Comparing Current Sensors for Power Measurement of Linear and Non-Linear Appliances

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Abstract—**Previously, households predominantly relied on linear equipment. However, in the present day, there is a growing trend towards using equipment with non-linear behavior. The utilization of such equipment can result in conducted electromagnetic interference, which in turn may cause inaccurate readings in energy meters. The current waveforms that cause interference are pulsed currents with a short pulse duration, fast rising slope, and large crest factor. In most households static meters are currently being used for billing purposes. It is therefore important that the static meters that are being used are reliable. Recent studies although have shown that there are a significant amount of cases in which the static meter show incorrect measurements. In order to verify if household equipment is causing measurements errors a low-cost reference sensor is needed. For this purpose, four different current sensing techniques are discussed, compared and measured under linear and non-linear circumstances. The sensing techniques that are analysed are the shunt resistor, the Rogowski coil, the Current transformer and the Hall effect sensor. The best low-cost sensor for linear situations was the KIWI Electronics SF-SEN-11005 (Current transformer). And the best low-cost sensor for non-linear situations was the YHDC HSTS016L (Hall effect sensor). For the current transformer the deviation in non-linear measurements were due to droop. The Hall effect sensor showed deviations between 2.5% and 6% across all measurements, which could not be solved with a different calibration or filtering. This leads to the conclusion that the hall effect sensor that was used had a too low accuracy in the range that was measured.**

I. Introduction

In most households static meters are currently being used for billing purposes. It is therefore important that the static meters that are being used are reliable. Recent studies although have shown that there are a significant amount of cases in which the static meter show incorrect measurements [1]. These deviations are due to electromagnetic interference (EMI) problems. EMI arises when equipment with non-linear behaviour is switching. This switching behaviour results in wave forms that have a pulsed nature with a short duration time, a large crest factor and fast rising slope. The use of non-linear equipment is increasing, since this type of equipment is more efficient and consumes less power. Electronic devices with this type of behaviour are for example harmonic disturbances, photovoltaic installations, various modern appliances, dimmed lighting equipment, a water pump for fish ponds, and multimedia equipment [2] [3]. The most notable deviations were +2675% for a water pump for fish ponds and 800W generated when energy was being consumed by multimedia equipment.

Because of the increasing amount of measurement errors it is important to develop a low cost reference meter in order to verify if the static energy meters used in the households give wrong measurements. This low cost reference meter should have a current sensor that will measure all connected appliances which includes linear and non-linear equipment. Additionally since this sensor will not be permanently installed in households but will be used along side the already installed sensors for a short amount of time, the current sensor should be able to attach and detach in a simple way. In other words the sensor should not be intrusive. The current sensing techniques that are low cost are; a shunt resistor, a current transformer, a Rogowski coil and a Hall effect sensor.

In [3] it was confirmed that measurement errors of the current transformer was caused by droop [4]. Droop is the phenomenon of saw-tooth behaviour at the fundamental frequency. This type of behaviour is caused by the sensors' behaviour at dc. Since the current transformer is only able to measure current when the flux changes, so when the current is not constant, it will not be able to measure dc currents. When the current remains constant the current within the current transformer will decrease exponentially with a time constant determined by Z_E, Zs and R_s, which is called droop. The Rogowski coil also displays droop, but in contrast to the current transformer this droop is caused by the capacitor in the integrator.

Furthermore in [5] it was determined that the deviations of the Rogowski coil in a static meter were not only due to droop but were actually mainly due to the clipping of the amplifier that is used when measuring with a Rogowski coil. The clipping of the amplifier happens when a current with a high slew rate is being measured. Because the slew rate is high the output of the Rogowski coil will be high, and will in most cases exceed the maximum input voltage of the amplifier. This then leads to clipping at the output of the amplifier, which ultimately caused the waveform to be distorted after integration.

Apart from this the shunt resistor is an intrusive current sensor making it not as suitable to be used for a reference meter.

Because of all this, the Hall effect sensor has to be further investigated and compared to the existing alternatives. In this paper it is researched what the best current sensor is for a low cost current meter. In Section II of this paper the different current sensing techniques are discussed and compared, as well as the parameters used for the measurements. In Section III The measurement setup and plan is discussed. Then in Section IV the results of the measurements can be seen. In Section V the results are discussed and Section VI is the conclusion.

II. Analysis

A. Current sensors

In this subsection four current sensors are discussed, a shunt resistor, a Hall effect sensor, a transformer current sensor and a Rogowski coil. These four sensors can be sorted into three categories current sensors based on Ohms law of resistance, current sensors based on Faraday's law of induction and current sensing by magnetic field sensors. For all the sensors the way they operate and the advantages and disadvantages are discussed. In table I a comparison is made between the sensors.

1) Shunt resistor: According to [1] a shunt resistor is a straightforward method for measuring current and voltage. It operates by measuring the voltage drop across a shunt resistor, which can then be used to calculate the current through the resistor using Ohm's law. The key advantages of this current sensing technique are its low cost, high accuracy, and ability to measure both ac and dc currents. However, there are several disadvantages to using a shunt resistor, the first being that since the shunt resistor is inserted into the current conducting path a significant amount of power loss is generated [6] caused by heating of the resistor. Other disadvantages are also that the shunt resistor has a limited bandwidth due to internal inductance, and is susceptible to noise and interference at high frequencies.

2) Hall effect sensor: Another method for measuring current is through the use of a Hall effect sensor, as explained in [1]. This type of sensor typically comprises a semiconductor that is connected to a current source and placed in the presence of a magnetic field. By measuring the voltage difference between the two sides of the semiconductor, which is known as the Hall voltage, the current can be determined. fig. 1a illustrates the basic working principle of a Hall effect sensor.

There are two types of Hall effect sensors commonly used in practice: open loop and closed loop (compensation type) transducers. Both types consist of a conductor carrying the primary current, a magnetic core, and a Hall element located in the gap of the core. The closed loop transducer includes an additional coil around the magnetic core that is proportional to the measured current, as shown in fig. 1b. The Hall effect current sensor offers several advantages, including high linearity, accuracy, the ability to measure both ac and dc current, and low power consumption [7]. However, it is important to note that these sensors can be sensitive to external magnetic fields from nearby currents.

3) Current transformer: fig. 2 illustrates the configuration of a current transformer (CT) which includes a primary winding directly connected to a measuring circle, and a secondary winding connected to a resistor [1]. The CT sensor ideally functions when the secondary winding is short-circuited with the resistor. This mode of operation is preferred because the current induced in the secondary winding creates a magnetic flux that compensates for the flux produced in the primary winding. As a result, the total flux is approximately zero, generating an electromotive force in the secondary winding

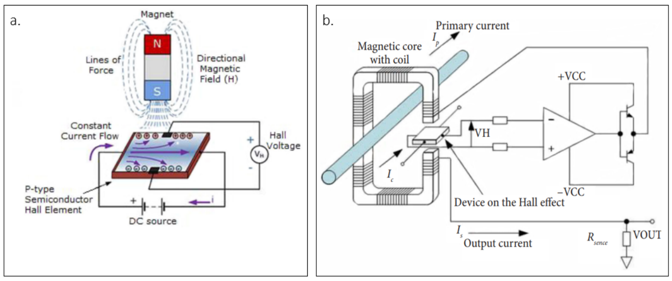

Fig. 1: a. Working principle of a Hall effect sensor. b. A compensation type Hall effect sensor [1].

proportional to the current in the primary winding. The CT sensor provides galvanic isolation and effectively filters out impulse noise, but it cannot measure direct current, has lower measurement accuracy, and is susceptible to magnetic fields [7].

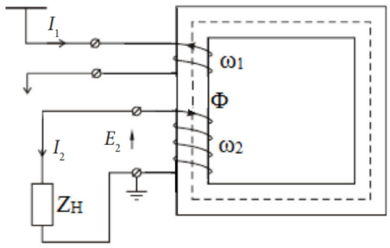

Fig. 2: The operation principle of a current transformer [1].

4) Rogowski coil: A Rogowski coil consists of a coil in the shape of a C with a current running through the middle of the C shape and an inverter that is connected to the C shaped coil [6]. The voltage induced into the Rogowski coil can be determined by the change in current. Because this current sensor is based on detecting flux change, which is proportional to the change in current, Rogowski coils are not suitable to measure low frequency currents such as dc or close to this Advantages of a Rogowski coil is that it does not demonstrate saturation and is naturally linear.

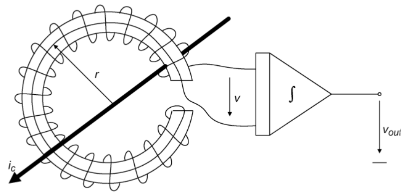

Fig. 3: The operation principle of a Rogowski coil [6].

B. Linear and non-linear currents

During power measurements a distinction is made between linear and non-linear waveforms. This distinction is made because these currents are very different from each other. A linear current will be a 50 Hz sine wave as can be seen in fig. 4. In contrast a non-linear current will be a pulsed current with a short pulse duration, fast rising slope and a large crest factor

TABLE I: Comparison between four current sensors [6].

Current Sensor	Bandwidth	Can meausre dc	Is intrusive	Accuracy	Thermal drift [ppm/K]	Limitations
Shunt resistor	MHz	Yes	Yes	0.1% - 2%	25 - 300	- Too much power loss due to heating - No galvanic isolation
Rogowski coil	kHz - MHz	No	No	0.2% - 5%	<100	- Droop at pulsed currents - Clipping of amplifier - Low sensitivity leads to not being able to measure small currents
Current transformer	kHz - MHz	No	No	0.1% - 1%	50 - 300	- Droop at pulsed currents - Sensitive to magnetic fields from other currents close to the sensor
Hall effect sensor	kHz	Yes	No	0.5% - 5%	50 -1000	- Too big thermal drift has to be compensated - Sensitive to magnetic fields from other currents close to the sensor

[3]. The crest factor being the ratio between the peak value and the effective value. An example of a non-linear current can be seen in fig. 5.

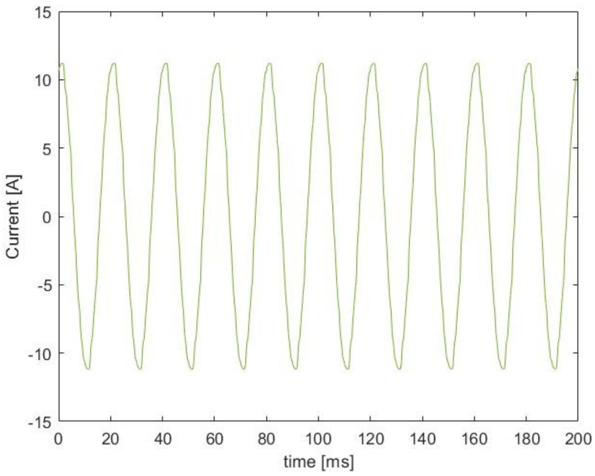

Fig. 4: Example of a linear current

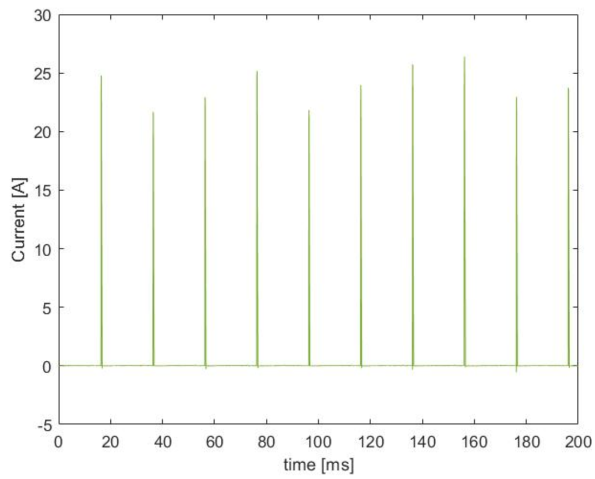

Fig. 5: Example of a non-linear current

C. Parameters for analysing current wave forms

In [8] it has been shown that for reliable energy measurements, only the fundamental components at 50 Hz has to be taken into account if the voltage source is 50 Hz. Even in the case of a sine wave with the most allowed distortion more than 97.5% of the power was still confined to the fundamental 50 Hz frequency component. By only taking the 50 Hz components into account the harmonics created by non-linear loads will be filtered out. As a result, not only are reliable active power and energy measurements obtained, but also there is no need for a high sampling frequency.

Apart from this the rise time, phase shift and power of the signal without the peaks in non-linear currents are also important. These parameters will provide additional information that is needed in order to conclude what differs from one waveforms to an other. With these parameters analysed it can be concluded what is the limiting factor of a current sensor is.

The rise time refers to the duration it takes for the amplitude to transition from 10% to 90% of the maximum value. In cases where the signal undergoes a two-step process to reach this range, the steepest and initial section is considered to calculate the slope of the current signal [2].

The phase shift is the amount of delay a signal has in degrees in regards to the reference current signal. It is important for the phase shift to be minimal because if the current signal is shifted compared to the voltage signal, a large error can occur when calculating the power. This is because when the current is shifted a different part of the current signal will be multiplied with the voltage signal, leading to a different power signal compared to the power signal without a phase shift.

Last since a non-linear current consists of a constant signal with periodic peaks, a good way to analyse such a signal is to exclude the peaks and only calculate the power of the constant part of the signal. This is a good way to identify what part of the signal caused the sensor in question to make errors.

III. Method

The measurement setup is as follows. The source voltage will be supplied by the Pacific Power Smart Source 140-TMX. Six current sensors are connected in series to the power of the voltage supply. The sensors in question can be seen in table II. PEM CWT-3 is the Rogowski coil.

The Keysight Technology sensor N2783b current probe is used as a reference sensor. The KIWI Electronics SF-SEN-11005 Current sensor-30A is current transformer 1 and the HIOKI 9694 clamp on sensor is current transformer 2. Pico technology TA 189 current clamp is a combination of hall effect sensor and current transformer. The Hall effect sensor, YHDC HSTS016L, will also be attached to a 3.3V power supply. Last Picoscope 4824A pc-based oscilloscope is used to read all the measured signals from the current sensors synchronously. First the sensors are tested under the linear load of a heater at 310W, 800W and 1800W. Second the senors are tested under the non linear load of a water pump. The measurement setup can be seen in fig. 6.

The measurements that are being done will be saved to a .mat

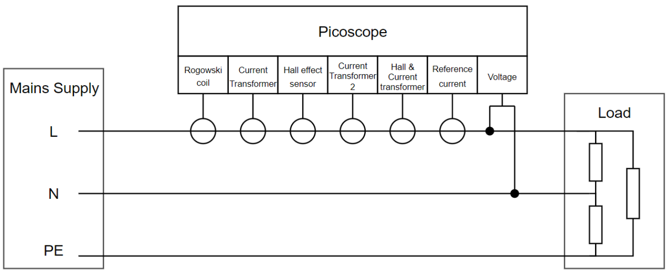

Fig. 6: Measurement setup

file, so that it can be processed in Matlab. Before the measured signals can be used to calculate the used power, the sensors will be calibrated to the reference sensor for linear situations. The calibration is done by first setting all the sensors up in a way that the mean is zero. The Matlab mean function is used in to determine the mean. Then small increments of 0.0005 or 0.001 are either added or subtracted to the measurement data of the sensor in question. After this the root mean square (RMS) of the sensors are calculated. This is done by the Matlab rms function. Then all the sensors have to be calibrated in a way that the RMS is the same as the reference sensor. This is done by adding or subtracting small increments of 0.01, or smaller when needed, to the number by which the data of the sensor in question is multiplied. For example the data of Current transformer 1 was being multiplied by 200 before calibration and after calibrating the data is multiplied by 200.04. The calibration points can be seen in fig. 7.

After calibration the power will be calculated by taking the average power over 10 seconds for both the linear and non-linear measurements. In Matlab first the measured current of the sensors is multiplied with the measured voltage, which results in the measured power. Then the mean function is used to calculate the mean power over the whole signal. Now that the average power is known the deviation can be calculated by subtracting the average power of the reference

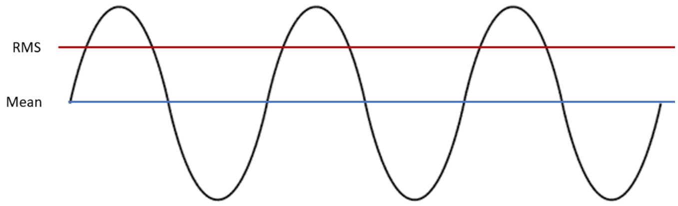

Fig. 7: Calibration points

signal from the average power of the sensor in question and then dividing that value by the average power of the reference sensor and then finally multiplying the value with 100.

When it needed a filter can be applied by using the lowpass Matlab function. The cutoff frequency will be the frequency of the bandwidth of the sensor in question. For example the hall effect sensor has a bandwidth of dc-25 kHz so the cutoff frequency will be 25kHz. This way no part important part of the measured signal will be filtered out.

After this for the linear measurements the phase difference of the current sensors in regards to the reference sensor will be calculated in order to know if the measurement error is a consequence of any delay's. The phase error is calculated by first taking the Fast Fourier Transform (FFT) of the measured current signals. The FFT is done with the fft Matlab function. Then the phase of the maximum peak in the FFT spectrum is taken. This peak should be the 50 Hz signal since this frequency should hold almost all power as was discussed before in section II C. The maximum peak was found by first using the abs function and then the max function with specifying that the result should be returned to a two column matrix in order to get the separate magnitude and phase components of the FFT. Next the angle function is used to calculate the phase in radians of the phase component of the maximum FFT value. Last the calculated phase of the current sensors are subtracted from the phase of the reference sensor and converter to degrees.

For the non-linear measurements the rise time and power without the peaks will be calculated also. The rise time is needed in order to know if any measurement errors are because of a deviation in the slope. The rise time is determined with the risetime function in Matlab. This number is then also checked by plotting the points which were used to calculate the rise time.

The power of the signal without the peaks is needed in order to verify what part of the signal contributes to the measurement deviation. This parameter is calculated by plotting the measured current signals and determining where the peaks begin and end. Next these sections of the signal are set to zero. Last the power is calculated by multiplying the edited current signal with the measured voltage signal. The average power can than be calculated by using the mean function.

TABLE II: Used sensors during measurements [9] [10] [11] [12] [13] [14]

Brand	**Sensor name**	**Type sensor**	**Price**	**Bandwidth**
PEM	CWT-3	Rogowski coil	€2.000	0.1Hz – 16 MHz
KIWI electronics	SF-SEN-11005 Current sensor-30A	Current transformer	€15	
HIOKI	9694 clamp on sensor	Current transformer	€320	40 Hz - 5 kHz
YHDC	HSTS016L	Hall effect sensor	€15	DC – 25 kHz
Pico technology	TA 189 current clamp	Hall effect sensor & Current transformer	€460	DC – 100 kHz
Keysight technology	N2783b current probe	Hall effect sensor & Current transformer	€5.000	DC – 100 MHz

IV. Results

In this section the measurements results will be shown.

A. Linear measurements

In fig. 9 one period of the measured signal of the heater at 1800 W can be seen. Most of the sensors are the same as the reference apart from the Rogowski coil and the Hall effect sensor. The Rogowski coil has a slight phase shift compared to the reference. This can also be seen in tab. III the Rogowski coil has here the biggest phase difference. Now the general shape of the Hall effect sensor is similar to the reference signal the difference is that the Hall effect sensor has a large amount of disturbances even after applying a 25k Hz filter. Furthermore, the Hall effect sensor has a slight phase shift. This phase shift decreases with a higher heater setting. Additionally the average power deviation also decreases with a higher heater setting. But when taking a look at the phase shift of the other sensors it can be seen from current transformer 1 that a very minimal error can be achieved with a similar amount of phase shift. Additionally, the average power deviation did not improve after the calibration discussed in the previous section, on the contrary the deviation actually increased slightly when comparing it to the calibration found in the data sheet. The sensor with the least amount of deviation is the current transformer 2.

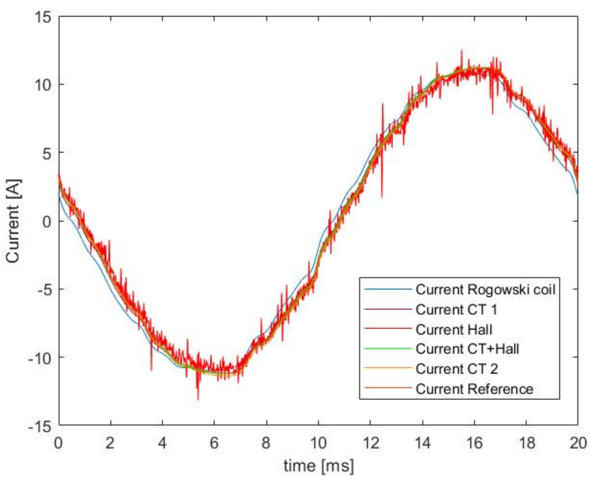

Fig. 8: Measured 1800W Heater signal

B. Non linear measurements

In fig. 10 one period of the measured signal of the water pump at level 1 can be seen. It can be seen that again the

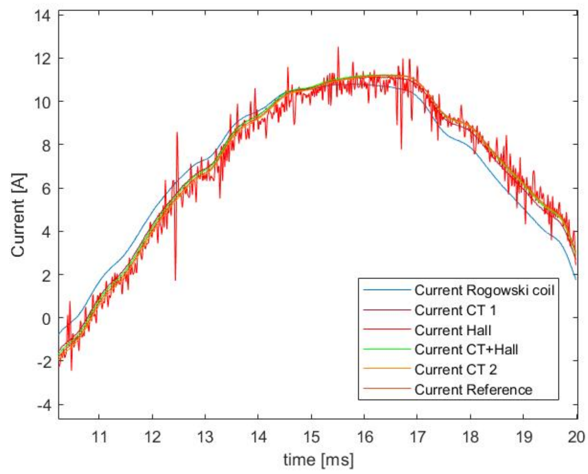

Fig. 9: Zoomed in measured 1800W Heater signal

Hall effect sensor display's a lot of disturbances, also after filtering at 25 kHz. When looking at the amount of average power deviation in tab. IV the big outlier is the Rogowski coil. For the water pump at level 1 the water pump has a deviation of -84.2%. From the measurement of power without peaks it can be seen that this big deviation is due to the fact that the Rogowski coil displays a sine wave in the parts between the peaks, when the reference here is approximately zero, see fig. 12. Apart from the Rogowski coil the current transformer also has a substantial amount of power without the peaks. This is because of the previous discussed droop, saw tooth wave behaviour at dc. When looking at the Hall effect sensor it can be seen that the power without the peaks is the lowest amount from all the sensors. The amount is even less than the reference which likely contributes slightly to the average power deviation. Furthermore, all the rise times of the sensors are almost the same except for the Hall effect sensor which always has a slightly faster rise time. But when looking at the average power deviation the Hall effect sensor has approximately on average 4% too little power compared to the reference. Which cannot be due to the faster rise time, but could be due to that the total bounded area of the peak is less for the Hall effect sensor than that of the reference sensor. The sensor with the least amount of deviation is the current transformer 2.

V. Discussion

In total the Current transformer 2 (HIOKI 9694 clamp on sensor) was the best for both the linear and non-linear measurements. This sensor did display droop, although the

TABLE III: Linear measurement results

Sensor	*Heater 310 W* Average power deviation	Phase difference	*Heater 800 W* Average power deviation	Phase difference	*Heater 1800 W* Average power deviation	Phase difference
Rogowski coil	-0.7%	-6.2°	6.2%	-5.8°	8.4%	-5.8°
Current transformer 1	-0.1%	-1.7°	-0.2%	-1.7°	-0.1%	-1.6°
Current transformer 2	-0.0%	-0.5°	0.1%	-0.6°	-0.0%	-0.7°
Current transformer & Hall	-0.0%	0.4°	-0.1%	0.2°	-0.1%	0.1°
Hall effect sensor	-5.8%	1.2°	-3.7%	0.9°	-2.8%	0.5°

TABLE IV: Non-linear measurement results

Sensor	*Water pump Level 1* Average power deviation	Power without peaks	Rise time [µs]	*Water pump Level 4* Average power deviation	Power without peaks	Rise time [µs]	*Water pump Level 9* Average power deviation	Power without peaks	Rise time [µs]
Rogowski coil	-84.2%	-371.0%	39.8	-38.4%	-60.2%	48.8	-16.2%	-19.1%	52.0
Current transformer 1	8.1%	16.2%	39.8	4.8%	12.8%	47.9	0.9%	7.3%	52.8
Current transformer 2	2.2%	10.5%	39.9	1.4%	9.1%	48.9	-0.4%	6.3%	52.3
Current transformer & Hall	-5.6%	3.5%	39.8	-2.8%	-2.5%	48.5	-1.4%	1.4%	51.4
Hall effect sensor	-3.9%	1.3%	33.9	-4.8%	-1.3%	42.6	-3.2%	-0.6%	46.3
Reference	-	3.2%	39.9	-	0.7%	48.8	-	1.8%	52.7

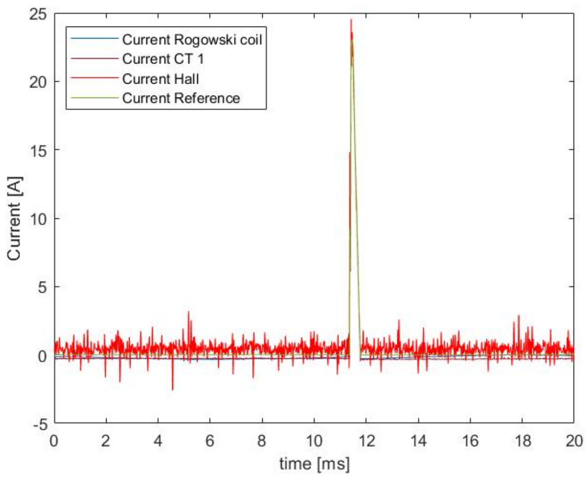

Fig. 10: Measured water pump 1 signal

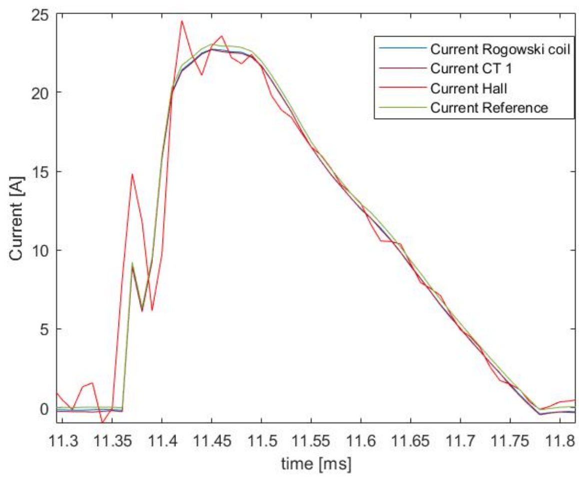

Fig. 11: Zoomed in measured water pump 1 signal

amount of increase in droop height was 0.03 A less then current transformer 1. And while current sensor 2 was the best in these measurements the occurrence of droop could result in measurement errors in the future. Additionally since a low cost application is needed this sensor is not suitable because, it costs around €320.

When looking at the low cost sensors the current transformer 1 (KIWI Electronics SF-SEN-11005 Current sensor-30A) is the best under linear circumstances, while the Hall effect sensor (YHDC HSTS016L) was the best under non linear circumstances. For the current transformer the deviation in non linear measurements were due to droop. For the Hall effect sensor a small part of the deviation under linear circumstances could be due to phase shift since the amount of deviation decreases as the phase shift decreases. An other reason for the amount of deviation for the Hall effect sensor could be that the sensor is not sensitive enough. This could be because the measurement range is $\pm 200A$ while the maximum output is $1.65V + 0.625V$, 1.65 V being zero and 2.275 V being 200A [13]. This means that when 1 A is measured the sensor will give an output of $1.65V + 0.003125V$, which is the smallest voltage difference among all the tested sensors. Furthermore the maximum measured current was less than 30 A. Which can explain why the Hall effect sensor has large disturbances.

For further research it is recommended to use a Hall effect sensor with a measurement range of $\pm 30A$. An example is the YHDC HSTS016L 30 A 1.65 ± 0.625 $+3.3V$ [13]. For the non linear measurements the Hall effect sensor was better than the current transformer 1, but still had an average power deviation around 4%. One of the reasons could be on what was mentioned before for the non linear measurements, the measurement range of the sensor being too big and in return the sensor not being sensitive enough. The peaks of the Hall effect sensor are overall lower than the reference sensor, this makes the Hall effect sensor measure always a little less than

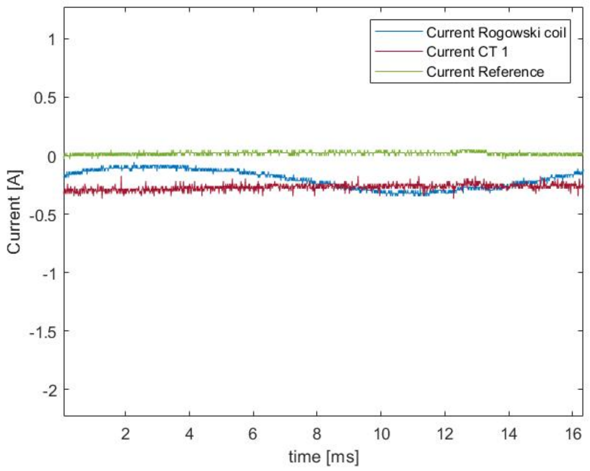

Fig. 12: Zoomed in measured water pump 1 signal of rogowski coil

the reference. A last reason for deviation in the Hall effect sensor in in non linear equipment is that the amount of power that is measured without the peaks is less then the reference contributing to the total deviation.

VI. Conclusion

In this paper six different current sensors were tested under linear and non linear circumstances in order to determine if the Hall effect sensor is a suitable sensor for a low cost reference sensor. All sensors were tested at three different heater sensors to determine the deviation for linear measurements. Furthermore, three different water pump levels were tested in order to determine the behaviour of the sensors under non linear circumstances. It was found that the best performing sensor was the HIOKI 9694 clamp on sensor (Current Transformer). The worst performing sensor was the PEM CWT-3 (Rogowski coil). This was mainly due to the performance of the sensor under non linear circumstances. This sensor had large deviations here due to the fact that the sensor displayed a sine wave while which contributed to a large power deviation. Additionally, the Rogowski coil also gave the most phase shift under linear circumstances. The best low cost sensor for linear situations was the KIWI Electronics SF-SEN-11005 Current sensor-30A (Current sensor). And the best low cost sensor for non linear situations was the YHDC HSTS016L (Hall effect Transformer). The Hall effect sensor had a large amount of deviation across all the measurements, which could be mainly due to a too large measurement range. In contrast to the other sensors the Hall effect sensor has a constant deviation between approximately 2.5% and 6%. and no apparent outliers. Furthermore, when calibrating the sensors all the sensors displayed lower errors after calibration apart from the Hall effect sensor which displayed larger errors after calibration. Additionally, after filtering the Hall effect sensor still had a lot of disturbances. Finally, for linear measurements a part of the deviation could be due to phase shift. And for non-linear measurements part of the deviation is too little power measured in between the peaks. An other part of the deviation could be due to the fact that the in the peaks of the Hall effect sensor are overall lower than the reference sensor.

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