Low-Cost Current Sensor for Power Capacitors Based on a PCB Rogowski-Coil

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Abstract

The paper presents a low-cost current sensor for power capacitors in power electronic converters, especially for DC link electrolytic capacitors of PWM converters. The sensor is based on a Rogowski-coil which is implemented very cost-effectively using a small standard printed circuit board (PCB) located directly at the capacitor terminals. Due to the measuring principle the output signal inherently is isolated from the power capacitor circuit. The required signal integration (being typical for Rogowski transducers) is performed by frequency separation (passive/active integration) using a low-cost operational amplifier located directly on the PCB. The presented unit aims to life-cycle monitoring systems of electrolytic capacitors and allows the implementation of such systems without modifying the original bus-bar wiring of the capacitor.

1. Introduction

Power electronic converters more and more are used in applications where high reliability is of vital importance. As an example converters for energy generation like photovoltaic inverters or for windmill applications shall be mentioned. In the vast majority today DC voltage link PWM converters based on IGBTs are used where the DC link is formed by electrolytic capacitors. Due to their electro-chemical operating principle these capacitors, however, show a pronounced ageing which in the worst case may lead to sporadic component failure. To avoid such converter breakdowns (which may cause high follow-up costs), life-status monitoring systems for electrolytic capacitors have been reported. Such systems usually evaluate the ESR value of the capacitor which serves as an excellent ageing status indicator if the actual capacitor temperature is considered. The calculation of the ESR commonly is based on voltage/current measurements taken from the capacitor (Fig.1). In, e.g., [1, 2] an ESR monitoring unit is described where the current is sensed by a simple ohmic shunt R_{SH}. The drawback of this method is that (besides the fact that the sensing signal does not show galvanic isolation) the insertion of the shunt “disturbs” the power wiring of the converter which may cause problems in case of over currents or emergency shutdown. This especially is true if the monitoring unit is implemented as a

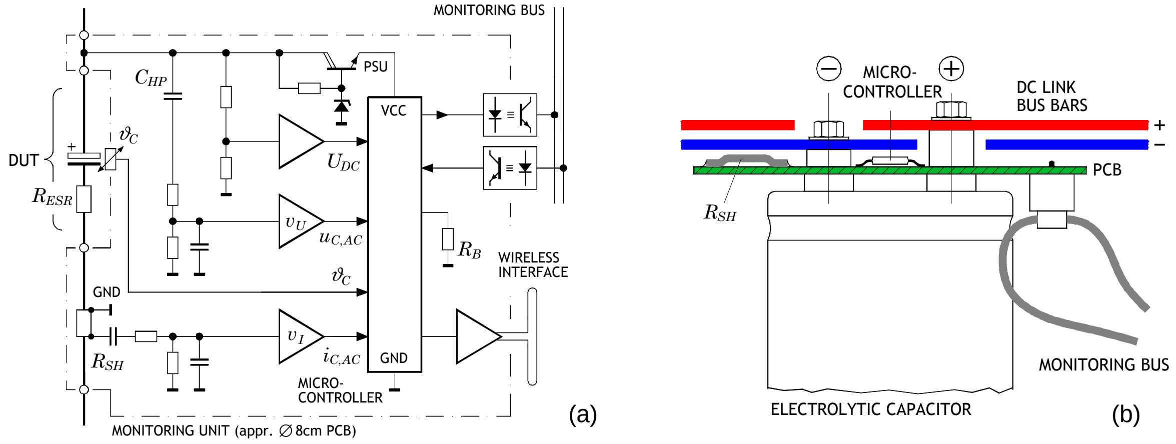


Fig.1: (a) Structure diagram of a monitoring unit for electrolytic power capacitors (DUT) according to [2]. (b) The unit is designed as a single PCB inserted between the capacitors power terminals and the converter bus bars.

PCB located between the capacitors power terminal pins and conducting distance sleeves connecting the converter bus bars as shown in Fig.1b. With this, the capacitor current is guided for a short distance via PCB traces resulting in the danger that the traces are destroyed in case of a heavy overcurrent condition. An alternative to (PCB-) shunts would be the application of standard current transformers, e.g., a flat ferrite toroid core (carrying a secondary winding feeding a burden resistor) applied to one of the capacitor terminal pins. This, however, shows the drawback of increased parasitic inductance of the converter's commutation path and shall not be treated further here.

2. Rogowski Coil Current Transducer

To overcome the problems of the shunt- or current-transformer-methods described before, a capacitor current sensor based on the Rogowski-principle is proposed. Rogowski current transducers are well known since many years but in general are used mainly for laboratory measurements hence they are rather expensive if a proper sensitivity is required. Remark: Laboratory-type Rogowski transducers usually are based on a coaxial cable where the shield is stripped-off partially and replaced by the sensing coil winded manually on the inner isolation tube of the cable. Because such a manufacturing is not adequate for low-cost mass production, Rogowski current transducers based on PCB-type windings have been proposed [3, 4]. These devices, however, show a rather low sensitivity M (coupling inductance) as a consequence of the few winding turns N which can be achieved if expensive fine pitch PCB techniques shall be avoided.

2.1. Transducer Sensitivity

In the following the sensitivity of a PCB-type Rogowski current sensor is calculated. Basically the output voltage $u(t)$ of a Rogowski coil is proportional to the rate of change of the current “surrounded” by the coil (here the capacitor current $i(t)$) according to $u(t) = M \cdot di(t)/dt$. A PCB transducer for power capacitor current measurement therefore has to be designed as indicated in Fig.2. The PCB shows two holes such that it can be directly attached on the capacitors power terminals similarly as for the shunt solution (Fig.1) but without affecting the capacitor current flow by power PCB traces. The Rogowski-winding is formed by radially copper traces on top and bottom layer of the PCB. The numerous (in total 2 x N) necessary through-hole vias may be seen as a drawback/reliability issue of such a transducer. In [4], however, good MTBF rates have been reported for PCB Rogowski coils, even for applications under nasty environmental conditions.

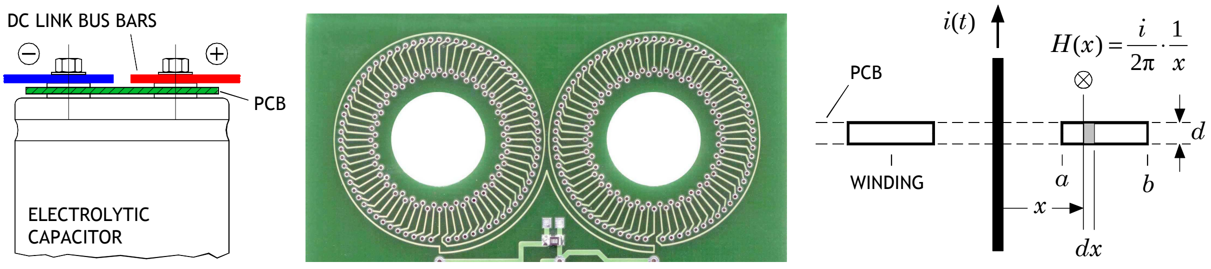
Calculating the total flux linked with a single turn using Ampere’s law $H(x) = i/(2\pi x)$ to determine the magnetic field $H(x)$ at distance x (Fig.2c) originated by the current $i(t)$ to be measured leads to

$$\phi(t) = \int B\,dA = \mu_0\, d \int_a^b H(x)\,dx = \mu_0 \frac{d}{2\pi} \cdot i(t) \cdot \int_a^b \frac{dx}{x} = \mu_0 \frac{d}{2\pi} \cdot \ln\frac{b}{a} \cdot i(t)\,. \tag{1}$$

With this, the total voltage induced in the Rogowski coil results to

$$u = N\frac{d\phi}{dt} = \mu_0 \frac{Nd}{2\pi} \cdot \ln\frac{b}{a} \cdot \frac{di(t)}{dt} = M \cdot \frac{di(t)}{dt}\ , \qquad \text{with} \qquad \boxed{M = \mu_0 \frac{Nd}{2\pi} \cdot \ln\frac{b}{a}} \tag{2}$$

representing the coupling inductance (=sensitivity) of the transducer. For a coil which is designed to fit



(a) (b) (c)

Fig.2: (a) Placement of PCB coil on monitored capacitor; (b) PCB Rogowski coil (actual width: 67mm); (c) geometric relationships for calculating the transducer’s sensitivity.

on an electrolytic capacitor of size Ø77x144mm the geometrical relationships typically are:

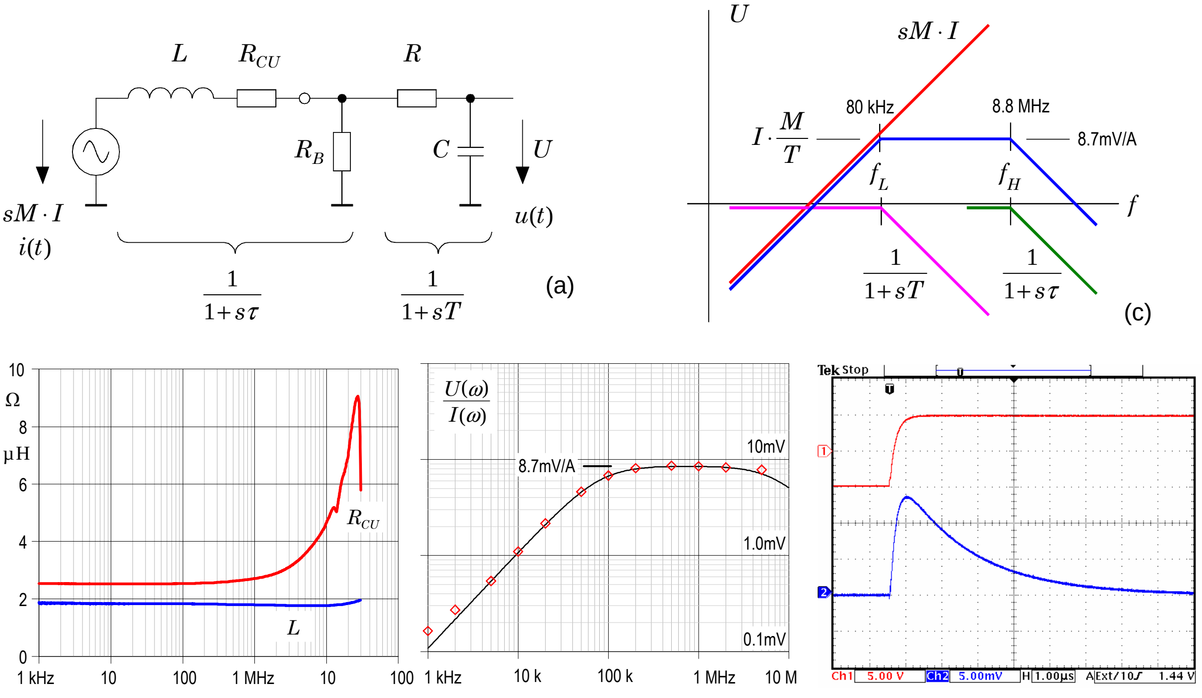
N = 2 x 72 = 144 turns a = 10mm b = 14.5mm d = 1.6mm leading to: $\underline{M = 17.4\text{nH}}$

The low number of turns which can be implemented by standard FR4-PCB techniques results in a rather low sensitivity which is a challenge for a low-cost signal conditioning amplifier/integrator.

2.2. Transducer Test using Passive Signal Integration

For achieving a current-proportional signal the output voltage of a Rogowski coil has to be integrated which can be performed, dependent on the frequency, (i) by the coil itself, (ii) by a passive (RC) integrator or (iii) by an active integrating amplifier (section 3). The equivalent circuit diagram (Fig.3a) of the transducer is formed by a voltage source representing the induced voltage $sM{\cdot}I$ in series to the self-inductance L and the ohmic component R_{CU} of the coil. For the case at hand the inner impedance of the coil described before has been determined to $L \approx$ 1.8µH and $R_{CU} \approx$ 2.5Ω using a Bode100© impedance analyzer (as given in Fig.3b no resonance effects appear up to several MHz). The coil now is terminated by a “burden” resistor of R_B = 100Ω which forms a low-pass filter with a time constant of $\tau = L/R_B$ = 18ns resulting in a cut-off frequency of f_H = 8.8MHz. Hence, for the frequency region being relevant for the ESR monitoring (typ. 10…100kHz) an explicit integrating stage is required. For a first test of the coil and for measuring its sensitivity M a RC-low-pass of $T = R{\cdot}C$ = 1kΩ·2nF = 2µs is used. According to the frequency characteristic of Fig.3c, the RC low-pass acts as integrator for frequencies $f > f_L = 1/(2\pi T)$ = 80kHz resulting in a total sensitivity of $U/I = M/T$ = 17.4nH/2µs = 8.7mV/A (because $R_{CU} << R_B$, R_{CU} is neglected).

The calculated sensitivity is verified using a standard function generator (output impedance 50Ω) which feeds a sinusoidal voltage of 20V$_{PP}$ via a “primary” (excitation) winding of 10 turns into a 50Ω load resistor (actually the input resistor of the measuring oscilloscope). This arrangement therefore gives a primary current excitation of 10·20V$_{PP}$/(2·50Ω)=2A$_{PP}$. The measured sensitivity $U(\omega)/I(\omega)$ (Fig.3d) shows a very good consistence with the calculated rates and with simulation results which is also true for a pulse response test (Fig.3e, Remark: The rise-time of $i(t)$ originates from the excitation windings self-inductance of $L_{PRIM} \approx$ 17µH resulting in $T_{PRIM} \approx$ 17µH/100Ω = 0.17µs).



(b) (d) (e)

Fig.3: (a) Equivalent circuit of coil, termination resistor R_B and passive integrator RC; (b) measured coil impedance; (c) passive integration frequency response; (d) measured frequency response (solid line: PSpice simulation); (e) pulse response of transducer, upper trace: $i(t)$ (1A/div), lower trace: $u(t)$ (5mV/div), 1µs/div.

3. Integrating Amplifier

The purely passive RC integration described before gives a good signal behavior for the high frequency region but results also in a poor lower cut-off frequency f_L. This transducers bandwidth could be extended to lower frequencies by using a higher time-constant $T=RC$ of the passive integrator. This, however, would also reduce the sensitivity M/T. To achieve low cut-off frequency and high sensitivity in general active integrators are applied for Rogowski coils. The well-known standard inverting OP-amp integrator (Fig.4a) shows good low-frequency response but problems appear at high signal frequencies. Due to the low amplifier gain at high frequencies (near the amplifier's unity-gain point f_U) the output impedance R_O is not compensated by the feedback loop. Hence the equivalent diagram transfers from an idealized inverting integrator at low frequencies (Fig.4b) in principle to a non-inverting voltage divider (R/R_O , Fig.4c) valid for very high frequencies. Due this behavior (which is somewhat similar to allpass filters) the frequency characteristic of a standard inverting integrator strongly differs from an idealized unit at high frequencies (Fig.4d).

A much better system response can be achieved if the integration task is split up into a passive circuit for integrating the high frequencies components and into an active part for low-frequency integration as proposed by [5]. This split-up is achieved by a series arrangement of a RC low-pass (LP) filter $1/(1+sT)$ located directly after R_B and a following PI-type amplifier of transfer function $(1+sT)/sT$ as indicated in Fig.4e. The frequency response of the total (non-inverting) circuit (Fig.4f) therefore again results to the required $1/sT$ leading finally to a transducer sensitivity of $M/T=$ 8.7mV/A (for frequencies below the coils cut-off frequency f_H), but now the high-frequency components do not have to be integrated by the op-amplifier stage and hence the output resistance effect is not as dominant as for the inverting integrator concept. As demonstrated by the simulation Fig.4d the non-inverting circuit roughly gives a tenfold upper frequency limit. The good dynamic performance is also demonstrated by the simulated pulse response of the transducer even if an ultra-low-cost op-amp (LM833) is used. On contrary, the inverting integrator of Fig.4a would result in a very pronounced overshoot.

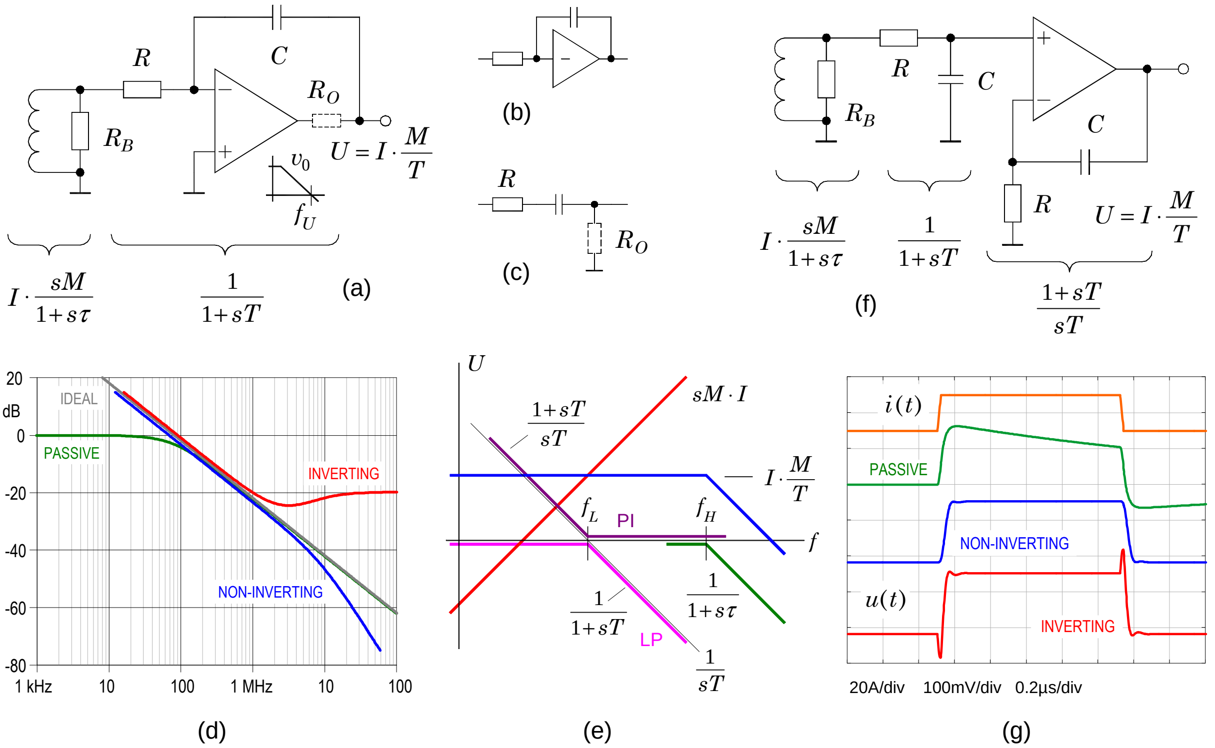


Fig.4: (a) Conventional (inverting) op-amp integrator; equivalent circuit for (b) low and (c) high frequencies; (d) simulation results of frequency response of different integration concepts (parameters: quasi-idealized op-amp, v_0= 100dB, f_U=10MHz, R_O=100Ω); (e) basic concept of non-inverting integrator: split-up of integration into a low-frequency PI-part and into a passive high-frequency circuit (LP) using circuit (f); (g) simulated pulse response (primary coil input current $i(t)$ to op-amp output voltage $u(t)$ using LM833 device).

4. Transducer Prototype

4.1. Circuit Design and Dimensioning

The sensitivity of the circuit analyzed in the previous section (8.7mV/A) still is rather low. For the projected application a about tenfold value would be optimal such that the output voltage shows an amplitude which can be well processed by microcontrollers (e.g. 25A scaled to ≈2V). A simple possibility to increase the sensitivity is to reduce the integration time constant (e.g., T= 2µs → 0.2µs). But this, however, also would shift the transition frequency for the active/passive integration from $1/(2\pi T)$ = 80kHz to 800kHz, i.e., there is a much higher requirement concerning the op-amp bandwidth. Consequently, a different approach is used here based on the fact that reducing the integrator time constant is similar to increasing the gain. Because low-cost op-amps usually are available in a dual amplifier configuration (two devices in a single case) the increased transducer sensitivity simply can be achieved by inserting an additional gain block $k = 1+R_1/R_2$ between passive and active integration stage (Fig.5). Furthermore, an additional bandpass filter is inserted between gain block and final (PI-type) integrator. This filter originates from the fact that for the aimed application (ESR monitoring of electrolytic capacitors) specifically frequency components have to be considered, where the capacitor's impedance is dominated by the ohmic ESR (typ. 1…30kHz). (Remark: For demonstrating the performance of the transducer this bandwidth has been widened here to ≈10Hz…1MHz.) The bandwidth filter also brings the advantage that the offset voltage component of the gain block is decoupled from the integrator stage which for similar reason is equipped with a 1MΩ feedback resistor in parallel to the integrating capacitor. Using the PCB coil of section 2.1, a component dimensioning according to Fig.5 gives k =11 and a total transducer sensitivity of $k \cdot M/T$ =11·17.4nH/2.2µs = 87mV/A. For the op-amplifier no specific high-performance device is required. A simple low-cost audio amplifier is sufficient which also gives the advantage of good noise performance. All components are directly mounted on the coil's PCB resulting in an very cheap easy-to-use device (Fig.6).

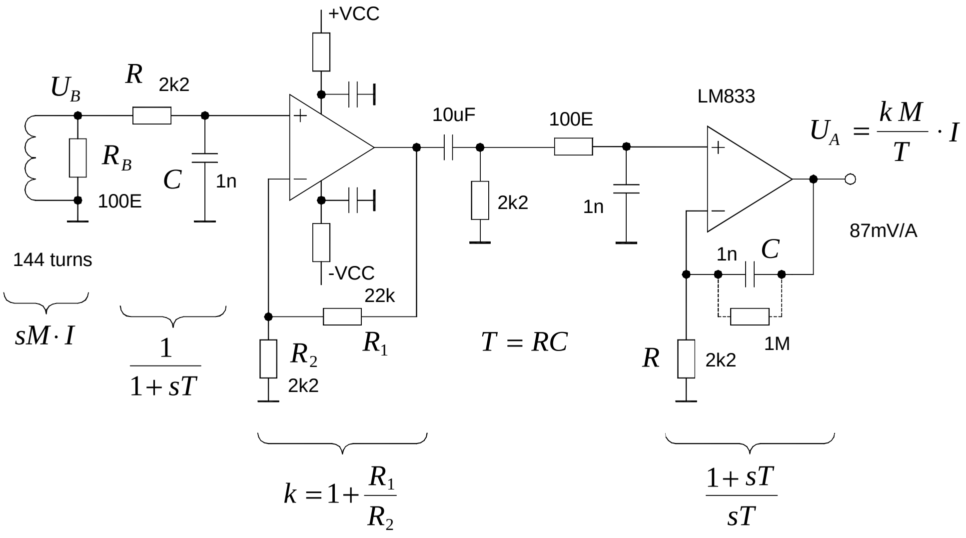


Fig.5: Circuit diagram of the implemented Rogowski coil transducer.

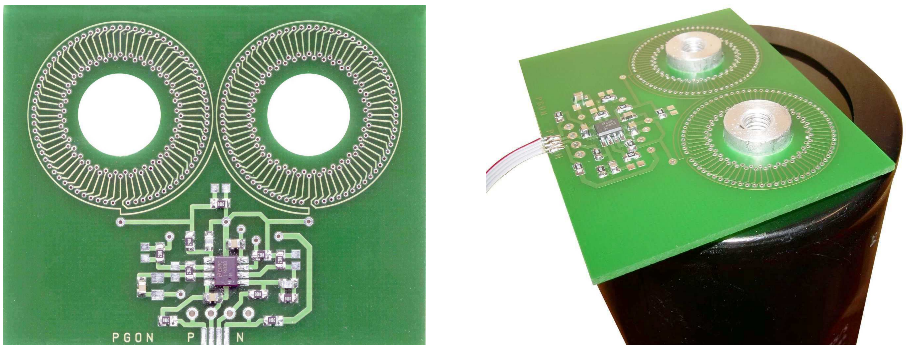
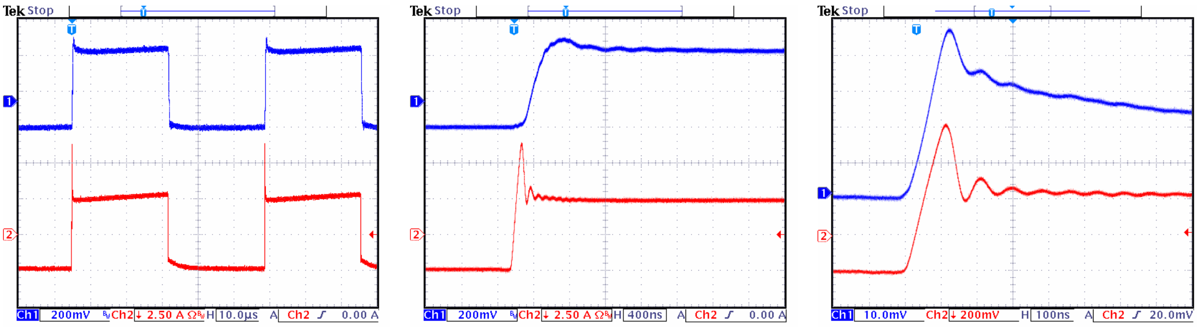


Fig.6: Implemented PCB transducer (left) placed to an electrolytic power capacitor for current measurement (right).



(a) (b) (c)

Fig.7: Measurement results of the Rogowski-coil transducer; (a, b): top curves: op-amplifier output voltage U_A (200mV/div), bottom curves: capacitor current measured by Tektronix TCP305 current probe (2.5A/div); (a) 20kHz DC link capacitor current of IGBT buck converter; (b) zoom view (400ns/div) showing high-frequency response (reverse recovery current of diode); (c) output voltage (upper trace) of passive integration stage (10mV/div, 100ns/div).

4.2. Measurement Results – Conclusions

The measurement results (Fig.7a) demonstrate that the circuit works very well for the aimed application. The output of the Rogowski-module (upper trace) closely matches the actual current (DC link capacitor current of a 20kHz buck converter taken with a 50MHz active current probe TEK305 (lower trace)). The current spike indicated by the TEK305 in Fig.7b (i.e., the reverse recovery current of the converters free-wheeling diode) however is missing. This effect (being not of significance for the aimed ESR monitoring application) is a consequence of using an ultra-low-cost op-amp for integrating. The PCB-coil itself gives an adequate transient response up to typically 30MHz (cf. Fig.7c, coil with pure passive integration) which can be utilized if required by application of a high-frequency op-amplifier.

The presented transducer gives a very cheap and reliable solution for measuring AC current components in PWM modulated converters. The required integration of the Rogowski coil’s output voltage is performed by a frequency split-up scheme using active integration for the lower frequency range and passive (low-pass) integration for high frequency signal components. With this a typical bandwidth of 100Hz to 1MHz can be achieved also by using standard op-amplifiers, especially if an “intermediate” amplifier/gain stage is used. Due to the very low output voltages of the coil (as a result of the low turns number of common PCB technology) the transducer, however, may be sensitive to surrounding high-frequency noise sources like MHz-power supplies for gate drivers etc. in close vicinity. For such conditions (provided that the signal frequencies are well beneath) additional passive filtering stages in the passive integration path are recommended.

5. Literature

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