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doi:10.15199/48.2015.04.08

Air core transducer with increased measurement sensitivity

***Abstract**. In this paper the construction and electrical parameters of an air core current to voltage transducer based on the Rogowski coil principle are presented. The transducer has been manufactured in PCB HDI technology with track width and track to track distance less than 100 µm. The sensitivity and the measurement bandwidth of the transducer has been presented together with considerations on the transducer output signal amplifier.*

***Streszczenie.** W artykule przedstawiono konstrukcję oraz parametry elektryczne bezrdzeniowego przetwornika prądu na napięcie pracującego na zasadzie cewki Rogowskiego. Przetwornik został wykonany w technologii PCB HDI przy szerokości ścieżki i szerokości odstępu między ścieżkami mniejszej niż 100 µm. Zaprezentowano czułość oraz szerokość pasma pomiarowego przetwornika oraz podano wymagania na wzmacniacz sygnału wyjściowego przetwornika. (**Bezrdzeniowy przetwornik prądu na napięcie o zwiększonej czułości pomiarowej)**.*

Keywords: Rogowski coil, PCB technology, voltage amplifier
Słowa kluczowe: cewka Rogowskiego, technologia PCB, wzmacniacz napięciowy

Introduction

Current-to-voltage transducers based on Rogowski coil principle are best suited for applications requiring measurement of large current in wide frequency bandwidth. The output voltage signal of Rogowski coil is proportional to the derivative of the current in the primary circuit. Typical Rogowski coil sensitivity, defined as the ratio of the RMS value of the output voltage to the RMS value of the 50 HZ sinusoidal primary current, is equal to 1 mV/A. The sensitivity of Rogowski coil depends on its geometrical construction and is proportional to the area of the turns that make the coil and to the density of the turns [1]. The output signal of the coil in the lower range of measured currents needs significant amplification. The advent of modern electronics and digital processing techniques have enabled the development of signal conditioning circuits that can take full advantage of large dynamic range and wide bandwidth of the Rogowski coil.

Construction of the transducer

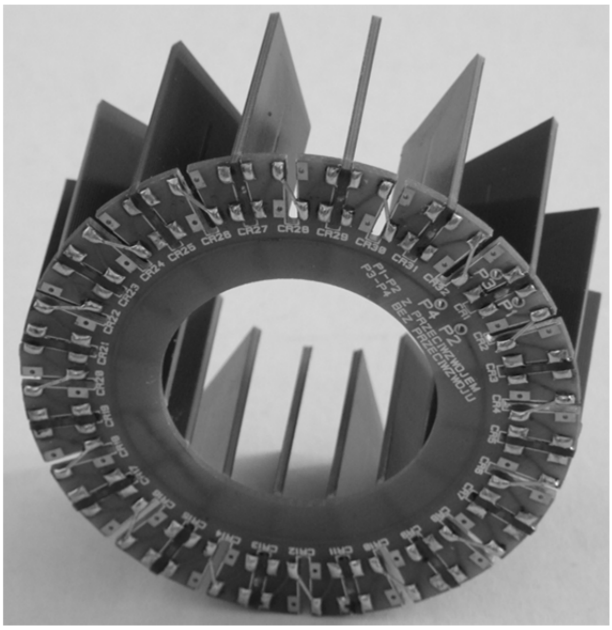

Fig. 1. Rogowski coil constructed in PCB technology

The traditional technology used for making Rogowski coil consisted in winding a wire on a nonmagnetic tubular carcass. The development of printed circuit board technology (PCB) has enabled new technologies of Rogowski coil manufacture [2]. The coil is constructed from multilayer PCB boards attached to a base board which provides mechanical support and connects all boards together electrically (fig. 1). The coil on each layer is in the form of a spiral and the coils on neighboring layers are connected by vias. The electrical parameters of Rogowski coil manufactured in multilayer PCB are similar to those obtained with traditional technology. The advantages of multilayer PCB Rogowski coils are the possibility of automating the manufacturing process and very high repeatability of electrical parameters of the coil.

PCB HDI technology in transducer manufacture

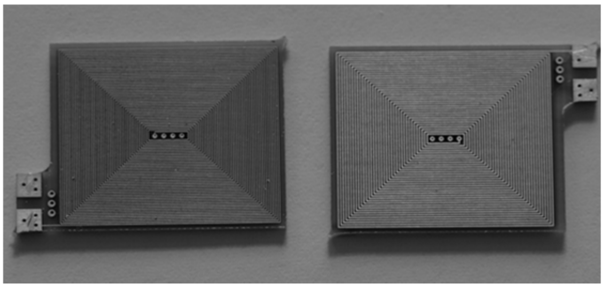

Fig. 2. Multilayer boards forming the PCB Rogowski coil

With traditional PCB technology (track width ≥ 100 µm, track to track distance ≥ 100 µm) and typical coil dimensions, the maximum coil sensitivity that can be obtained is about 5 mV/A [2]. The method to increase the sensitivity of the Rogowski coil manufactured in PCB technology is to increase the effective area of a single spiral coil [2]. This can be done by increasing the number of spiral turns that together make the inductance on a single layer. For that purpose, the multilayer PCB HDI (High Density Interconnect) technology can be used. This technology is characterized by track width and track to track distance less than 100 µm. With 50 µm PCB HDI technology, theoretically twice as many turns as with 100 µm PCB technology can be placed on each layer. The effective coil area then increases by a factor of two and accordingly the sensitivity increases by the same factor. Two boards with printed circuit coils of different track width have been shown in fig. 2. The board at the left has coil with 48 turns and the board at the right has coils with 36 turns.

Decreasing the track width by a factor of two and increasing the track length by the same factor effectively quadruples the coil resistance. That means that the thermal noise at the transducer output is doubled. Because the sensitivity of the coil is also doubled, the signal to noise ratio remains the same.

Another way to increase the transducer sensitivity is to use the printed coils with larger area, fig. 3. With this method it is possible to quadruple the sensitivity of the transducer without significantly compromising other measurement parameters like bandwidth.

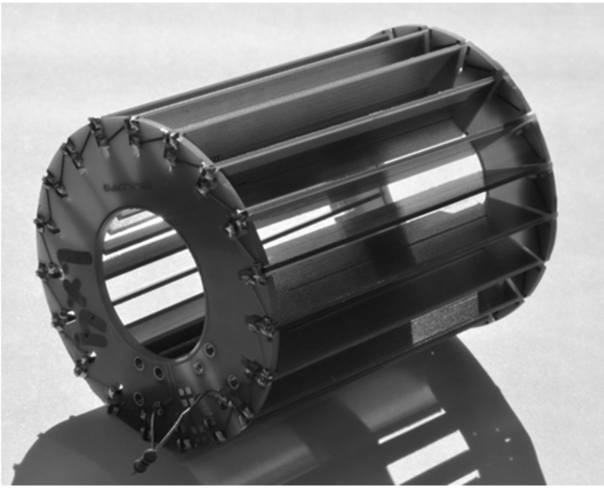

Fig. 3. Transducer with printed coils elongated in the direction of measured current

Electrical parameters of the transducer

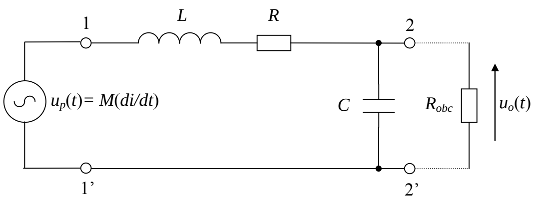

Fig. 4. Rogowski coil electrical equivalent circuit

The equivalent electrical circuit of the transducer based on Rogowski coil principle is presented in Figure 4. The voltage source up(t) is proportional to the derivative of the primary current with the proportionality constant equal to the mutual inductance M. M depends on the geometry of the transducer and determines its sensitivity. R is the resistance of the copper track that makes the transducer inductance. L is the self-inductance of the coil. C is the inter-coil capacitance. R, L and C determine the transducer frequency bandwidth. The frequency characteristic of the two-port between 1-1' and 2-2' terminals exhibits a resonance at a frequency f_r equal to

$$f_r = \frac{1}{2 \cdot \pi} \sqrt{\frac{1}{LC} - \frac{1}{2}\left(\frac{R}{L}\right)^2} \tag{1}$$

Values of R, L, C and f_r for typical transducers made in traditional and HDI PCB technology are presented in Table 1.

Table 1 Transducer parameters

Parameter	R [Ω]	L [H]	C [pF]	f_r [kHz]
Traditional PCB technology	1000	0,01	121	144,248
HDI PCB technology	8000	0,065	145	49,957

The resonance frequency of the transducer, f_r, manufactured in HDI PCB technology, with R, L, C values from Table 1 is equal to 43.8 kHz so the bandwidth of the transducer is still wide enough for current measurement up to 40th harmonic.

The transducer resistance, R, shows large spread during the manufacturing process. This is due to the over etching of the copper track that makes the coil during PCB board manufacture. The large value of R is disadvantageous because of the thermal noise at the transducer output. For R = 8 kΩ, T = 343 K (it corresponds to 70 °C), the RMS noise in the bandwidth from 0 Hz to 10 kHz, is equal to 1.3 μV. The thermal noise limits the current measurement resolution to about 1.3 mA with coil sensitivity 1 mV/A. It means, that the measurement uncertainty due to noise is 1.3 % when measuring 100 mA current.

Methods to compensate the temperature influence

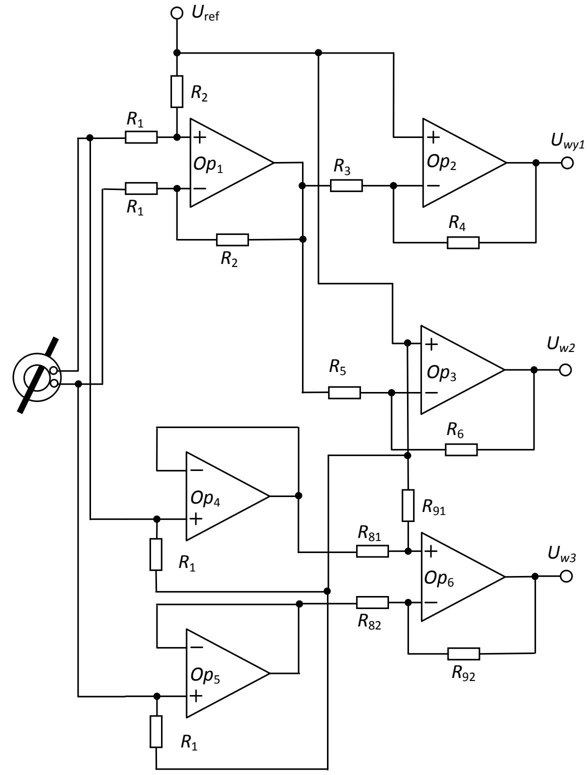

Fig. 5. High impedance amplifier in the Rogowski coil signal conditioning path

The transducer resistance together with the amplifier input resistance form a voltage divider that is temperature dependent. With coil resistance equal to 8 kΩ and input resistance of the amplifier equal to 50 kΩ (this is the typical input resistance of differential input amplifier), the voltage divider ratio is equal to 0.8621. The copper resistance temperature coefficient is equal to 0.39 %. However, the resistors forming the amplifier input resistance are temperature compensated. Assuming 50 °C temperature change, the coil resistance changes to 9.56 kΩ and the voltage divider ratio changes to 0.8395. The percentage change in voltage divider ration is equal to 2.6 %. Such change in the input path amplification ratio with temperature is unacceptable so measures have to be undertaken to compensate for the temperature influence.

There are three possible solutions to eliminate the temperature influence on the amplification of the signal input path. One possible method consists in using a thermistor in the input voltage divider. Another solution is to eliminate the temperature influence programmatically but one needs to measure the temperature to apply this method. The best solution is to increase the input amplifier resistance by an order of magnitude. The circuit diagram of high impedance input amplifier has been shown in figure 5. The operational amplifiers Op4 and Op5 work in high impedance voltage follower mode and, together with Op6, they cover the lower part of measurement range. The operational amplifiers Op2, Op3 and Op1 provide the amplification necessary to cover the higher part of the measurement range of the transducer.

Conclusion

High Density Interconnect (HDI) technology makes it possible to construct a magnetic field transducer working on the Rogowski coil principle with measurement sensitivity equal to 10 mV/A that is unattainable with traditional PCB technology. However, the increase in sensitivity comes at a cost which is the increased impedance of the transducer. This increased impedance demands the use of high impedance input amplifier and additional shielding from the external magnetic fields.

Acknowlegement

This work was supported in part by Polish The National Centre for Research and Development (Project No. PBS1/B4/2/2012).

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