Influences of Parasitic Capacitances in Wide Bandwidth Rogowski Coils for Commutation Current Measurement

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Keywords

≪Integrated Rogowski coils≫, ≪Current sensor≫, ≪Component for measurements≫, ≪Parasitic elements≫, ≪Noise≫

Abstract

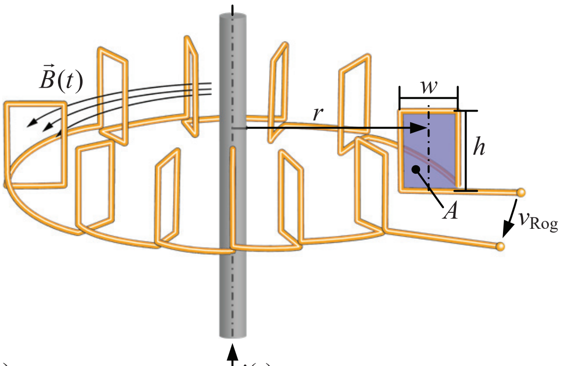
This paper focuses on the capacitive coupling of PCB integrated Rogowski coils for commutation current measurement. It investigates the cause and the influence of parasitic capacitances on the measurement signal. It discusses the advantages of a differential winding arrangement and the reasons why shielding is not an option in this application. The parasitic capacitance of three different winding arrangements are measured and compared to a Rogowski coil approach with minimized parasitic capacitance. On the base of sensor prototypes, the influence on the measurement is investigated in a pulsed current source.

Introduction

The use of wide bandgap (WBG) semiconductor devices made from silicon carbide (SiC) and gallium nitride (GaN) as semiconductor material is strongly increasing. Their ability to operate at higher switching frequencies, due to lower switching and conduction losses compared to silicon devices, is the key factor for high efficient and compact power electronic converter systems [1]. The switching speed of these devices is progressively increasing and an accurate measurement of the switching current becomes more challenging due to higher requirements. The bandwidth of current sensors for the characterization of WBG semiconductor devices needs to keep up with the steeper current transients. Due to progress in the packaging technology of power semiconductor devices, the parasitic inductance and capacitance of switching cells is decreasing [2]. For a commutation current sensor the smallest possible insertion impedance is desired for a non-invasive measurement. With higher possible integration levels and higher changing rates of the drain-source voltage during the switching transient (dV/dt) also the measurement environment becomes more challenging.
Measuring the voltage drop across a resistive shunt is the simplest way to measure a current. The sensing resistance is implemented in the current path and can provide a wide bandwidth measurement signal [3, 4]. For a precise measurement the resistance value needs to be known exactly and the parasitic inductance should be as low as possible. Otherwise the influence of the parasitic inductance needs to be compensated in a post processing step [4]. Besides these advantages, shunt based current sensing leads to additional losses and can not provide a galvanically isolated measurement signal, which is often required. For an isolated current measurement magnetic field sensors or a high frequency current transformer can be used. Magnetic fields sensors like Hall, fluxgate or tunneling magnetoresistance sensors

suffer from a limited bandwidth. High frequency current transformers suffer from their size and insertion inductance. An alternative option is a Rogowski coil. The concept of the Rogowski coil is more than 100 years old and has been the subject of research ever since [5]. The sensing technique offers many degrees of freedom, which can be utilized for the different kind of applications, for instance in current probes [6,7], compact current sensors [8] or fully integrated Rogowski coils in the PCB for commutation current measurement [9, 10]. The concept of a hybrid current sensor combines a Rogowski coil (high frequency current measurement) with magnetic field sensors (low frequency current measurement) to extend the bandwidth of the sensing techniques [11]. In this way galvanic isolated current sensors with a bandwidth from DC up to several hundred MHz can be realized. Such current sensors can be used for the control of power electronic circuits [12, 13], fully integrated in a chip [14] or as a commutation current sensor, which is integrated with a low inductive coaxial housing into the switching cell [15–18]. This paper focuses on the design of PCB integrated wide bandwidth Rogowski coils for commutation current measurement. It investigates the influence of parasitic coupling capacitances on the measurement system and why shielding is not an option in this application. Three state-of-the-art winding arrangements are compared in terms of their design parameters, bandwidth and the parasitic coupling capacitance to a coaxial housing. A new developed Rogwoski coil approach is presented, which aims for a minimized coupling capacitance in this kind of application. This minimized approach is compared to the state-of-the-art designs. The influence of the coupling capacitance is investigated in sensor prototypes in a pulsed current source.

Basic Principle of a Rogowski Coil



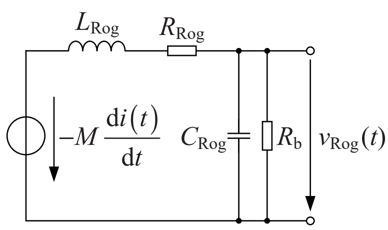


Fig. 1: Basic realization (a) and the equivalent circuit diagram (b) of a Rogowski coil

The principle of a Rogowski coil is based on Faraday's law of induction [3]. A change of the magnetic flux density $\vec{B}$ in a conductor loop induces a voltage v. Hence, a Rogowski coil uses a number of N conductor windings, which are arranged around the current carrying conductor, see Fig. 1 a). With the use of Ampère's law the relation between the derivative in the current $i(t)$ and the voltage at the Rogwoski coil terminals v_{Rog} is described by:

$$v_{\mathrm{Rog}}(t) = -N \cdot A \cdot \frac{\mathrm{d}|\vec{B}(t)|}{\mathrm{d}t} = -\frac{\mu_0 \cdot N \cdot A}{2\pi \cdot r} \frac{\mathrm{d}i(t)}{\mathrm{d}t} = -M\frac{\mathrm{d}i(t)}{\mathrm{d}t} \tag{1}$$

Besides the number of turns, the induced voltage is depending on the winding area A and the radius r between the center of the conductor and the winding. These parameters form the mutual inductance M of the Rogowski coil, which describes the sensitivity. In an equivalent circuit diagram, see Fig. 1 b), this behavior is modeled by means of a voltage source. In addition, the parasitic elements of a Rogowski coil, the self-inductance L_{Rog}, the parasitic interwinding capacitance C_{Rog} and the winding resistance R_{Rog} complete the model. The bandwidth of the Rogowski coil is defined by the resonance frequency f_{res}

resulting from L_{Rog} and C_{Rog}. This resonance pole can be damped with an additional burden resistance R_b. In the Laplace domain the damped Rogowski coil is described with the following transfer function [19, 20]:

$$\frac{v_{Rog}(s)}{i(s)} = \frac{-sMR_b}{s^2 L_{Rog} C_{Rog} R_b + s(L_{Rog} + C_{Rog} R_{Rog} R_b) + R_{Rog} + R_b} \tag{2}$$

The resonance frequency f_{res} is determined by (3) and defines the upper frequency limit of the bandwidth of the Rogowski coil.

$$f_{res} = \frac{1}{2\pi} \cdot \sqrt{\frac{R_{Rog} + R_b}{L_{Rog} C_{Rog} R_b}} \tag{3}$$

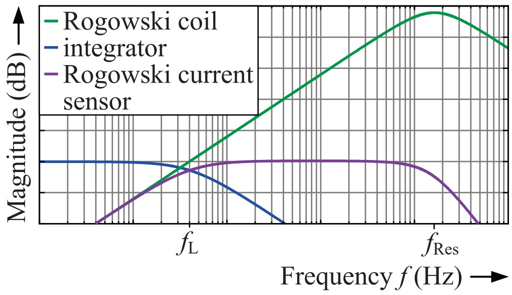


Fig. 2: Frequency response of a Rogowski coil current sensor

To reconstruct the temporal course of the current from the induced voltage, an integrator at the Rogowski coil terminals is required. The integrator can be either realized in a passive or an active way and acts as a low pass filter. This low pass filter defines the lower frequency limit f_L. The combination of the frequency response of the Rogowski coil (green) and the integrator (blue) results in the band-pass characteristic of the current sensor (purple), see Fig. 2.

Influence of the parasitic capacitances

There are two ways to integrate a Rogowski coil into the commutation path for current measurement. The direct way integrates the winding arrangement in the PCB of the switching cell [10]. For an indirect way, a measurement point for the Rogowski coil is added for example with a coaxial housing, replacing a through hole connection in the switching cell [21], see Fig. 3. In any case there will be a capacitive coupling of the current sensor and the switching cell. Especially the windings of the Rogowski coil represent a large area, which causes a parasitic coupling capacitance. Due to the high dV/dt during the switching transient, these parasitic capacitances have a strong impact on the measurement signal of a commutation current sensor. In Fig. 4 a) this effect is taken into account in the equivalent circuit diagram of a Rogowski coil. The switching potential is represented by an additional voltage source $v_{sp}(t)$ resulting in a current through the parasitic capacitances $C_{P,n}$. This current leads to an additional voltage $v_{CC}(t)$ at the terminals of the Rogowski coil caused by the capacitive coupling. This effect causes additional oscillations on the measurement signal, which result in a distortion. In that case the measurement signal of a current transient during the characterization of a device can be flatter or even steeper then the actual current. The parasitic capacitance is therefore a major source for measurement errors. Unfortunately, shielding the Rogowski coil is not an option for a commutation current sensor, because of the required bandwidth [22]. Additional shielding layers significantly increase the interwinding capacitance and decrease the bandwidth of the Rogowski coil. Other

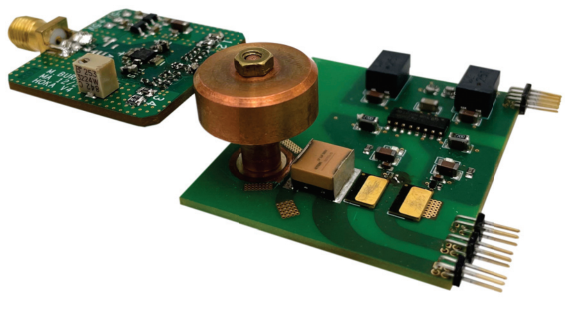


Fig. 3: Current sensor integration with a coaxial housing into the commutation path

ways must be found to reduce the influence of the parasitic capacitance of the Rogowski coil in this application. One common optimization approach is to realize a fully differential Rogowski coil by splitting

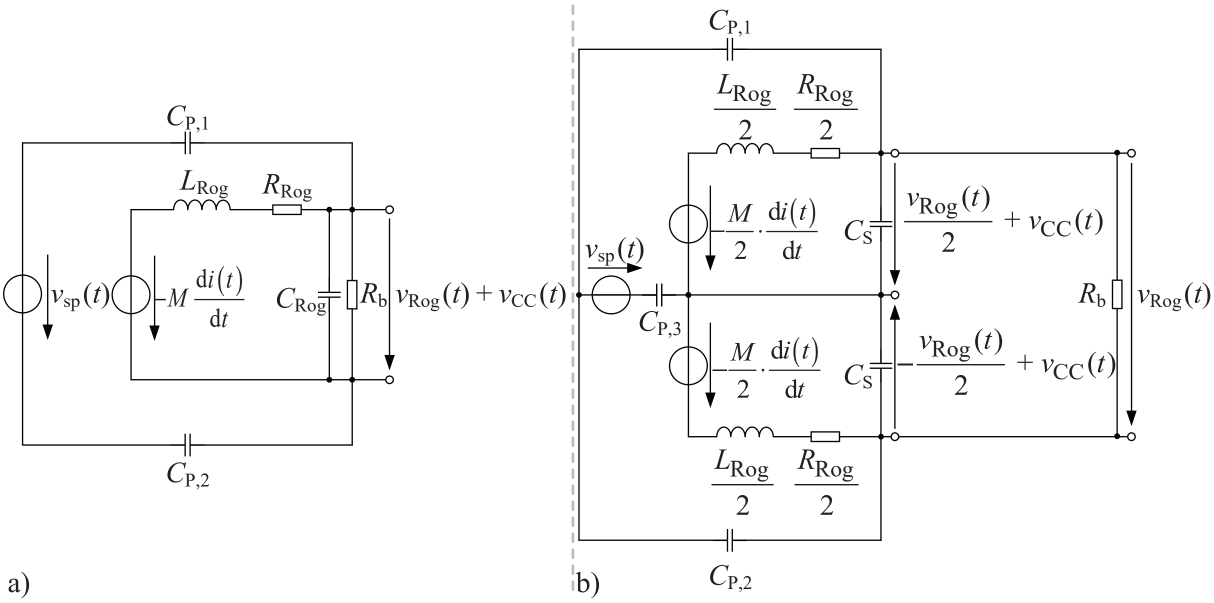


Fig. 4: Influence of capacitive coupling on (a) a single winding and (b) a differential winding

up the winding in two coils with different winding directions and a common ground. This also splits up the coupling path and the resulting additional voltage $v_{CC}(t)$, see Fig. 4 b). In an ideal symmetrical realization this leads to a cancellation of the additional voltage at the output terminals due to the opposite winding directions [22]. Due to technical and manufacturing reasons an ideal differential coil can not be realized and there will still be an influence of the capacitive coupling. The coupling capacitances form a resonance circuit with the self-inductance of the Rogowski coil. This resonance circuit leads to an oscillation and additional noise on the measurement signal in the switching transition. For this reason different winding arrangements are investigated and compared.

Comparison of different winding arrangements

In this work three state-of-the-art winding arrangements (sawtooth, zickzack and double winding [9]) are investigated and compared to a new approach, which aims to minimize the parasitic capacitances. To investigate the influence of shielding, the sawtooth structure is also modified with a shielding layer on the top and bottom layer, which also acts as return conductor. To make the shielding possible, the winding structure has to be realized in the two inner layers of the PCB. The realization of the winding arrangements of the state-of-the-art Rogowski coils are depicted in Fig. 5. The minimized concept is

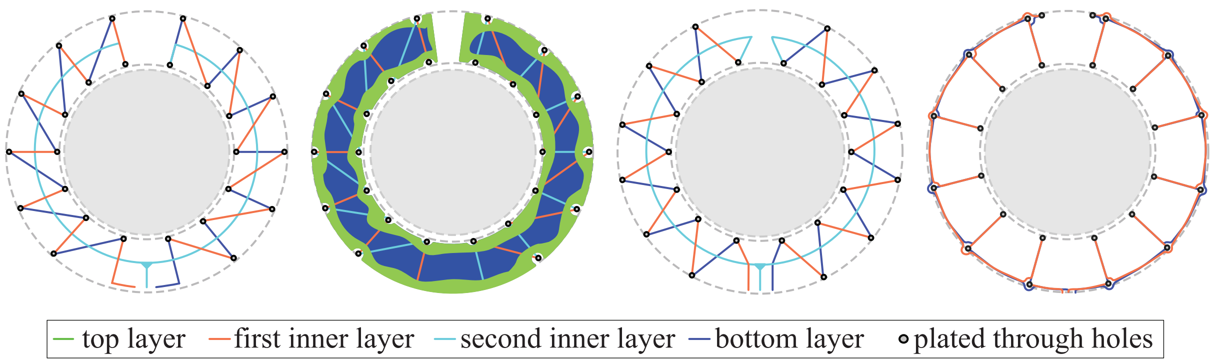


Fig. 5: Winding arrangements: sawtooth, shielded sawtooth, zickzack, double winding

designed for a fixed setup in a coaxial housing, whereby the number of turns can be reduced due to the fixed placement. To achieve the same mutual inductance and sensitivity, as the other approaches, the height of the windings is increased and adjusted to the usable height of the coaxial housing. This approach allows a reduction of the parasitic elements C_P, C_{Rog} and L_{Rog} by reducing the number of turns and the overall trace length to a minimum. This reduces the effect of the parasitic coupling and increases the resonance frequency and therefore the bandwidth of the Rogowski coil. The realization of the minimized approach is depicted in Fig. 6. Each winding is manufactured on a separate PCB with

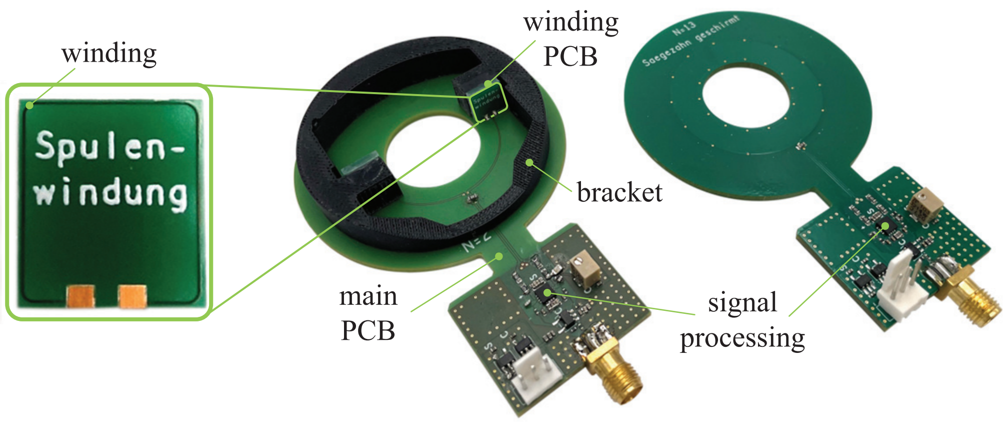


Fig. 6: Realization of the minimized approach (left) and one of the state-of-the-art sensors (right)

minimal trace widths. The two winding PCBs are soldered to a main PCB, which carries the signal processing. In order to guarantee a 90 degree angle between the winding PCB and the main PCB and to give the structure more stability, the windings are additionally fixed by a bracket. This approach is compared with state-of-the-art winding arrangements, all manufactured in a four layer PCB. In Tab. I the parameters of the different Rogowski coils are presented. In the following sections the design aspects of the approaches are discussed as well as the measurement method.

Table I: Parameters of the Rogowski coils

	Sawtooth	Sawtooth (shielded)	Zickzack	Double winding	Minimized approach
Number of turns N	13	13	13	12	2
Inner radius r_i (mm)	11	11	11	11	11
Outer radius r_o (mm)	16.5	17.5	16.5	17.1	17.5
Height h (mm)	1.4	1.2	1.4	1.4	8.1
Trace length l (mm)	261	199	248	343	172
Disturbance area A_d (mm²)	54.7	-	33.4	1.2	3.2
Self-inductance L_{Rog} (nH)	108.8	62.2	99.7	131.1	57.2
Interwinding capacitance C_{Rog} (pF)	1.61	5.31	1.66	1.72	1.17
Coupling capacitance C_P (pF)	40.5	307.6	40.4	55.1	3.5
Resonance frequency f_{res} (MHz)	380.4	276.1	391.8	335.6	610

Dimensions

An attempt is made to set the parameters of the Rogowski coils as equal as possible for the comparison, but due to the winding structure of the double winding a turns number of $N = 13$ is not possible. Therefore, the turns number is reduced to $N = 12$ and the outer radius r_o is slightly increased to achieve the same mutual inductance. To realize the shielding of the sawtooth winding the top and bottom layer is used. Therefore, the Rogwoski coil is routed in the two inner layers. To compensate the decreased height, the outer radius r_o is slightly increased. All Rogowski coils are designed in a fully differential way with the focus on the design to be as symmetrical as possible and a mutual inductance of $M = 1.45\,\mathrm{nH}$. The double winding concept focuses on the reduction of the disturbance area A_d. Therefore, the conductors are placed above each other resulting in the longest trace length l. The minimized approach also significantly reduces the disturbance area compared to the sawtooth and zickzack winding. This approach also offers the shortest trace length, which also leads to the smallest parasitic elements and the highest resonance frequency f_{res}.

Mutual inductance

The mutual inductance M of the different designs is also determined to evaluate the design parameters as well as manufacturing tolerances. For this purpose, the induced voltage v_{Rog} at the terminals of the Rogwoski coil is measured during a rising edge of a current pulse. With the value of the derivative of the current over time the mutual inductance is calculated with (4) .

$$M = \left| \frac{v_{Rog}}{\frac{\mathrm{d}i}{\mathrm{d}t}} \right| \tag{4}$$

The results are listed in Tab. II. The resulting values are in the range of the desired mutual inductance of $M = 1.45\,\mathrm{nH}$. In addition to manufacturing tolerances, the deviation can be caused by measurement inaccuracies in the voltage measurement as well as the determination of the current derivation.

Table II: Measured mutual inductance M

	Sawtooth	Sawtooth (shielded)	Zickzack	Double winding	Minimized approach
Mutual inductance M (nH)	1.6	1.39	1.6	1.65	1.54
Deviation (%)	9.6	4.1	9.6	13.8	6.3

Frequency response

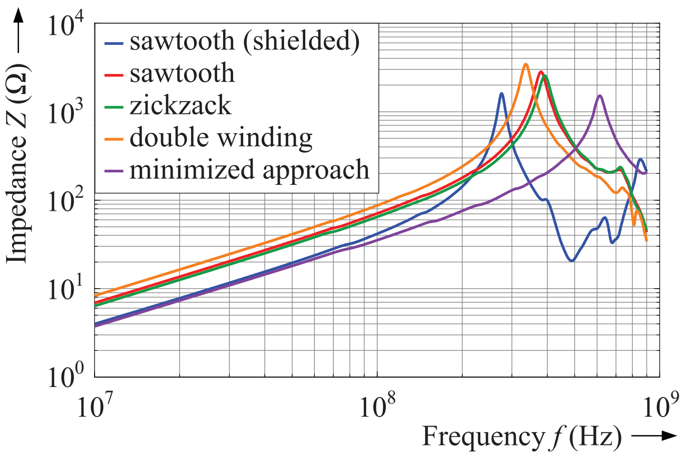


Fig. 7: Measured frequency response of the Rogowski coil designs

With a network analyzer (Keysight Technologies E5061B) the frequency response of the different winding arrangements is measured and depicted in Fig. 7. It is seen that the minimized approach leads to the highest resonance frequency f_{res}. The sawtooth and zickzack structures lead to almost the same course due to only slight differences in the winding arrangement and trace length. In the double winding the trace length is increased compared to the other state-of-the-art structures, causing the lowest resonance frequency. Only the shielded version of the sawtooth structure leads to an even lower resonance frequency. The self-inductance L_{Rog} is determined with the use of the gradient of the impedance course during the linear section below 100 MHz. With the knowledge of the self-inductance and the resonance frequency the interwinding capacitance C_{Rog} is calculated. Two main aspects of the winding arrangements can be identified. First, with increasing trace length also the self-inductance increases. The second aspect is that the interwinding capacitance is in the same range in all structures except in the shielded structure. The shield leads to a significant increase of the interwinding capacitance and therefore, to a decrease of the resonance frequency. Depending on the desired bandwidth of the Rogowski coil a shielding layer on the top and bottom layer is therefore acceptable or not. For commutation current measurement a bandwidth as high as possible is desired and prevents the use of a shielding.

Disturbance area

The principle of the Rogowski coil is based on the induced voltage caused by a change of the magnetic flux density $\vec{B}$ going through the winding structure. Not only the current in the center conductor, which is intended to be measured, causes a changing flux density. Also external sources, like nearby conducters, can induce a voltage with a changing flux density $\vec{B}_\mathrm{d}$ through the disturbance area A_d of the winding structure. For the sawthooth winding and double winding this area is depicted in Fig. 8. There are

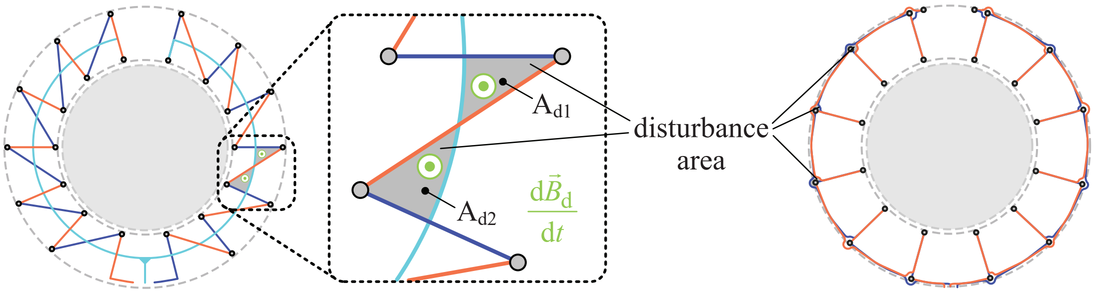


Fig. 8: Measured frequency response of the Rogowski coil designs

two options to reduce the influence of the disturbance area. The double winding concept focuses on a minimization of the area [9]. Due to the overlapping traces only a very small area around through hole connections is left. A second option is to design the disturbance area in a way, which leads to an cancellation due to a superposition. In the example in Fig. 8, the areas A_d1 and A_d2 lead to opposite signs of the induced voltage. A design with the focus on the same area can reduce the effect. In this work same areas are not realized in the state-of-the-art winding. But the effect of the superposition is considered in the values of the disturbance area stated in Tab. I. An optimization to realize the same areas could be the change of the return conductor in the second inner layer from a circular form to a polygon with its corners under the conductors on the top and bottom side. The radius of this polygon needs to be adjusted in a way that the resulting areas are identical. In the minimized approach the disturbance area is also small due to connection lines routed close to each other. In the shielded version of the sawtooth structure, the shield prevents a disturbance area.

Coupling capacitance

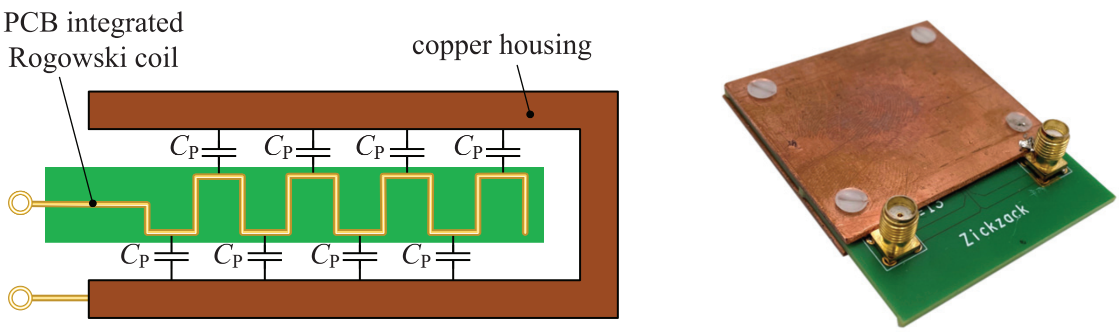


Fig. 9: Measured frequency response of the Rogowski coil designs

For the measurement of the coupling capacitance C_P each Rogowski coil is placed in a copper housing, see Fig. 9. With a network analyzer (Omicron Lab Bode 100) the capacitance is measured between the winding and the copper housing using a high impedance measurement setup. The values in Tab. I show that the coupling capacitance of the minimized approach is significantly reduced compared to the state-of-the-art winding arrangements.

Measurement results

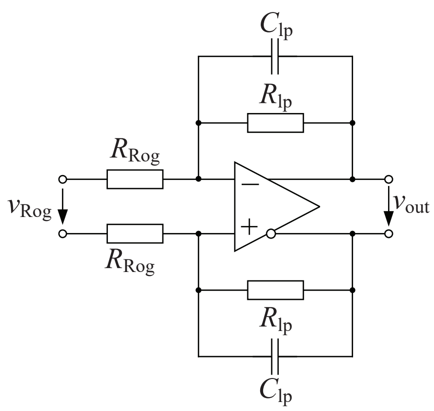


Fig. 10: Realization of the signal processing

For every winding arrangement a prototype of a current sensor is built and characterized. Due to the highest bandwidth and the similar parasitic capacitance of all state-of-the-art prototypes, the zickzack winding is used as reference to the minimized approach. The signal processing in all prototypes is designed in the same way. It consist of an active low pass filter realized with one fully differential operational amplifier (Texas Instruments THS4513) in the configuration depicted in Fig. 10 [18]. The signal level of v_{out} then is increased with a second amplifier (Analog Devices AD8009) resulting in the sensor signal v_{Sen}. The measurement range of all sensors is set to $I_{max} = \pm 110A$ with a sensitivity of 18 $\frac{mV}{A}$. The sensors are tested in a pulsed current source with current transients similar to the occurring commutation current of fast switching semiconductor devices [23]. The current sensors are placed in a coaxial chamber, which carries the current. The advantage of this chamber is the low inductance, which allows steep rise and fall times. For the prototypes of the zickzack winding and the minimized approach, the measurement results of a current edge are depicted in Fig. 11 a). A high frequency current transformer (Bergoz Instrumentation, CT-B1.0-S) with a bandwidth from 200 Hz up to 500 MHz is used as a reference. The measured current courses of both sensors are compared to the course of the Bergoz current transformer. The occurring deviation is related to the measurement range of $I_{max} = \pm 110A$. The deviation of both sensors is less then $\pm 1\%$.

To investigate the influence of the coupling capacitances, the sensor signal is measured with the voltage supply of the signal processing turned off. In this case the sensor signal represents the voltage across the burden resistance, which is damped by the resistors of the signal processing, forming a voltage divider with the 50Ω input impedance of the oscilloscope. The measured sensor signals for the zickzack winding arrangement $v_{Sen,zz}$ and the minimized approach $v_{Sen,ma}$ are depicted in Fig. 11 b). To put the sensor courses into context, the current course i of the pulsed current source is depicted as well. The course of the minimized approach almost follows an ideal trapezoidal course during the current rising and falling edge. Only a small oscillation is superimposed. In contrast, the course of the zickzack winding arrangement shows almost double the amplitude in the current transients, which occurs due to an oscillation of the resonance circuit formed by the coupling capacitance and the self-inductance. Due to the higher values of the parasitic elements in the zickzack winding, the oscillation is larger compared to the minimized approach and decays more slowly. This oscillation also leads to more noise in the sensor signal and measurement deviation.

Conclusion

The ongoing development of wide bandgap semiconductor devices leads to shorter switching times. This increases the requirements for the commutation current measurement in terms of bandwidth and immunity against high dV/dt. In this paper the influence of a parasitic coupling capacitance between the winding of the Rogowski coil and a coaxial housing is investigated. Three state-of-the-art winding arrangements and a shielded version are compared to a new minimized approach in terms of their bandwidth, the parasitic elements and an occurring disturbance area. The new minimized approach is designed for a fixed setup in a commutation current sensor and focuses on a reduction of the coupling capacitance. In addition this approach leads to an increased bandwidth. With the investigated winding arrangements, current sensors are realized and tested in a pulsed current source. It is seen that the coupling capacitance is forming a resonance circuit with the self-inductance leading to measurement deviation.

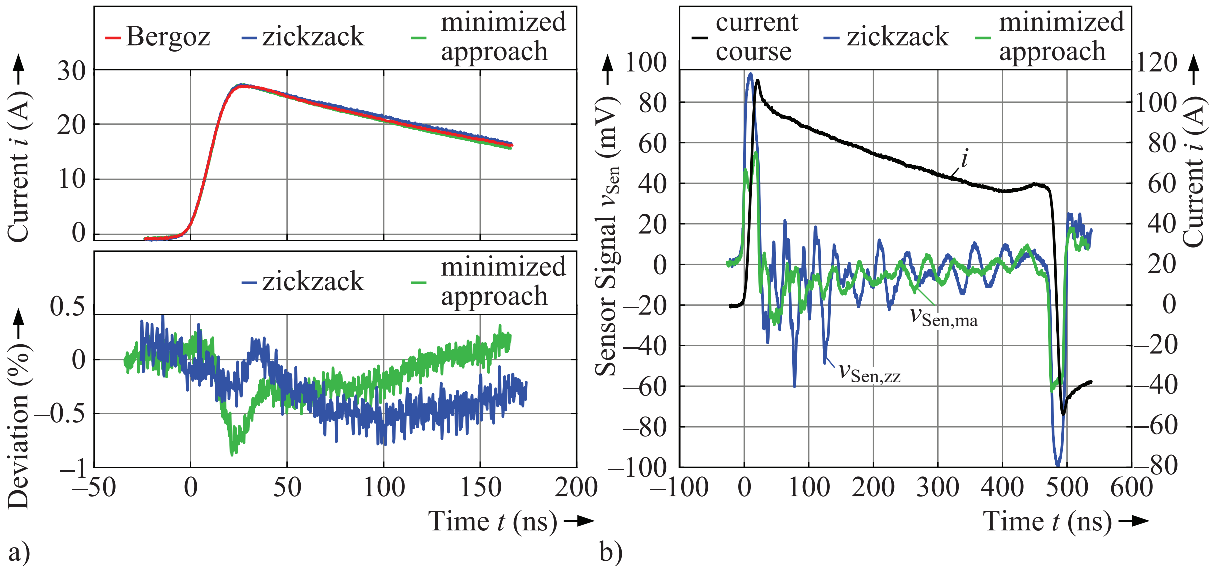


Fig. 11: Measured current rise and the occuring deviation (a); Sensor signal with turned off voltage supply (b)

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