A new current measuring principle for power electronic applications

Nicolas Karrer[1] Patrick Hofer-Noser[2]
Electrical Engineering and Design Lab (EEK)
Swiss Federal Institute of Technology, Zürich
Gloriastr. 35/ETZ, CH-8092 Zürich, Switzerland

***Abstract*— A new isolated current measurement principle named HOKA is presented. A current probe based on this principle has been realized. It was designed for a current rating of 200 A. The probe incorporates two different sensors: a Hall sensor and an air coil. DC currents of 200 A as well as transients with a di/dt of 2.5 kA/μs have been measured with a relative error of 5%.**

I. Introduction

Current probes for power electronic applications like the current monitoring of paralleled IGBTs [1] should be able to measure DC currents as well as transients ranging up to some kA/μs. Other aspects like the small size, the unsaturability, the DC-insulation and costs should be considered as well. Most current probes for DC currents have an upper band limit in the range of some hundred kHz while probes for fast transients have a lower band limit of some tens Hz. So far only shunt resistors and fiber optical sensors based on the Faraday-effect [2] are able to measure currents from DC to hundreds of MHz. The former is a DC-coupled sensor, the latter needs a consuming opto-electrical evaluation electronic.

II. The new principle

An overview of the new current probe is displayed in Fig. 1. The current measuring principle is indicated in Fig. 2 from which the transfer function (TF) $H_{ideal}(s)$ (1) can be obtained. This new principle states that it is possible to realize a probe with an unlimited bandwidth to measure a certain quantity, e.g. current, position, velocity, etc.. However, this principle applies only if the quantity can be measured with two sensors having each a different TF. One sensor must deliver a signal which is proportional to the measured quantity, the other sensor must deliver a signal which is proportional to the time derivative of the measured quantity.

These kind of sensors, such as Hall sensors for the former type and Rogowski coils for the latter type are available for current measurement.

Before analysing this principle more in detail, these two sensors are described.

$$H_{ideal}(s) = \frac{V_I}{I} = sM\left[\frac{K_s T_H}{M(sT_H+1)}\right] + \frac{K_H}{sT_H+1}\left[\frac{K_s}{K_H}\right] = K_s \quad (1)$$

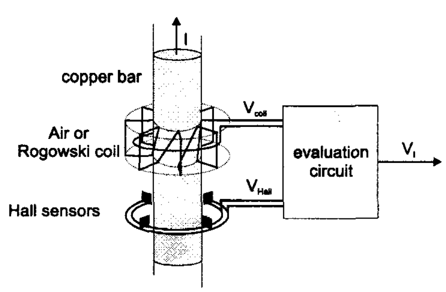

Fig. 1. Overview of novel current probe

III. Rogowski coil

Transformers and their magnetical coupling are known since more than a hundred years. The well established Rogowski coil, mainly used for isolated current measurements, is a little more than a hundred years old.

Chattock, its inventor [3], constructed in 1887 his helix by winding a wire around a solid indiarubber, leaving a small space between the turns to allow the indiarubber to bend. In 1912 also Rogowski and Steinhaus [4] wound a wire compactly around a strawboard band. All used their device to measure the magnetomotive force (mmf) between two points.

Heumann [5] described a coil which is wound on ceramic tubes. He used his device for precision current measurements and called it a mmf measuring device. The error of his device is about 0.5%.

These authors emphasize that the turns per unit length must be constant as well as the cross section of the material where the wire is wound around. For a helix built this way, the reading of the mmf is always the same no matter how the band is bent as long as the two ends of it are kept in the same position.

When the wire is wound forming a helix, the return wire can be wound also as helix backwards or can return in the center of the helix. In both ways a substantial reduction of perturbation voltages induced by stray fields is obtained because the induction surface is drastically reduced. This wire return is the main difference between a current measuring coil and a normal coil. A *Rogowski coil* is a helix wound around a torus so that the wire ends are joined. The torus must be made of nonsaturable material.

Today Rogowski coils are mainly used for current measurements, e.g. the mmf of a closed path. The main problems when employing only a Rogowski coil for current measurement is the need to integrate its output signal and the inability to measure a DC current. The new principle does not require the integration of the coil's signal, which is a topic often mentioned [5], [6], [7], and the DC current is measured by the second sensor of the HOKA probe.

Sometimes the question arises about the difference between a current transformer and a Rogowski coil since both are based on the magnetic coupling. The former delivers a signal which

[1] e-mail:karrer@eek.ee.ethz.ch
[2] Now with Atlantis Solar Systems

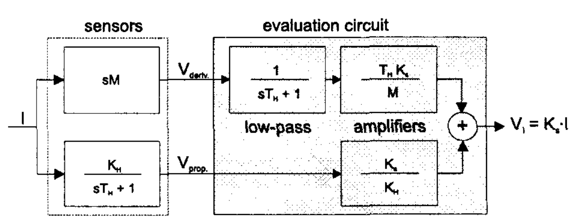

Fig. 2. Ideal HOKA current measuring principle

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is proportional to the current while the latter delivers a signal which is proportional to the time derivative of the current. This question can be answered with the transformer model Fig. 9 from which the TF (2) can be obtained.

$$\frac{V_c}{I_1} = \frac{sM}{s\frac{L_c}{R_d} + 1} \tag{2}$$

On the values of M and L_c/R_d can be decided if the coil's output signal is proportional to the current I_1 or to the time derivative of the current I_1.

Above the corner frequency of the low-pass $\omega_{cf} = R_d/L_c$ the output voltage is proportional to the current and the TF is $(MR_d)/L_c$. Below ω_{cf} the output voltage is proportional to the time derivative of the current and the TF becomes sM. These can be seen when drawing the Bode plot of (2).

In the following the coil we developed for our probe is described.

A. Air coil

The output signal of a Rogowski coil does not depend on the curvature of the helix. This is accomplished by tight winding. The disadvantage is that the interwinding capacitance is high and therefore the coil's resonance frequency is low. Since di/dt of kA/μs should be measured, a coil with a resonance frequency of some tens of MHz is required.

Coils with resonance frequencies up to 180 MHz have been built. Such a coil is basically designed like a Rogowski coil. The main difference is that it has few windings far apart from each other. The induced voltage becomes position dependent and the coil must be fixed with respect to the current bar. This is the reason why we called this an air coil.

The coil is realized on a multilayer printed circuit board (PCB). A winding is formed through a strip on both sides of the PCB and the respective via. The return wire is realized on an inner layer. In Fig. 3 some windings of the coils are shown. In the middle the current bar is visible (black thick line) and around the bar the magnetic field H is visualized (grey thick curve). The induced voltage can be expressed by $v_{emf} = Mdi/dt$. The mutual inductance M is computed using (3) with the parameters r and b of Fig. 3 and the number of turns N. The relative error of this formula is about 10%. The mutual inductances of the realized coils are around 10 nH.

$$M = \frac{Nb\mu_0}{2\pi} log(\frac{r_c + r_a}{r_c + r_i}) \tag{3}$$

B. Model, simulation and measurement

The impedance (4) as well as the current to voltage transfer function (5) of the coil can be derived from the coil model Fig. 4. This coil model works well till a little over the resonance frequency of the coil. The resonance frequency of this coil is $f_r = 53.2$ MHz as shown in Fig. 5. The coil's capacitance C_c and its inductance L_c are extracted from the measured frequency response Fig. 5 (thin line with '+') while the resistance R_c is measured: $L_c = 1.05$ μH, $C_c = 8.52$ pF, $R_c = 2.7$ Ω. The thick line in Fig. 5 corresponds to (4) with the above values.

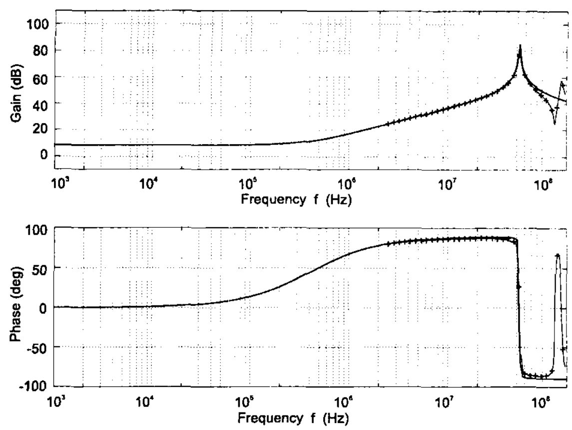

Fig. 5. Measurement and simulation of $Z(s)$

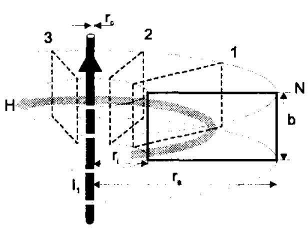

Fig. 3. Coil geometry

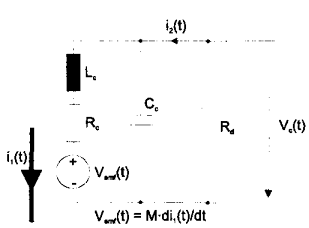

Fig. 4. Model of air coil

$$Z(s) = \frac{V_c}{I_2} = \frac{sL_c + R_c}{s^2 C_c L_c + sC_c R_c + 1} \tag{4}$$

Considering Fig. 4 the voltage to current TF (2) is replaced by (5) which is a more accurate model for an air coil.

$$H_{real}(s) = \frac{V_{emf}}{I_1} = \frac{sM}{s^2 L_c C_c + s(\frac{L_c}{R_d} + R_c C_c) + (\frac{R_c}{R_d} + 1)} \tag{5}$$

IV. Hall sensor

Hall sensors generate a voltage which is proportional to a magnetic field. The cutoff frequency of a Hall sensor can be between some kHz and some MHz. The main disadvantages of Hall sensors are the temperature stability and the offset voltage. New devices like the spinning current or the double-Hall sensor should help to overcome these weaknesses. Hall sensors are often used in current compensated probes where these effects can be reduced.

A. Model

Hall sensors can be approximated by a low-pass term (6).

$$U_H(s) = B(s)\frac{K_H^*}{sT_H + 1} = I_1(s)\frac{K_H}{sT_H + 1} \tag{6}$$

We have chosen the KSY 44[1]. We have been assured by the manufacturer that we can assume a cutoff frequency of 1 MHz. The TF as well as the cutoff frequency have not yet been verified since the experimental results of the probe show a good performance.

V. Hoka current probe

In the following section the new principle is implemented in a new current probe. Through simulation and measurement the advantages of this principle are demonstrated.

[1] Siemens

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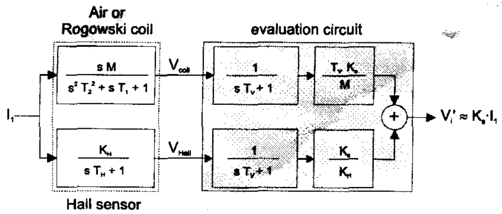

Fig. 6. Realistic HOKA current measuring principle

A. Model and simulations

With the above models of the sensors a block diagram of the current probe can be realized as shown in Fig. 6. This model describes the real probe more accurately than the one of Fig. 2.

The resonant characteristic of the coil as well as the low-pass characteristic of the amplifiers have been introduced. The cutoff frequency of the low-pass is 10 kHz. It must be lower than the one of the Hall sensor. In this more realistic case, the TF of the probe is approximately K_s until about 20 MHz due to the resonance frequency of the coil as shown in Fig. 7.

It is very important for the feasibility of the amplifier's gain to consider the probe's sensitivity K_s. In the simulation the following output ratio is used: 1 kA = 1 V.

The response of the probe model Fig. 6 to a current of 1 kA and di/dt of 1 kA/μs and 5 kA/μs is shown in the upper picture of Fig. 8. The waveform of the current was chosen to look like a switching cycle of a power switch with tail current. The current signal, the coil path signal and the Hall path signal at the summing point are displayed as well as the output signal of the probe. At this scale no error can be seen between the scaled current signal and the probe's output signal.

The absolute error between the input signal of the probe and its output is shown in the lower picture of Fig. 8. For this plot the output of the probe was backscaled to ampere.

B. Insertion impedance

The insertion impedance of a current probe as well as its dimension should be small. From Fig. 9 and the transformer equation (7) an aproximation for the insertion impedance can be computed (8). The term $R_1 + sL_1$ describes the additional copper bar length (about 10 mm) needed when the probe is inserted. The third term can generally be neglected for coils

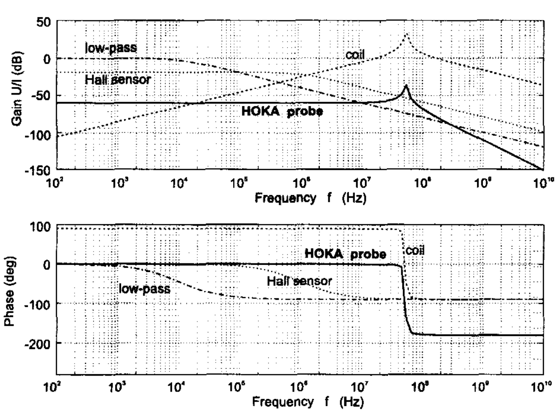

Fig. 7. Transfer function of the probe

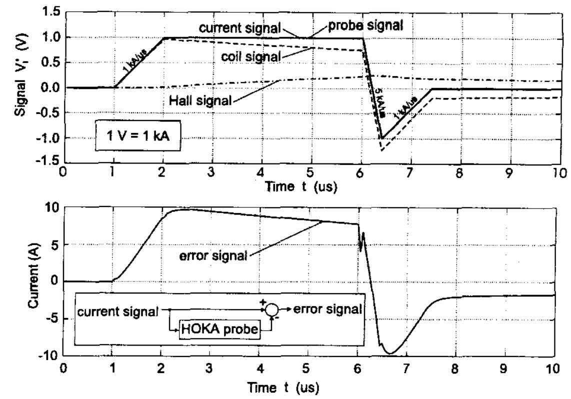

Fig. 8. Measurement simulation

realized as described.

$$
\begin{aligned}
v_1 &= R_1 i_1 + L_1 \frac{\mathrm{d}i_1}{\mathrm{d}t} + M \frac{\mathrm{d}i_2}{\mathrm{d}t} \\
v_c = v_2 &= R_d i_2 + M \frac{\mathrm{d}i_1}{\mathrm{d}t} + L_c \frac{\mathrm{d}i_2}{\mathrm{d}t} \qquad (7) \\
Z_{insertion}(s) &= R_1 + sL_1 - \frac{s^2 M^2}{sL_c + R_d} \qquad (8)
\end{aligned}
$$

C. Prototype

To verify this principle a prototype probe as in Fig. 10 has been built. The coil is realized on a multilayer PCB because of its return wire in the middle of the windings. The rest of the evaluation circuit is realized on the same board. To remain compact, surface mounted devices (SMD) were used. Since no core is used to increase the magnetic field for the Hall sensor, special care must be taken for its placement. When eight or more Hall sensors are placed around a copper bar, as suggested in Fig. 1, even without a core material a measurement error of less than 1% can be achieved in an environment contaminated by stray magnetic fields. Since no ferromagnetic material is used for the probe, no material saturation effect can occur. The output signal of the Hall sensor KSY 44 is proportional to the magnetic flux density as long as B is smaller than 1 T. Should the magnetic flux density generated by the current exceed this value, then the Hall sensors must be placed further away from the bar. Here again stray fields must be considered. Overload or surge currents can neither destroy the Hall sensor nor the air coil, but special care must be taken to protect the electronic circuit in case of high di/dt. In the case of a di/dt of 5 kA/μs and a coil with a mutual inductance of 10 nH the induced voltage is 50 V.

The probe was placed in an aluminum cage to shield it from stray electric fields.

The probe has been tested in two different setups and compared with different current probes. As reference for the com-

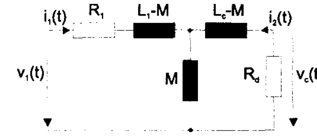

Fig. 9. Model of transformer

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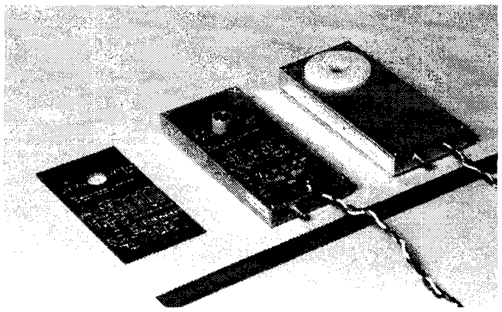

Fig. 10. Current probe prototype

putation of the relative error the output signal of a specific probe was chosen.

D. Measurements

Two different current measurement setups have been used. One is able to generate a pulse while discharging a capacitor array. Therefore there is a decrease in current for long pulses as can be seen in Fig. 11. The second setup allows to generate double pulses with di/dt of several $\mathrm{kA}/\mu\mathrm{s}$.

In Fig. 11 the low frequency performance is demonstrated comparing the HOKA output with three well established current probes: Pearson 410 [2], ILA SMZ 200 [3] and PEM CWT 15 [4]. With a pulse of 5 ms the core of the Pearson 410 saturates while the ILA and the PEM have about the same output behaviour. The output of the ILA current probe was chosen as reference. The relative error is computed referring to 200 A which is the nominal DC current of this probe. Except for the spike, which is caused by the sampling interval, the relative error is about +/- 5%.

In Fig. 12 the high frequency performance is demonstrated comparing the HOKA output with a LEM 25/10 [5] coaxial shunt resistor and the PEM CWT 15. The shunt signal has been chosen as current reference because of the oscillations of the PEM probe. As before, the relative error is about +/- 5%.

These comparisons between the HOKA current probe and the traditional probes clearly show the feasibility of this new

[2] Pearson Electronics, Inc., Palo Alto, CA, USA

[3] ILA, University Stuttgart, D

[4] PEM, Nottingham, UK

[5] LEM SA, Geneva, CH

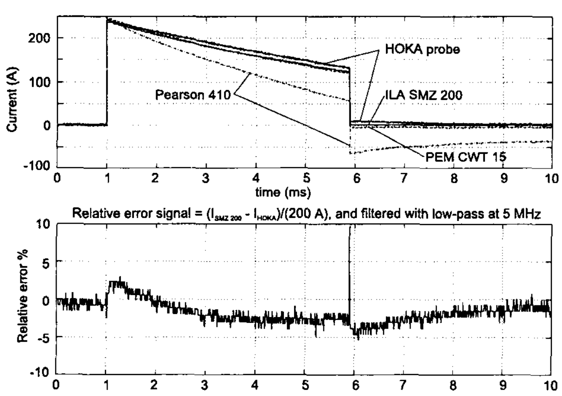

Fig. 11. Current probe comparison, long pulse

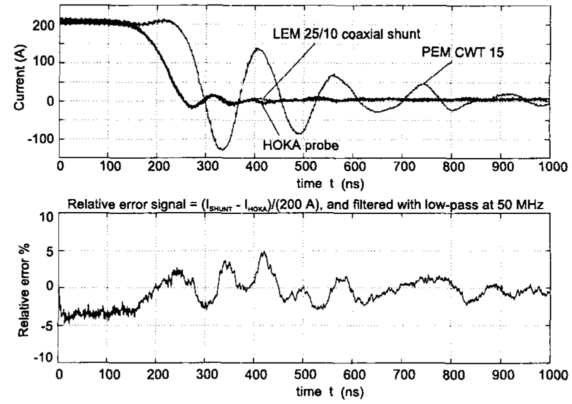

Fig. 12. Current probe comparison, trailing edge, 2.5 $\mathrm{kA}/\mu\mathrm{s}$

current measuring principle.

VI. Conclusions

A current probe has been developed based on the new current measuring principle HOKA. Practical measurements have shown the feasibility of this approach with currents of 200 A and di/dt of 2.5 $\mathrm{kA}/\mu\mathrm{s}$. With this probe DC as well as AC currents can be measured. There is no deterioration of the signal due to a saturated core. Over currents or surge currents do not alter the probe's behaviour if the necessary precautions are taken to protect the evaluation circuit against high voltage from the air coil. The probe can be assembled in SMD. A further reduction in size can be achieved when the evaluation circuit is included in an IC. The insertion impedance is very small and the required additional copper bar length can be less than 10 mm. For general purpose e.g. where the interference fields are not exactly known, shielding can be necessary increasing the probe's size.

New power devices like IGBTs are able to switch currents of 1500 A at voltages of 4500 V. Such a device must be turned on and off quickly to keep the switching losses as small as possible. The stray inductance in the high current loop must be minimized and therefore the space available for a current probe is limited. We are convinced that the HOKA probe which is small in size and measures DC as well as fast switching transients will be successful in this and in other applications. Further research is being performed to improve the probe's overall performance.

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