ANALYTICAL ASSESSMENT AND CIRCUIT SIMULATION TO STUDY THE BEHAVIOUR OF ROGOWSKI COIL INTEGRATORS FOR MEASUREMENT OF NONSINUSOIDAL CURRENTS

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ABSTRACT

In the paper, the performance of current measurement devices based on Rogowski coils is analysed. In order to show the influence of the slope of the current waveform di/dt on the measurement accuracy, the results of a set of simulations in GNU Octave and LTSpice® are presented. The simulations are complemented by some measurements, which were done with different smart meters using the Rogowski technology for current measurement. It is demonstrated that potential measurement deviations are a reproducible physical characteristic of this measurement type. The paper presents simple tools easy to adjust to real conditions that e.g. appear in low voltage networks.

INTRODUCTION

Current probes based on Rogowski coils are widely accepted in the research community for power quality as well as in industry. A broad choice of bandwidths as well as current measurement ranges allow reliable determining of transients and harmonics. However, not the Rogowski coils itself but the integrator electronics limits the magnitude and steepness of the signal to be integrated. The integrator non-linearity is affected by the amplifier gain limitations [1]. Digital integration is limited by the performance of the AD converter.

Recent studies showed that the measurement accuracy of some electricity meters based on Rogowski coils current sensing technology can be unsatisfying under certain network conditions. One of the influencing parameters is the slope of the current waveform $\mathrm{d}i/\mathrm{d}t$.

In order to show systematically the performance of a measurement device based on Rogowski coils, the proposed paper presents the results of a set of simulations done in GNU Octave and LTSpice®. The target is to show a correlation between a certain $\mathrm{d}i/\mathrm{d}t$ and the deviation of resultant measurement values from expected values. The simulations are accompanied by some measurements, which were done with different smart meters using the Rogowski technology for current measurement.

In conformity procedures for electricity meters only the energy values are verified, as only those are relevant in calibration regulations and for billing. Most modern electricity meters have the option to show power values as well. For the reason of simplification, in this paper only the power values are considered.

GNU OCTAVE

Procedure and general results

In GNU Octave the application of a passive Rogowski coil without analogue hardware integrator is represented. The simulation supposes a coil, which is directly connected to an AD converter and a digital integration. If the sampled voltage is too big for the AD converter, it is clipped.

In GNU Octave ideal signals for a sinusoidal terminal voltage with U_{rms} = 230 V, f = 50 Hz and the current of a load using leading edge phase cutting are created. The signals are considered with 2^{16} samples per period. A digital filter based on a 'Bessel' function is applied. The resultant signals are used to calculate a reference power. A hard clipping behaviour is emulated by reducing the maximum value of the Rogowski voltage in positive as well as negative half cycle. The current samples obtained after 'clipping' are used to calculate the real power representing the result of a measurement device based on a Rogowski coil. The power drawn by the load and the Rogowski power are compared and the deviation can be analysed. The procedure is repeated for different firing angles φ of the current. It can be shown, that the deviation is nonlinear. For angles from 0° to < 90° the deviation is negative, which means the Rogowski power is lower than the reference power. For angles > 90° up to 180° the deviation increases in the positive direction and can reach values of several 100 %. That means that the Rogowski power is higher than the reference power. At 90° the deviation for the integrated power is approximately zero although the shape of the instantaneous power over time is so much different from the reference power. That might be the reason why the unwanted effects are not observed at tests according to DIN EN 50470-3 [2], which are used to determine the special characteristics of electronic counting devices.

Different slopes of the current

Most of the simulations are done with a Bessel filter of twelfth order with 300 kHz bandwidth, to limit the slope of the current to approximately 2.7 A/µs for an ohmic load with I_{rms} = 10 A and a firing angle of 45°. For a flatter slope of the current, a bandwidth of 5.12 kHz with a resultant slope of the current of 0.05 A/µs under the same conditions is used.

Figure 1 shows the simulation results for a terminal voltage with U_{rms} = 230 V, f = 50 Hz, I_{rms} = 10 A, phase angle cut at 45°, and a slope of the current 2.7 A/µs. The value given for I_{rms} here (and in the following sections) refers to the full load condition with firing at 0°.

Table 1 opposes the results for relative deviation of the current I and the real power P as well as the deviation of the phase angle of the fundamental current $\Delta\varphi_{i1}$. It can be seen that the slope of the current has no influence on the relative deviation of the current. The deviations for current and power are both negative, as it can be expected for clipping and following integration. The deviation of real power is higher for steeper slopes of the current, but also for the moderate slope of the current, the deviation still is considerable. For same clipping value the flat slope of the current results in a deviation of the real power of -30.4 % and -35.0 % for the steeper slope of the current.

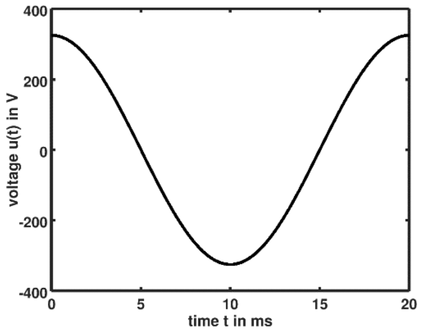
Different clipping voltages

To study the influence of the clipping, the clipping voltage is varied for fixed current, a firing angle of 45° and a fixed slope of the current of 2.7 A/µs. The results are summarized in Table 2. The relative deviations for the current and power do not differ much. They are always negative.

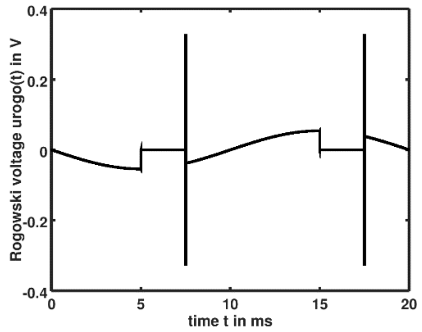
Different firing angles

To study the influence of the firing angle, the value is varied between 0° and 180° in steps of 5°. Figure 2 shows the relative deviation from the real power P in % as a function of the firing angle. Again, the current signal is filtered with an 300 kHz Bessel filter, what leads under the condition of a firing angle of 45° and an ohmic load with I_{rms}= 10 A to a slew rate of 2.7 A/µs. It can be seen that the deviation is negative for angles from 0° to < 90°. For angles > 90° the deviation increases in the positive direction and can reach values of several 100 %. For better clarity, the diagram is limited to 135° here. Table 3 summarizes the results for 45°, 90° and 135°. The currents and instantaneous powers are shown in Figure 1 c) and d), and Figure 3. The differentiation and further integration to get from the load current to the Rogowski current leads to negative current values in case of negative but also small positive load current values. This can be seen for example in Figure 1 c), between approx. 4 ms and 14 ms. For firing angles above 90° the effect is more severe than for firing angles below 90°.

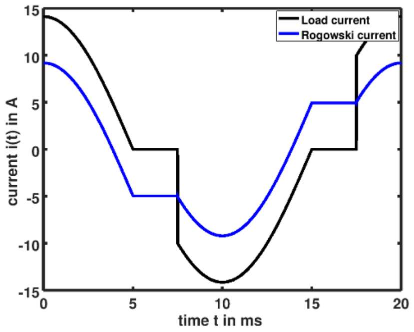
a) Terminal voltage



b) Clipped voltage



c) Currents for firing angle 45°



d) Instantaneous powers for firing angle 45°

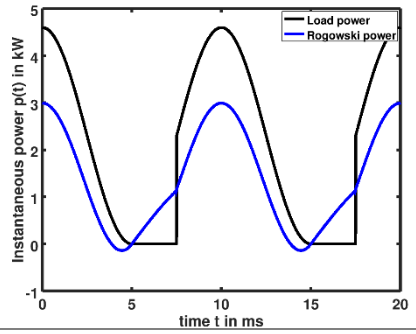


Figure 1: Results for I_{rms} = 10 A, *firing angle* 45°, *slope of the current* 2.7 A/µs

Table 1: Comparison of results for different slopes of the current, I_{rms} = 10 A, *clipping at* 325 mV, *firing angle* 45°

slope of the current	**2.7 A/µs**	**0.05 A/µs**
rel. deviation of *I* in %	-34.4	-34.4
$\Delta\varphi_{i1}$ **in °**	+24.9	+20.4
rel. deviation of *P* in %	-35.0	-30.4

Table 2: Comparison of results for clipping values, I_{rms} = 10 A, *slope of the current* 2.7 A/µs, *firing angle* 45°

clipping at	**0.325 V**	**3.25 V**	**32.5 V**
rel. dev. of *I* in %	-34.4	-33.8	-27.7
$\Delta\varphi_{i1}$ **in °**	+25.0	+24.1	+16.6
rel. dev. of *P* in %	-35.0	-34.0	-26.1

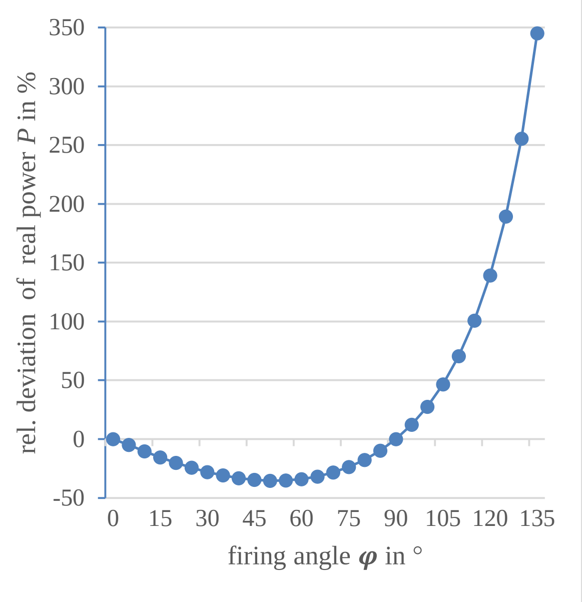


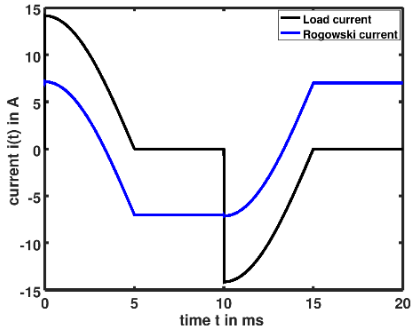
Figure 2: Relative deviation of real power P in % as a function of the firing angle, I_{rms} = 10 A, 300 kHz *Bessel filter, clipping at* 325 mV

Table 3: Comparison of results for firing angles, I_{rms} = 10 A, 300 kHz *Bessel filter, clipping at* 325 mV

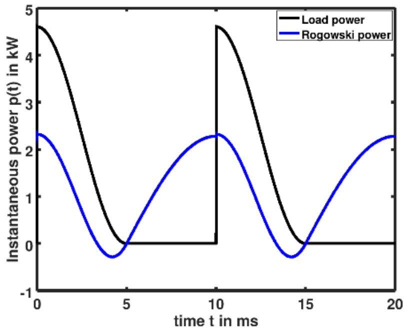
Firing angle	**45°**	**90°**	**135°**
rel. dev. of *I* in %	-34.4	-14.8	+51.1
$\Delta\varphi_{i1}$ **in °**	+25.0	+64.8	+81.4
rel. dev. of *P* in %	-35.0	-0.006	+348.0

At 90° several effects lead to a relative deviation of the real power *P* close to zero. For deeper analysis, the clipping value at 90° is varied. The relative deviations for the current and real power have a good match. Especially the deviation of the power is almost independent of the clipping value. But the phase of the current inverts its sign with increasing clipping. At a clipping at 325 mV the phase changes from -32.5° for the load current to +32.3° for the Rogowski current. It seems that the effects of a deviation of the current amplitude and the phase shift compensate each other at 90° for the real power. That explains why the phenomena did not show up during tests according DIN EN 50470-3.

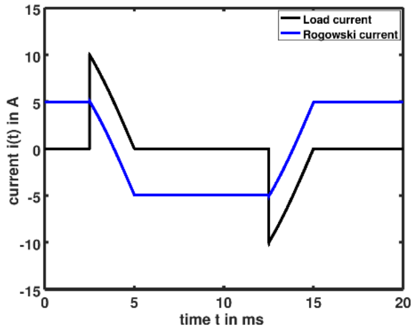
a) Currents for firing angle 90°



b) Instantaneous powers for firing angle 90°



c) Currents for firing angle 135°



d) Instantaneous powers for firing angle 135°

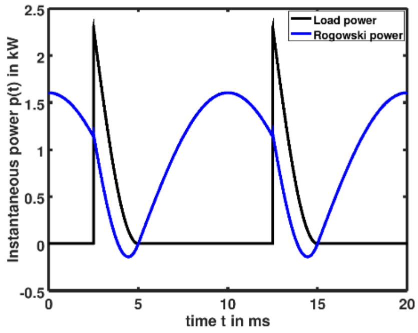


Figure 3: Results for I_{rms} = 10 A, *firing angles* 90° *and* 135°, 300 kHz *Bessel filter*

Further parameter variations

For further analysis the value of the current I_{rms} is varied between 5 A and 60 A, which are the nominal values of commercially available electricity meters. The resultant deviations for current and real power only differ in very small ranges, so that it can be stated that this parameter has no significant influence on the measurement results.

In practise, in addition to loads, which use a current leading edge phase cut as studied here, there will be always loads that draw almost pure sinusoidal currents. To answer the question whether the measurement of this sinusoidal current would be influenced by the clipping, the simulations are repeated for a current leading edge phase cut with $I_{\text{rms}} = 10$ A and an additional sinusoidal current of 1 A, 10 A and 100 A respectively.

The results show that the sinusoidal current is measured with almost no additional error; solely the sampled values during the clipping are faulty. It can be stated that a load that causes clipping only disturbs its own consumption measurement but not the one of other loads.

LTSPICE

LTSpice® allows a more intuitive simulation of a real circuit than the functional simulations done in GNU Octave. To confirm the findings of the GNU Octave simulations, a circuit with a triac, as shown in Figure 4, is built in LTSpice®. The triac simulates the behaviour of a dimmer such as used for lamps. It is programmed to operate for different firing angles to provide phase angle control behaviour with same angles as used in the GNU Octave simulations. A Rogowski coil with a diode clipping circuit, as shown in Figure 5, is added. The resultant waveforms and calculated powers correlate to the results from GNU Octave. The slope of the currents after clipping is the same as in the GNU Octave simulations. Specific values mainly depend on the chosen slope of the current of the current and the load value.

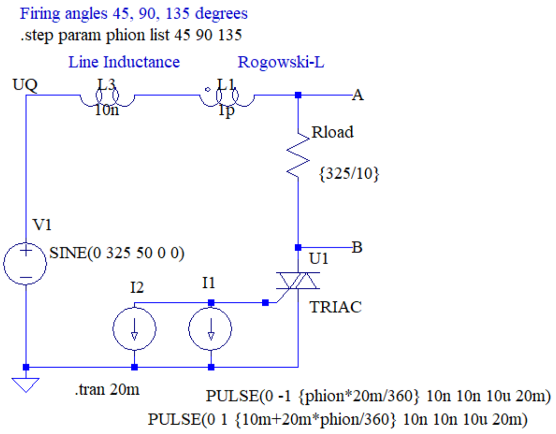


Figure 4: Circuit in LTSpice® with triac to simulate dimmer such as used for lamps

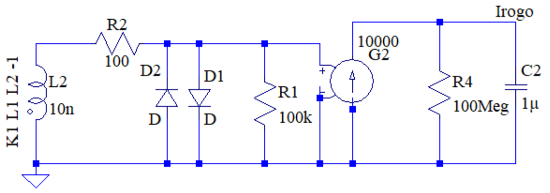


Figure 5: Rogowski coil with clipping circuit in LTSpice®

MEASUREMENTS

Several electricity meters with Rogowski current sensing technology were tested at a commercial meter testing facility. The meters were operated at $U = 230\,\text{V}$, $f = 50\,\text{Hz}$, a current $I = 2.5\,\text{A} \dots 60\,\text{A}$ and a slope of current of approx. 1.1 A/µs. The tests were done with an ohmic load and firing angles of 90° and 135°. The tests were repeated for three-phase voltage supply and three-phase symmetric current measurement as well as for three-phase voltage supply and single-phase current measurement as well as for single-phase voltage supply. The maximum deviation, which could be displayed, was 100 %. Higher deviations were accounted as 100 %.

The results for three-phase voltage supply, single-phase current measurement and firing angles of 90° and 135° are shown in Table 4 and Table 5. These results show that high currents and a firing angle of 135° can lead to deviations in the current measurement of the meters. If the meters are used only single phase, the deviation is slightly higher, as shown in Figure 6. For a firing angle of 90°, the deviations fulfill the limits of DIN EN 50470-3.

In the following further measurements were done to analyze the critical $\mathrm{d}i/\mathrm{d}t$ at which the meters are disturbed. For this purpose a setup with a Dewetron system as reference and a controllable single-phase load was used. The root mean square value of the load current with a firing angle of 135° was varied between 1.21 A and 3.92 A. The respective slopes of the current were determined via an oscilloscope. The results for meter 1 are shown in Figure 7. With increasing $\mathrm{d}i/\mathrm{d}t$ the percentage deviation increases. For the considered meter for $\mathrm{d}i/\mathrm{d}t = 1151\,\text{mA/µs}$ the deviation is higher than 5 %.

Table 4: Deviation of current for three electricity meters for different load currents, firing angle 135°

			Meter 1	**Meter 2**	**Meter 3**
I_{rms} in A, $\varphi = 135°$	0.745	deviation of I in %	-1.11	-0.99	-0.72
	1.51		-0.59	-0.67	-0.48
	3.03		-0.31	-0.49	-0.33
	4.78		12.83	-0.48	-0.71
	6.04		52.18	-0.82	-0.64
	7.50		88.57	8.54	2.76
	9.05		100	42.4	37
	12.06		100	100	100
	15.08		100	100	100
	18.10		100	100	100

Table 5: Deviation of the current for two electricity meters for different load currents, firing angle 90°

I_{rms} in A, $\varphi = 90°$		deviation of I in %	Meter 1	Meter 2
	1.76		-0.1	-0.21
	3.53		-0.05	-0.08
	7.09		-0.02	0.02
	11.27		-0.31	-0.21
	14.13		-0.11	-0.23
	17.69		-0.08	-0.27
	21.17		-0.03	-0.31
	28.21		1.33	0.66
	35.27		1.55	0.54
	42.33		1.51	0.48

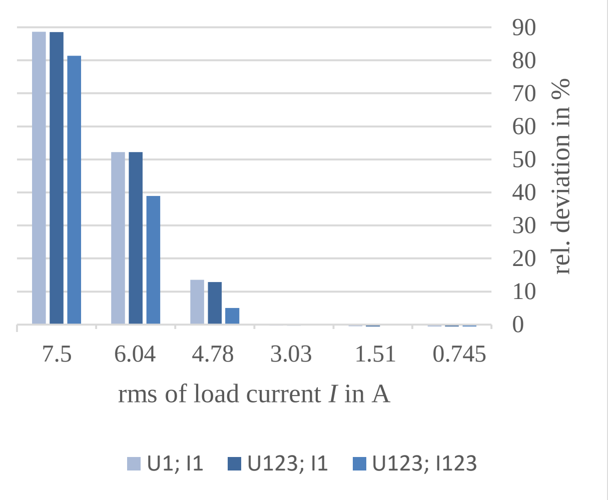


Figure 6: Deviation of current for meter 1 for three-phase and single-phase supply voltage and different load currents, firing angle 135°

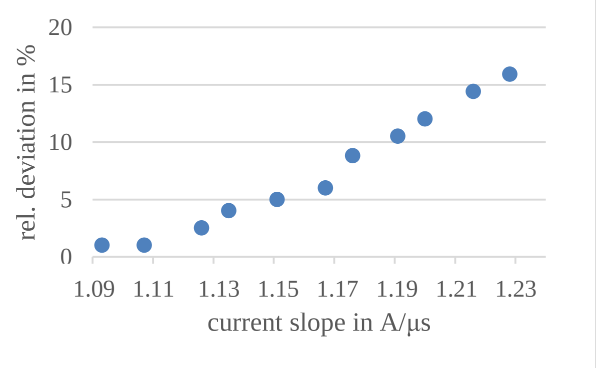


Figure 7: Deviation of current for different slopes of the current, firing angle 135°

Table 6: Slopes of the current and deviation of real power for three meters, firing angle 135°

Meter	**I_{rms} in A**	**I_{max} in A**	**di/dt in mA/µs**	**rel. dev. in %**
1	2.53	8.4	1151	5.1
2	2.8	9.3	1260	5.6
3	7.51	25	> 2500	< 1.5

Table 7: Deviation of real power for different meters and fixed di/dt

Meter	**I_{rms} in A**	**I_{max} in A**	**di/dt in mA/µs**	**rel. dev. in %**
1	3.02	10	1368	35.2
2	3.02	10	1368	17.1
3	3.02	10	1368	20.7

The critical slopes of the current for three different meters are summarized in Table 6. Meter 1 shows the highest interference to high di/dt so far, as it can be seen in Table 7, where the deviations of power for three meters for a fixed di/dt is shown.

CONCLUSION

The presented simulations allow understanding potential measurement deviations for metering devices based on Rogowski coils. It is a reproducible physical characteristic of this measurement type. It could be shown, that direct sampling of the Rogowski output voltage can lead to significant deviations, if certain current slopes appear.
The paper presents simple tools easy to adjust to real conditions that e.g. appear in low voltage networks such as presented in [5]. If the maximum occurring current slope which exists in the specific application is known, it would be possible to improve the test method according to DIN EN 50470-3 [2]: The test current slope should be with some margin bigger than the maximum occurring ones. Further on, the tests should not only be performed at the uncritical 90° firing angle but also at 45° and 135°. In this way, the Rogowski coil is specified not only by amplitude but also in maximum current slope.

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