximum specified in the regulations, the fundamental active power still does not have a large error. The relatively large THD number of 0.11 for the voltage and 0.34 for the current still only result in a 2.5% error in the fundamental active power. This has also been proven by an experiment using a full bridge rectifier. When the frequency components of the current are measured, it can be seen that the amplitude of the harmonics are almost as high as the energy of the 50 Hz component. It has also be shown that due to constructive or destructive interference with higher harmonics, the apparent power can vary a lot. [5].

Since the higher harmonics of the current result in steeper inclinations and do not add to the active power, it seems likely that adding a low pass filter in the current measuring devices of a static energy meter could contribute to robuster readings. To do this, an evaluation board is used to know the exact signal path of for example the current. Using such a board also allows for easy modification of the current measuring element, to let the signal first pass through the low pass filter and then continue towards the energy metering IC. Like mentioned before, the measurement errors occur when using a Rogowski coil, so this is used during testing.

This report will go through the design and testing of a Rogowksi coil in conjunction with a low pass filter in the following sections: Section II gives further analysis into the problem and determining the filter requirements, Section III shows the setup configuration and filter design, Section IV gives the measurement results and Section V is the conclusion.

II. ANALYSIS

To determine which of the harmonics contribute mostly to the high frequency noise, some common power management circuits are analysed. Using LTspice, a full bridge rectifier and triac based dimmer are analysed [6]. For simplicity sake, a purely resistive load is attached to the output of these power management circuits. Using the FFT function in LTspice, an analysis of the frequency components from the source current can be performed. This can be seen in Fig. 1 below. It can be seen that all the harmonics after 150 Hz contribute to the current measurement for both the rectifier and the dimmer, as was also derived in [5].

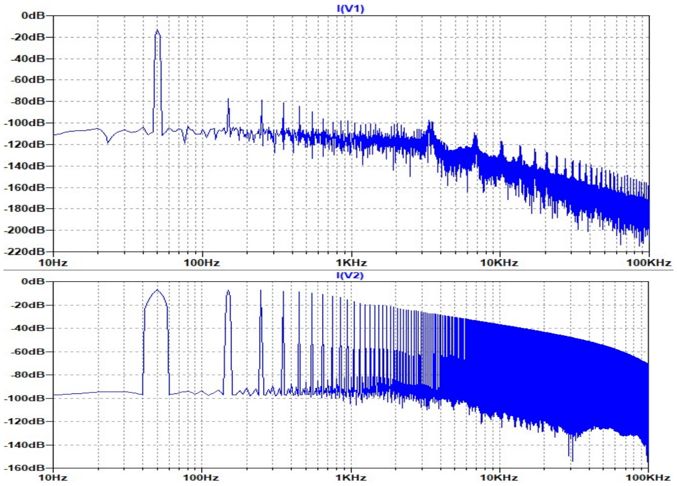

Figure 1. FFT graphs of the Triac dimmer (top) and full brige rectifier (bottom)

The main requirement for the low pass filter is that it should not create an error during measurements. If this goal is satisfied, one can look at how the filter can improve the robustness of the energy measurements. The main parameters of the low pass filter that are important are the phase shift and the pass-band ripple, since both of them could result in measurement errors when chosen incorrectly. It is especially important that these parameters are low at 50 Hz, since it has been determined that the active power is only present at this fundamental frequency [5]. The phase shift of the filter should be as close to zero as possible, since some of the calculations performed by the energy meter consist of multiplying the current and voltage [9]. Pass-band ripple is a parameter which cannot be adjusted that easily, but is very low in a regular RC low pass filter. This should therefore not be a problem.

Ideally, the low pass filter should attenuate all frequencies above 50 Hz. However, since brick wall filters do not exist, the attenuation at 150 Hz could be used as a goal. Using the cut-off frequency formula for a RC low pass filter, as can be seen in Eq. 1, a filter with a cut-off frequency of 60 Hz is created. This filter was then used for some preliminary testing in LTspice. Since the roll-off of a first order RC filter is -20 dB/decade, multiple filter order are necessary. To obtain a signal power of -60 dB at 150 Hz, the filter should be at least 6th order. For a signal power of -40 dB, the filter order should be at least 4. The problem with these higher filter order however, is that these tend to give very large phase deviations. This can result in faulty readings and thus violates the first goal, therefore these higher order filters will not be used.

$$f_c = \frac{1}{2\pi RC} \tag{1}$$

Instead of trying to filter out all the harmonics, the focus for designing the filter is on the phase deviation. To minimize this, the cut-off frequency of the filter should be about an order of magnitude higher than for the ”filter everything” approach. The cut-off frequency is then still low enough to filter out most of the harmonics, since the majority of harmonics only appear after 1-2 kHz, as can be seen in Fig. 1.

The requirements for the filter are therefore not very strict. Since a first order filter will be used, the phase and magnitude become relatively linear when a higher cut-off frequency is used. The cut-off frequency can be chosen relatively freely between about 300 and 700 Hz.

III. METHODOLOGY

In this section, the physical measuring setup is explained. After this the associated configuration of the energy metering IC is discussed. Lastly, the filter design is elaborated.

A. Setup

As a test setup, the same hardware as mentioned in [2] will be used. This includes a Yokogawa WT5000 reference meter, a water pump with dimmer and a heater. To test the filter, an Analog Devices EVAL-ADE7953 evaluation board is used. The EVAL-ADE7953 is provided with software that allows easy access to the registers on the energy metering IC. The software manages the read and write operations with the IC using the SPI interface [7][9]. In conjunction with the evaluation board, several current metering devices can be used such as a shunt resistor and Rogowski coil. Since the erroneous measurements mostly result from a Rogowski coil, the measurements will be focused around such a coil[3][5]. The Rogowski coil used in the setup is a Pulse Electronics Sidewinder PA3202NL[9].

The Rogowski coil has three wires, two (black and white) connected to the coil and a green ground wire [9]. These can all be connected to the current channel A terminal block P2. The green wire should be connected to the ground of the board (right-most terminal)[7]. The orientation of the black and white wire can be checked using the evaluation board software. When a load is connected, the active power register (AWATT) can be read out or plotted using the waveform sampling functionality [7]. When this power is negative, the black and white wires should be switched around. To power the board, a 3.3 V power supply is connected to terminal block P1. Lastly, phase and neutral lines are connected to terminal block P4.

A large part of the evaluation board is not isolated. At the same time, the ground of the power supply and the neutral wire are connected [7]. This means that the board is floating at that potential. A related issue is that the power plug always needs to have the correct orientation, otherwise the neutral and phase will be switched around. This could result in the evaluation board floating at mains voltage. For this safety concern, the evaluation board has been put into a box. The setup in this box can be seen in Fig. 2. If something needs to be changed, mains voltage needs to be switched off and then the work can proceed. To prevent a potential short to ground through the board, only differential probes should be used when probing the non-isolated part of the board directly.

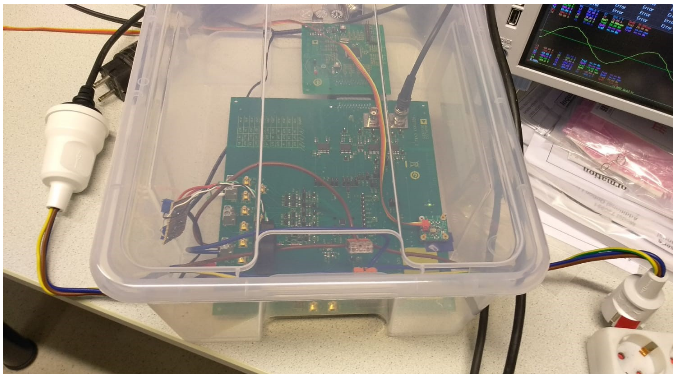

Figure 2. Evaluation board setup

B. Register configuration

The measurements using a Rogowski coil require the use of an integrator, since the Rogowski coil measures the derivative of the current. The ADE7953 has internal integrators which can be turned on and off, for both current channels, using the CONFIG register. By default both integrators are turned off, which gives a register reading of x8004. To use the integrator on current channel A, the least significant bit should be turned to 1. So the hexadecimal value x8005 should be written to the register [9].

The ADE7953 can provide the output of different registers on the CF1 and CF2 pins. Most importantly, the active energy can be measured by counting the pulses on a CF pin. The pin is high by default and will turn low for 80 ms when a pulse occurs. The frequency at which these pulses occur do have to be calibrated first. This is done by using the WT5000 and formulas given in the application note AN-1118. This application note gives two formulas, one gives the expected frequency of the pulses and the other gives the CFxDEN register value . These formulas can also be seen in Eq. 2 and Eq. 3 [10]. The output frequency is related to the digital-to-frequency converter(DFC) and the CFxDEN register, which indicates the number by which the output of the DFC should be divided. The DFC converts changes in the register values to a frequency [9].

$$CF_{expected} = \frac{C_m * P_l}{3600} \tag{2}$$

In Eq. 2 the formula for the expected frequency ($CF_{expected}$) can be seen, where C_m stands for the meter constant in impulses per kWh, P_l stands for the expected power consumed by the load in kW and 3600 is a constant that represents the amount of seconds per hour [10]. In this calibration the load of the heater at its second highest setting is used. The WT5000 indicates a power usage 1.3524 kW. For simplicity, a meter constant of 1000 imps/kWh or 1 imp/Wh is used. This results in an expected frequency of 375.7 mHz.

$$CFxDEN = \frac{F_{fs} * V_{op\%} * I_{op\%}}{CF_{expected}} \tag{3}$$

In Eq. 2 the formula for CFxDEN can be seen, where F_{fs} is the DFC frequency at full scale inputs, $V_{op\%}$ stands for the operating percentage of the voltage channel input, $I_{op\%}$ stands for the operating percentage of the current channel input and $CF_{expected}$ is the previously calculated expected frequency [10]. The datasheet of the ADE7953 indicates that the frequency at full-scale inputs is 210 kHz. The RMS voltage and current indicated by the WT5000 are 230.0 V and 5.880 A. These values have to be converted to peak voltage and current and converted to voltages at the IC. The voltage is divided by 1000 on the evaluation board, which results in a measured voltage of about 325.3 mV [7]. This is 65.05% of the full range, which is 500 mV [9]. The current is converted to a voltage by the Rogowski coil, with a factor of 0.416 mV/A [9]. Next to this, the ADE7953 has a programmable gain amplifier (PGA). The gain can be set to 1,2,4,8,16 and 22. This effectively lowers the input range while increasing the resolution of the current channel. The peak voltage at a gain of 22 is equal to about 22.7 mV. This is then equal to 15.22% of the input range, which is again 500 mV. Filling in the formula then gives a value of 55418, which converted to hexadecimal is xD87A. This value can then be entered in the CFxDEN register.

At this point the board is ready for measurements. When the CF1 register is turned on in the software, the J1 connector and the D1 LED on the evaluation board also receive the energy pulses [7]. The easiest way to measure CF1, is to connect an oscilloscope to J1 and measure the frequency between the pulses. Another way to do this, is by using for example an Arduino with a light sensor and measuring the pulses from the D1 LED on the evaluation board. This can in some cases be more useful, since it allows the user to take an average period of multiple pulses. To do this, the Arduino outputs the time at which a pulse occurs to a serial connection. These values can then be saved in Matlab for further conversion to pulse frequency and power. Since the meter constant of 1 imp/Wh was chosen, the power can be calculated by multiplying the pulse frequency by 3600.

There can however still be an error in the measurements. To compensate for this, the AWGAIN register can be used. The default value of x400000 can be lowered or raised, to lower or raise the calculated power [9]. This then also lowers or raises the frequency of the pulses as a consequence. To perform this part of the calibration, it is best to use the largest load possible. The main reason for this is that the error becomes more visible. For example, if there is a 4% error, this will result in an error of 4 W with a 100 W watt load, but results in a 40 W watt error at 1 kW. One disadvantage from using a large load is however that small voltage fluctuations from the grid will also result in larger power differences.

Using the waveform sampling functionality mentioned before, the current can also be plotted. This current represents the waveform after the PGA and integrator [9]. These waveforms can be saved to a txt or csv file for further processing [7]. The values in the graph are however register values, and thus need to be converted to mV, which is done with Matlab. The datasheet indicates that the maximum decimal value of the register at full scale inputs is 6,500,000 [9]. If the sampled values are divided by this maximum register value and multiplied by the maximum input voltage of 500 mV, the measured voltage can be determined. For purely 50 Hz current signals, this can then be converted to measured current by multiplying with the coil sensitivity and dividing by the PGA gain [11]. The sensitivity of a Rogowski coil is however not linear over different frequencies, so this conversion should not be done when the load is non-linear [9].

C. *Filter design*

The ADE7953 has built in phase compensation, which can be used in the case of phase deviation due to for example the Rogowski coil or a current transformer. To check whether compensation is necessary, there is also the ANGLEA register which displays the measured phase shift between current and voltage. This is a 16 bit signed register with resolution of 0.0807 degrees phase shift per Least Significant Bit (LSB) at 50 Hz [9]. The value of the ANGLEA register can however fluctuate up to plus minus 2 LSB's. The Rogowski coil only gives an ANGLEA value of around 1. This means that the fluctuation of the register is higher than the offset generated by the coil. Additional phase calibration is therefore not required.

The phase compensation register (PHCALA) is a 10 bit register, of which the Most Significant Bit (MSB) indicates the direction of the phase shift. The resolution of this register is 0.02 degrees per LSB at 50 Hz. This gives a maximum phase compensation range of -7.66 to 7.66 degrees [9].

To still have a good margin of error, the filter is designed around a maximum phase shift between 5 and 6 degrees. Using LTspice, it can be seen that this corresponds to a cut-off frequency around 500-600 Hz. Based on this requirement, a resistance value and capacitance value can be found using the cut-off frequency formula for a RC low pass filter. Using the same formula, as seen in Eq. 1, it can be determined that using a bigger capacitor results in lower resistance values for the same cut-off. Since the current channel on the ADE7953 essentially acts as a voltage meter and thus has a high input impedance, it is best to choose low resistance values [9]. Namely, this reduces the voltage dividing effect that the resistor has with the input impedance. The biggest capacitance available with a single capacitor is 330 nF, so this will be used in the filter

The final values chosen in the design of the filter are a resistance of 900 Ω and a capacitance value of 330 nF. This results in a cut-off frequency of around 536 Hz and a phase shift at 50 Hz of -5.33 degrees. Since the output of the Rogowski coil is differential however, the filter design also has to be made differential [9]. To do this, the resistance value is divided by 2 and a similar resistor is placed on the "ground" wire. This design can be seen in Fig. 3 below. Using LTspice it is verified that the differential filter yields the same cut-off frequency and phase deviation as the single ended filter. Both resistance values are lowered by roughly 25 Ω, since the Rogowski coil has a significant series resistance of around 50 Ω. The exact value of the resistors can be off by a couple of ohms, as long as both resistors have equal resistance. Therefore, after some tuning, it was found out that the value of 424 Ω was easiest to reach with the available potentiometers.

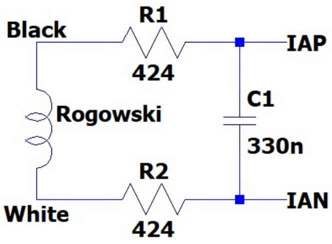

Figure 3. Differential Filter design

IV. RESULTS

Several sets of measurements have been performed both with and without a filter to determine what the effect of the filter is. First, the results from the callibration are shown. Then the measurements determining the largest error. After this, the measured power with the water pump at its lowest setting are compared. Lastly, the current wave forms at different PGA gains are shown.

A. *Calibration results*

The calibration of the evaluation board with the Rogowski coil was performed as mentioned above. An AWGAIN register value of x3F5000 was found give accurate results. The heater has 6 different power settings, which are used to test the calibration over different loads. The average period of the pulses was taken over a 2 minute time span. The current gain was set to 8X, but could be varied since it has no influence on the results with the correct CFxDEN value and the linear load of the heater. The corresponding CFxDEN register value for 8X gain is x4EA0. The results of this test with the heater can be seen in Table I below.

For the measurements using the filter, a second PA3202NL was used. By doing this, the coil can be soldered directly to the filter. This does however require a new calibration. As expected, the filter caused a phase deviation. The measured deviation in the ANGLEA register was x0037. Using the resolution of 0.0807 degrees per LSB, this gives a phase shift of 4.44 degrees. To compensate for this, the value xDE was found using the resolution of 0.02 degrees per LSB of the PHCALA register [9]. This phase shift is however in the wrong direction. Changing the MSB to 1, resulting in a register value of x2DE, changes the direction [9]. Verification using the ANGLEA rgister shows that the phase shift is now zero. The AWGAIN value of x3EB000 was used for accurate results. The results of testing the filtered setup with the heater can be seen in Table II.

Table I
CALLIBRATION VERIFICATION WITHOUT FILTERING

Actual power (W)	Measured power (W)	Deviation
1768	1767.96	-0.002%
1312	1313.28	+0.098%
823	825.48	+0.301%
537	537.48	+0.089%
337.5	338.40	+0.267%
212.5	212.76	+0.122%

It is important to note however, that the power measured by the WT5000 fluctuated significantly, due to voltage changes. For the highest load these fluctuations could be as big as plus-minus 5 W, while the smallest load fluctuated less than a watt. To determine what the actual power drawn by the heater was, the WT5000 was monitored continuously during the 2 minute measurements. Due to these fluctuations, the actual power usage of the larger loads is only given in whole watts.

Table II
CALLIBRATION VERIFICATION WITH FILTERING

Actual power (W)	Measured power (W)	Deviation
1735	1737.72	+0.157%
1285	1286.64	+0.128%
811	813.60	+0.321%
526	527.04	+0.198%
338.0	338.40	+0.119%
212.0	212.04	+0.019%

It can be seen from these calibration measurements that the filter does not impact the accuracy of the measurements of a linear load. This shows that the 50 Hz component of the current is measured correctly, while improving robustness.

B. Finding the biggest measurement error

As [2] shows, the largest error could be found when the water pump was set to it's lowest setting. The actual power at this setting was around 23-25 W, while the measured power was fluctuating around 315 W. The relative error becomes smaller when a higher setting is chosen, and becomes insignificant when the pump is at it's highest setting. There were however exceptions to this general trend at settings 3 and 9. At setting 9, the measured power was about 80-90 W lower than the actual power consumption. At setting 3, the measurements were still higher than the actual power usage, but were below the value suggested by the trend. Next to this, the values tended to fluctuate a lot from about 40 to 140 W at setting 3.

A possible explanation for this fluctuation would be a combination of phase shift and an internal threshold for the energy register. The phase shift induced by the dimmer would be at such a point that the power calculation would give low values [2][3]. When these values are lower than an internal threshold, they are not counted towards the energy measurement [9].

C. Filtered vs. Unfiltered power

Next to changing the dimmer setting, different current gains of the amplifier have also been tested. Setting 1 on the water pump was used, since it gave the largest possible error. During measurements it could be seen that the different current gains have a strong effect on the size of the error, so all the gains have been tested both with and without filtering. The measurements are taken over a time span of 10 minutes, since the power used by the pump and thus also the pulse frequency were expected to be low. This was also reflected again by the fact the energy threshold had to be lowered for the measurements at 1X gain. At this low gain, the measured power would often not exceed the energy threshold. This results in high fluctuations in the pulse frequency.

To change the energy threshold, the value of the AP_NOLOAD register can be changed. The default value of this register is xE419 or decimal 58,393 [9]. For the measurements at 1X gain, this value is changed to xD419. This resulted in the measured power being more consistent and closer to the actual power. For the other measurements, the threshold register was left at the default value.

The results from the power measurements at different gain levels can be seen in Table III.

Table III
WATERPUMP POWER MEASUREMENTS

Gain	Unfiltered power (W)	Filtered power (W)
1X	27.36	26.28
2X	89.64	25.56
4X	482.76	25.56
8X	740.16	26.64
16X	440.64	293.40
22X	321.48	372.24

It can be seen that the measured power at 1X gain is close to the actual power of 23-25 W for both setups with and without the filter. This however quickly changes when the gain is increased. The measured power without filter increases until 8x gain, after which it drops down again. Since the largest error of 740.16 W could be measured at 8X gain, this is the biggest point of interest. With the filter in place, this error at 8X gain is close to completely removed. This shows that filter is able to remove the unwanted higher frequencies, while leaving the 50 Hz component intact. As can be seen in the right column,

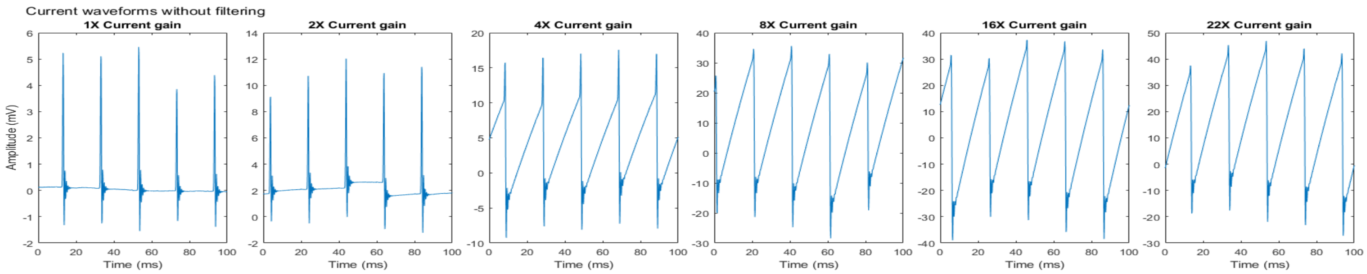

Figure 4. Current waveforms for different PGA gains without filter

the measurements remain relatively accurate below 16x gain. At 16X and 22X, the high frequency noise is not attenuated enough and causes errors again, which could be solved with a steeper filter.

D. Current wave forms

As mentioned before, the evaluation board software can sample and store the register value of the current register. This can give more insight into what is going wrong in the current measurements. For both setups, with and without filter, the current wave forms have have been saved for all possible gains. These values have then be converted to mV and plotted using Matlab. The graphs resulting from this can be seen in Fig. 4 and Fig. 5, for the setup without and with a filter respectively.

It can be seen that without a filter, the current waveform quickly changes from the actual pulse that is being drawn. At 1X gain, there is some visible oscillation after a pulse, but no other disturbance can be seen. At the following gain setting, offsets are created after some of the pulses. The error really becomes visible at 4X gain, since the signal between the pulses gets a slope. At 8X gain this slope has become large enough that a saw tooth wave remains. Even though the power lowers after 8X gain, the wave forms of 16X and 22X gain still have the saw tooth shape. This lower power likely results from the amplitude of the pulses not being as high as expected. Up til 8X gain, the pulse amplitude roughly doubles with each 2X increment. However the pulses at 16X and 22X are much lower than the expected 60 and 75 mV peak voltages.

With a filter, the disturbance to the pulses only becomes visible at 16X current gain, and roughly becomes a sawtooth wave at 22X gain. Another effect of the filtering is that the oscillations after the pulses are mostly gone. The amplitudes of the peaks at 16X and 22X are however still not at their expected levels. The pulses at gains up til 8X gain are almost identical, only differing in the amplitude as expected. This shows that the high frequency noise is not attenuated enough at 16X and 22X, as mentioned before in the power measurements.

Comparing these results with the measured power, it can be seen that disturbance to the period in between the pulses causes the measurement error. Seeing that this problem arises at higher gains, it seems that something could be clipping. This could be either the PGA or the integrator. Since a Rogowski coil becomes more sensitive at higher frequencies, it could be that some high frequency noise is causing this clipping effect. This also explains why the low pass filter reduces the disturbance. Since the filter is however not perfect, it does not attenuate the higher frequencies enough to correct the error at 16X and 22X gain. A solution to this would be to use a filter with a steeper roll-off, or to use a lower cut-off frequency and phase compensation.

V. CONCLUSION

A first order low pass differential filter has been designed. The main requirement for this filter was to not induce more possible errors, and only possibly make energy measurements more robust. It has therefore been determined that the phase shift induced by this filter should be minimized, while still attenuating the majority of the harmonics. This majority roughly is above 1-2 kHz. The ADE7953 energy metering IC has built in phase correction from -7.66 to 7.66 degrees at 50 Hz. The filter was therefore designed around a phase shift between 5 and 6 degrees at 50 Hz. The components used for this filter are two potentiometers set to 424 Ω and a capacitor with 330 nF

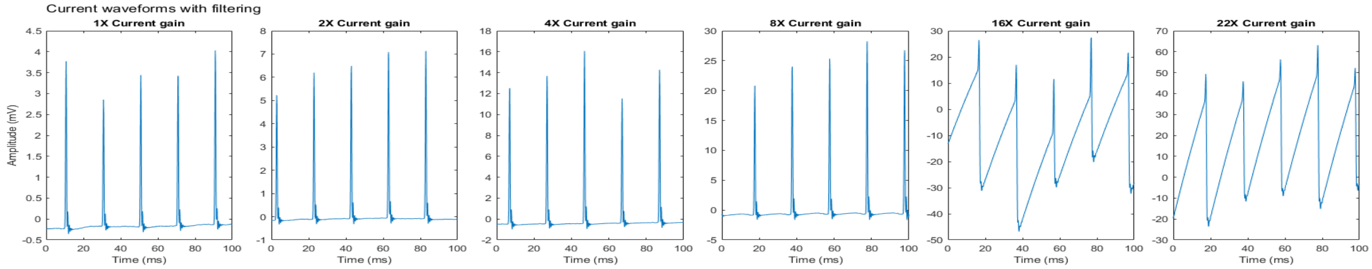

Figure 5. Current waveforms for different PGA gains with filter

capacitance. This gives a cut-off frequency of around 536 Hz and a phase shift at 50 Hz of -5.33 degrees.

Calibration for the output of the ADE7953 was performed by writing correct values to the CFxDEN and AWGAIN registers. Next to this, the aforementioned phase compensation was performed by writing the correct value of x2DE to the PHCALA register. The calibration was successfully verified with the linear load of a heater, for both the setup with and without filter. This shows that 50 Hz component of the current signal, and therefore the active power, is not attenuated. The robustness of the measurements is improved while not sacrificing accuracy.

From the results with the non-linear load of the water pump, it can be concluded that the filter does improve the robustness of the energy measurements using a Rogowski coil. It can be seen that the measuring errors occur when the input range of the current channel is exceeded. Namely, if the gain on this channel is lowered to 1X, the measurements without a filter also become relatively accurate. This however also results in a loss of resolution. If the gain is however raised, it can be seen from the measured current wave forms that the pulsed shape is lost and a saw tooth like wave form remains. The current wave forms show that this occurs at 4X gain for the setup without filter and only at 16X gain with the filter. This gives a maximum measurement improvement of about 714 W at 8X gain. At this gain, the setup without filter gives its largest error, while the filtered setup measures the power accurately.

As mentioned before, the measurement error can still occur at high current channel gains. This means that the measurement errors can also occur when a large non-linear load is used. To solve this issue, a higher order filter could be used. The trade off in that case would however be more phase deviation for a steeper filter. However, as long as the phase shift is relatively linear around 50 Hz, this could be compensated.

Seeing that the (partial) solution to measurement errors with a Rogowski coil can consist of as little as 3 passive components, it should not be a problem for manufacturers to incorporate such a filter in their designs.

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